

Modern Antenna

Anyong Qing
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Microwaves, Millimeter Wave and Terahertz Liquid Crystals

Preparation, Characterization
and Applications

 Springer

Modern Antenna

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Anyong Qing · Yizhe Zhao · Zhiyong Zhang

Microwaves, Millimeter Wave and Terahertz Liquid Crystals

Preparation, Characterization
and Applications

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Foreword by Prof. Yongxin Guo

In essence, the emerging high-bandwidth 5G communications and the forthcoming 6G communications would be impossible without cutting-edge microwave, millimeter wave and terahertz technologies. One of the serious challenges the community has been facing is the more and more stringent requirement on size and weight of high-performance devices. Reconfigurability has long been proposed as one of the most promising solutions. A number of approaches such as ferrite, piezo-electrics, micro-electro-mechanical systems, solid-state positive-intrinsic-negative diodes, ferroelectric barium strontium titanate and ferrimagnetic yttrium iron garnet have been examined. Unfortunately, as the operating frequency is pushed higher and higher, the performance of traditional tunable elements degrades while their fabrication complexity and cost increase.

Liquid crystal has been witnessed as the more recent game player or even the game changer for reconfigurability. Incorporating liquid crystal can bring about many advantages over its counterparts. Extensive and intensive researches on microwave, millimeter wave and terahertz liquid crystal in the past two decades have blossomed numerous exciting reconfigurable devices. Unsurprisingly, microwave, millimeter wave and terahertz liquid crystal has been one of the hot research frontiers, engaging scientists and engineers all over the world. Unfortunately, no focused book has been published as of today although a number of featured review articles have been diversely scattered.

I am privileged to read in advance Anyong's new book on microwave, millimeter waves and terahertz liquid crystal. Anyong, Yizhe and Zhiyong not only draw the full picture of the state of the art but also showcase their impressive ingenious research progress. As far as I know, this must-have monograph is the first ever in this interdisciplinary field.



Prof. Yongxin Guo
Fellow, IEEE
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Foreword by Qun Frank Yan

It is my great pleasure to read *Microwaves, Millimeter Wave, and Terahertz Liquid Crystals: Preparation, Characterization and Applications*. This interdisciplinary monograph is a timely and important addition to the field of liquid crystal research.

Liquid crystal display (LCD) technology has revolutionized the information-display industry and benefited our human being in modern society. However, the potential of liquid crystals extends far beyond displays, and this book serves as a testament to the exciting and rapidly evolving research in this field. In the past two decades, liquid crystals have shown impressive progress in various fields, including biology, biomedicine, chemistry, materials science, medicine, optics, optoelectronics, pharmaceuticals, photovoltaics, physics and electromagnetic applications, particularly in microwave, millimeter wave and terahertz frequencies.

Professor Qing and his team have made significant contributions to this field, including the development of liquid crystal-based digital metamaterials of arbitrary base. This book provides an extensive and comprehensive overview of the current state of the art and future trends of liquid crystal research, making it an essential resource for researchers, professionals and industrial practitioners interested in liquid crystal materials. Furthermore, it is a valuable reference for scientists, engineers and students from various disciplines, such as materials, chemical, electrical, biological and biomedical engineering.

Overall, this book is an excellent contribution to the field of liquid crystal research, and I highly recommend it to anyone interested in this exciting and rapidly evolving area of study.



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Preface

A Little Background

Liquid crystal, sometimes referred to as the fourth state of matter or mesophase, is a unique state of matter that has properties between those of conventional liquids and those of solid crystals. It has changed our vision of matter by shattering the three-state paradigm. Within a specific temperature range, liquid crystal materials do not change from crystals or solids directly to isotropic fluids when they melt but go through a series of thermodynamically stable intermediate mesophases.

For a long time, liquid crystals were merely scientific curiosity. A few groundbreaking discoveries in the 1960s led to the overwhelmingly ubiquitous LCD today. With more and more liquid crystal properties explored and exploited, liquid crystal quickly accelerates its momentum beyond the narrow niche of display.

Liquid crystal is inherently promising for electromagnetic applications because of its tunable electromagnetic anisotropy. Extensive and intensive researches have significantly advanced liquid crystal into one of the hot research frontiers for cutting-edge microwave, millimeter wave and terahertz technologies. With the arrival of 5G communications and the forthcoming 6G communications, liquid crystal has been anticipated to play a crucial role to meet the imperative need for compact, versatile and lightweight microwave and millimeter wave devices in portable devices and communication hubs. We have been witnessing soaring applications in the past two decades.

Although numerous papers have been published, to the best knowledge of the authors, this is the first ever interdisciplinary monograph on microwaves, millimeter waves and terahertz nematic liquid crystals.

About This Book

Contents

This book opens with an introduction and elementary physics of generic liquid crystal, followed by a retrospective review of microwave, millimeter waves and terahertz applications of nematic liquid crystals. Latest in-house research progress including synthesis of liquid crystal, measurement of dielectric properties, fabrication of functional devices and a few representative advanced functional devices is then presented.

Chapter 1 gives an introduction to generic liquid crystals. First of all, the basic concept of liquid crystals is explained. Some well-known examples of liquid crystals are given to familiarize readers with first hand impression. Next, the history of liquid crystal is chronologically presented. Historical milestones and pioneers are highlighted. After that, a systematic classification of liquid crystals is conducted. This chapter ends with a briefing of applications of liquid crystals based on the latest literature survey, featuring only well-established, commercialized or even industrialized applications.

The performance of liquid crystal is dependent on a variety of internal and external factors. A crucial step in the industrial applications of liquid crystal is the theoretical understanding of the liquid crystal phases for controlling, predicting and even engineering liquid crystal properties. In Chap. 2, elements of the intricate interdisciplinary liquid crystal physics are briefed. Attention is focused on nematic liquid crystal. More importantly, in consistency with the featured applications of liquid crystal in microwave, millimeter wave and terahertz frequencies, electromagnetic properties critical for such electromagnetic applications as well as effect of electromagnetic fields on liquid crystals are given more concerns.

Chapter 3 begins with a brief introduction of the electromagnetic spectrum with intensified interest in microwave, millimeter wave and terahertz wave bands. An overview about applications of liquid crystal at microwave, millimeter wave and terahertz wave frequencies is next presented. The overview and the following topical reviews are based on a literature survey and the collected literatures. Finally, brief reviews on more specific topics are given.

Synthesis of novel nematic liquid crystal mixtures with high dielectric anisotropy, low dielectric loss, and low melting point for K-band application is presented in Chap. 4. The effect of molecular structure on dielectric properties is studied first, followed by a study on the temperature dependence of dielectric property and viscosity of liquid crystal. Forty-five intermediate liquid crystal compounds in 5 series with high dielectric anisotropy, and low melting point are then synthesized. Ultimately, seven new microwave nematic liquid crystal mixtures with different dielectric anisotropy are developed.

In Chap. 5, a new perturbation method of double-ridge waveguide resonator is proposed for microwave characterization of liquid crystals. It meets the requirements

of accurately testing the dielectric anisotropy, dielectric tuning characteristics, dielectric loss and required working frequency band of the microwave nematic liquid crystal. This method provides valuable information for understanding microwave nematic liquid crystals and further research and development of microwave nematic liquid crystal materials.

Liquid crystal cell is one of the essential elements in reconfigurable microwave, millimeter wave and terahertz functional devices. In Chap. 6, a process for fabricating nematic liquid crystal cells for microwave, millimeter wave and terahertz functional devices is presented. It is based on a xenomorphic substrate and solves the packaging and uniformity issues of large and thick nematic liquid crystal layer.

Microwave phase shifters are one of the core components in electronic information systems and phased array radar systems. In Chap. 7, a miniature K-band microwave nematic liquid crystal-based phase shifter that can realize 360° phase shift in K-band is proposed.

A frequency tunable and pattern reconfigurable 1×4 phased array antenna is designed in Chap. 8. Numerical simulation proves that the antenna can dynamically adjust its operating frequency between 14.5 GHz and 16.4 GHz and continuously and dynamically control the beam direction between -20° and 20° .

In Chap. 9, nematic liquid crystal (NLC) is introduced to develop novel metamaterials, namely multifunctional digital metamaterials of arbitrary base. A proof-of-concept prototype consisting of a superstrate of quartz, an array of metallic patches, a substrate of NLC and a ground is proposed. The novel coding mechanism has been proven through both numerical simulation and preliminary experiments. The potential of the novel metamaterial is demonstrated by two representative applications.

Readership

The presented studies will attract scientists, engineers and students from various disciplines, such as materials, chemical, electrical, biological and biomedical engineering. The book is intended for undergraduates, graduates, researchers, professionals and industrial practitioners who are interested in developing novel liquid crystals and further extending liquid crystals beyond display.

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I would like to take this opportunity to thank editor Mengchu Huang for coordinating the publication of this book and Prof. Junping Geng for accepting this book into the prestigious book series. I would also like to thank other editors and reviewers for their hard team work. Special thanks would go to Prof. Qun Frank Yan and Prof. Yongxin Guo, Prof. Junhong Wang of Beijing Jiaotong University, Prof. Zengrui Li of Communication University of China, Prof. Weirong Chen of Southwest Jiaotong University, Mr. Zhidong Wang of BOE Technology Group Co., Ltd. (BOE) and all members of my group.

Preparing a book is a long and arduous process. I could not have done it without the support of my family. I have been a Professor of National Young Thousand Talent since November 2012, leaving all of my family in Oakville, Canada. It is very hard to imagine the hardship my wife and my children have undergone until today. They have made so much sacrifice to support me. Thank you so much, Jiaoli, Chen and Tian.

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Chapter 1

Introduction to Liquid Crystals



This chapter gives an introduction to generic liquid crystals. First of all, the basic concept of liquid crystals is explained. Some well-known examples of liquid crystals are given to familiarize readers with first hand impression. Next, the history of liquid crystal is chronologically presented. Historical milestones and pioneers are highlighted. After that, a systematic classification of liquid crystals is conducted. Liquid crystals are classified according to different criteria. As far as the authors know, such a classification is unique from the point of view of comprehensiveness of classification criteria. This chapter ends with a briefing of applications of liquid crystals based on the latest literature survey, featuring only well-established, commercialized or even industrialized applications.

1.1 Fundamentals of Liquid Crystals

1.1.1 *Basic Concept*

Liquid crystal (LC) is an oxymoron term that does not bear scrutiny and triggered polemics and passionate reactions [1–3]. Otto Lehmann's excessive attachment to the concept probably led to errors that required several decades to correct (Fig. 1.1). Lehmann's term "liquid crystal" remained widespread in scientific usage even today.

Liquid crystal, sometimes referred to as the fourth state of matter or mesophase (Greek: *mésos* = center), is a unique state of matter that has properties between those of conventional liquids and those of solid crystals. It has changed our vision of matter by shattering the three-state paradigm. As a matter of fact, a liquid crystal is not crystal at all, but a peculiar liquid with some hint of solid properties [4, pp. 90]. Within a specific temperature range, liquid crystal materials do not change from crystals or solids directly to isotropic fluids when they melt but go through a series of thermodynamically stable intermediate mesophases. In this sense, the term

Fig. 1.1 Otto Lehmann

mesophase was coined and advocated by Georges Friedel in 1922 [5] to represent the intermediate states more accurately and has since been widely accepted.

In the mesophase state, liquid crystal materials retain both the fluidity and continuity of fluid and the orientation order and anisotropy of crystal. A liquid crystal may flow like a liquid, but its molecules may be oriented in a crystal-like way. Both the transformation from crystal to liquid crystal state and the transformation from liquid crystal state to fluid have a fixed temperature, enthalpy change, and entropy change.

Liquid crystal materials are a key component in today's technology because they possess unique optical and electrical properties. As research into this field continues and as new applications are developed, liquid crystals will play an even more important role in modern technology.

1.1.2 Examples

Examples of liquid crystals can be found in both the natural world and technological applications. Widespread liquid-crystal displays (LCD) use liquid crystals. Many

common fluids, such as soapy water, are in fact liquid crystals. Soap forms a variety of LC phases depending on its concentration in water [6].

1.1.2.1 Biological Liquid Crystals

Lyotropic liquid-crystalline phases are abundant in living systems. In particular, biological membranes and cell membranes are a form of liquid crystal. Many other biological structures, for instance, spidroins, the concentrated protein solution that is extruded by a spider to generate silk, actively-driven cytoskeletal filaments [7], and monolayers of elongated cells [8], exhibit liquid–crystal behavior.

1.1.2.2 Mineral Liquid Crystals

Mineral liquid crystals [9–11], [12, pp. 119–172], [13], for example, vanadium(V) oxide, have been found in as early as 1925. Rapid development of nanosciences and the synthesis of many new anisotropic nanoparticles brings quickly increasing number of mineral liquid crystals with carbon nanotubes and graphene such as H3Sb3P2O14 [14, 15].

1.2 History of Liquid Crystals

In this section, we briefly retrospect the history of liquid crystals [1, 2, 16–27]. It is by no means exhaustive since this area is still very open and very active to this day.

1.2.1 *Discovery of Liquid Crystals*

The discovery of liquid crystal was generally credited to Austrian botanist Friedrich Reinitzer (Fig. 1.2) [28] for his detailed description of the surprising “two melting points” of cholesteryl benzoate [29–31], and more importantly, his acute insight of the existence of a new state of matter which flows like a liquid but has the optical property of double refraction characteristic of crystals. It was one of the most important discoveries of the nineteenth century [4, 26] and opened the door to further liquid crystal research and eventually displays and other applications.

The first scientific record of the unusual behavior of liquid crystals can be traced back to Buffon’s complete works published in 1840 [32, 33] where he speaks of “writhing eels” obtained by dilacerating wheat or rye ergot in water. Under the polarizing microscope, Buffon observed the growth of tubular objects, the myelin figures, at the myelin-water interface [33]. In 1857, the ophthalmologist Carl von

Fig. 1.2 Friedrich Reinitzer

Mettenheimer also observed birefringence and myelin figures in myelin, a soft sheath surrounding nerve fibers identified by Rudolf Virchow in 1850 [26, 33–37].

In 1854, Virchow [38] observed the distinct color effects in myelin in contact with water when cooling them just above the freezing point. Upon cooling, the material exhibited violet and blue colors, which then disappeared, leaving the substance cloudy but still liquid. The phenomenon was soon observed in cholesterol esters [26, 39–42].

Unfortunately, none of these biologists realized that they were dealing with new states of matter other than the liquid state and the crystalline solid state. Interesting, Marcellin Berthelot and others falsely attributed this remarkable phenomenon to contamination of their preparations. What is worse, the complexity of their observations and the difficulty of duplicating them did not encourage them to pursue their investigations.

In 1888, at the Institute of Plant Physiology of the German University of Prague, while working on crystals of cholesterol derivatives extracted from a carrot's root to elucidate their structure, Reinitzer observed the unexpected “two melting points”. The small crystals lost their rigidity at 145.5 °C—this “first” melting point was the temperature at which the solid turned into a milky fluid. At 178.5 °C—the “second” melting point, later named the clearing point—the drop of material became perfectly transparent. Besides, Reinitzer also observed the reflection of circularly polarized light, and the ability to rotate the polarization direction of light by cholesteric liquid crystals. On May 3, 1888, Reinitzer published his early observations of liquid crystals with colours and double melting [43], although he did not recognize them as such.

1.2.2 *Proof of Liquid Crystals*

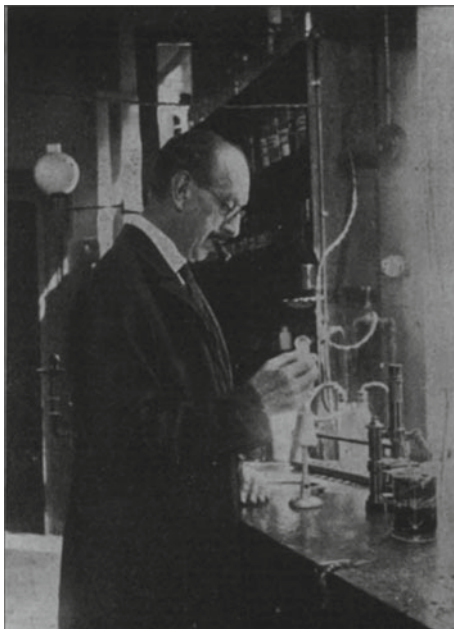
The amazing accidental discovery of “two melting points” was communicated in a 16-page letter dated March 14, 1888 to crystallographer Otto Lehmann with two samples of cholesterol-acetate and cholesterol-benzoate [3, 26, 29, 33]. Lehmann was approached for his renowned expertise in polarizing microscope and work on isomorphism and polymorphism of crystals. They exchanged numerous letters and samples before April 24. Lehmann examined the intermediate cloudy fluid and reported seeing crystallites.

After Reinitzer’s discovery, Lehmann, the prime researcher of liquid crystals and the only one to promote the subject for more than a decade, launched a profound study on cholesteryl benzoate and more than 100 related liquid crystal materials. He was quickly convinced that the milky liquid had the characteristics of both a crystal and of a liquid. He reported his first results on August 20, 1889 in a letter to Reinitzer. By the end of August 1889 he had published his results in the *Zeitschrift für Physikalische Chemie* [44] in which he used the term “flüssige Kristalle” or crystal that flows. Lehmann published numerous papers between 1890 and 1900 [45, 46], and the names followed each other: flowing crystal, viscous liquid crystals, crystalline fluid, liquid crystals forming drops. The term “liquid crystals” first appeared in a compiled generous treatise [26, 47] in 1904.

Reinitzer’s discovery and Lehmann’s proof of liquid crystals undercut the presumption that solid and liquid are adjacent states of matter. However, at the end of the nineteenth century, most scientists did not believe in the existence of “liquid crystals” as promoted by Lehmann even though an increasing volume of similar observations were reported following the seminal works of Lehmann. Lehmann’s main opponents from 1890 to 1905 include Georg Hermann Quincke, Gustav Heinrich Johann Apollon Tammann [48, 49], Wulff [50], and Walther Nernst. Essentially, these scientists were suspicious about the turbidity of the samples studied by Lehmann and clearly challenged the purity of the compounds. The colloidal hypothesis was put forward to explain Reinitzer’s discovery. Heated debates opposed those that pleaded for chemically and physically homogeneous phases to the ones holding that the optical turbidity was a result of either demixing impure substances or incomplete melting of the crystalline phase. It was argued that Lehmann’s liquid crystals were in fact a colloidal solution, either suspension or emulsion. The controversies were so vivid that nobody else was engaged in the field for fifteen years and the recognition of mesomorphic states of matter by the scientific community required more than two decades.

The colloidal hypotheses did not fit very well with the observations. In 1889, Ludwig Gattermann (Fig. 1.3) and A. Ritschke made the first chemical synthesis of liquid-crystal molecules: para-azoxyanisole (PAA) and para-azoxyphenetole (PAP). The purity of these compounds was an argument against the hypothesis of poorly controlled mixtures given by Lehmann’s opponents. Gattermann and Ritschke observed similar birefringence and fluidity in PAA [33, pp. 14] soon after the publication of Lehmann’s paper. They published an article in 1890 [51] in which the

Fig. 1.3 Ludwig Gattermann



term “liquid crystal” (Flüssige Kristalle) appeared for the first time. In 1904, electrophoresis experiments [52, 53] excluded the hypothesis of a colloidal fluid because no separation of particles by applying an electric field to liquid crystals can be observed as expected. In 1905, in a conference seminar [26], the physical chemist Rudolf Schenck (Fig. 1.4) gave a solid demonstration of a discontinuity in the density and viscosity at the clearing point, which could not be the behavior of an emulsion. In addition, purification did not change the behavior; “liquid crystals” did exist. From this moment on, the controversy gradually died down, although an explanation of the famous liquid crystals was still lacking.

1.2.3 Mesomorphic States of Matter

In 1903, an article [54] on the origin of liquid–crystal phases appeared from the group of Daniel Vorländer (Fig. 1.5) at University of Halle, Germany. It focused on the classification of compounds based on whether or not they give rise to a liquid–crystal state. In 1907, Vorländer [21, pp. 84–88], [55] showed that the real origin of liquid crystallinity is not so much a microscopic shape as noted by Lehmann but rather molecular shape. He pointed out that most substances that give rise to liquid–crystal phases are made with rod-like molecules. In the same year, Emil Bose provided the first theory of the liquid–crystal state [26], based on the work of Schenck and Vorländer.

Fig. 1.4 Rudolf Schenck



Fig. 1.5 Daniel Vorländer



D. Vorländer

Fig. 1.6 Georges Friedel

Georges Friedel (Fig. 1.6) at St. Étienne, France was the first to come up with the idea that liquid crystals are distinct states of matter in their own right, whose molecular structures were intermediary between ordinary isotropic liquids and crystals. In 1910, Friedel and his assistant Grandjean [56, 57] agreed that Lehmann's liquids are representatives of a new state of matter. But different from Lehmann Friedel called them anisotropic liquids instead of liquid crystals. Friedel gave a complete overview of the 230 space groups in 1911 and obtained a clear comprehension of the structure at the molecular level, allowing for the classification of all possible crystalline structures in three dimensions [58]. Finally, in 1922, Friedel named the new states of matter "Mesomorphic States of Matter" [5], [21, pp. 139–161]. By this designation of liquid crystalline phases, Friedel intended, on the one hand, to avoid the semantic controversies triggered by the discrepancy of the terms "crystalline" and "liquid" and, on the other hand, to point out that they were genuine states of matter whose molecular properties are intermediary (meso-morphic) between those of crystals and those of ordinary liquids.

1.2.4 Liquid Crystal Physics

When Reinitzer discovered liquid crystals, theories on phase transitions and polymorphism were just appearing. Reinitzer and Lehmann had no idea of the molecular composition of cholesterol esters. The real molecular structure of "liquid crystals" or "crystalline liquids" became more and more important.

Liquid crystal physics really began in 1922 with the publication of Friedel's now famous treatise [5], [21, pp. 162–173] in which he introduced modern liquid crystal

terminology. He proposed the first classification of mesomorphic states which is still in use today. He also affirmed three mesomorphic phases of matter, smectic, nematic and cholesteric. In 1931 Georges with his son Edmond published the results of their X-ray crystallography studies [59].

From mid-1920s to early 1960s, liquid crystals were not popular among scientists for uncertain prospect of practical applications [21]. Although very valuable research activities [60–62] continued, they were rare, isolated and unnoticed by the mainstream scientists. The topic remained a pure scientific curiosity in the journey through the desert.

After a long period of inactivity on liquid crystal research, in 1957, Glenn H. Brown at the University of Cincinnati and later at Kent State University, one of the first U.S. chemists to study liquid crystals, published an article [63] and sparked an international resurgence in liquid crystal research. The discoveries of Domains [64–66], [67, pp. 17], [68] by Richard Williams and guest–host effect [67, pp. 19–22], [69–71] and dynamic scattering [67, pp. 23], [72–76] by Heilmeyer (Fig. 1.7) clearly pointed out opportunities to use liquid crystals in information-display technology and gave liquid crystal research a strong boost. A great worldwide revival occurred in the 1960s, evidenced by the first international conference on liquid crystals in 1965, with about 100 of the world's top liquid crystal scientists in attendance. Liquid crystals started again to focus the attention of the scientific community, but now for other reasons. People suddenly took out patents for thermography, display, and many other practical applications for these unique materials [77].

In the early 1970s, liquid crystal physics entered a stage of expansion that continues to the present day. Martin Schadt (Fig. 1.8) started to investigate correlations between liquid crystal molecular structures, material properties, electro-optical

Fig. 1.7 George H. Heilmeyer



Fig. 1.8 Martin Schadt

effects and display performance to obtain criteria for novel, effect-specific liquid crystal materials for TN- and subsequent field-effect applications. His interdisciplinary approach involving physics and chemistry became the basis for modern industrial LC-materials research and led to the discovery and production of numerous new functional molecules and new electro-optical effects. In 1991, Pierre-Gilles de Gennes (Fig. 1.9) received the Nobel Prize in physics “for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers” [78].

1.2.5 Synthesis of Liquid Crystals

In 1889, Ludwig Gattermann and A. Ritschke made the first chemical synthesis of liquid-crystal molecules: para-azoxyanisole (PAA) and para-azoxyphenetole (PAP). From the beginning of the twentieth century until his retirement in 1935, Daniel Vorländer [21, pp. 84–88], [54, 55, 79, 80] had synthesized most of the known liquid crystals up to his date.

After World War II, work on the synthesis of liquid crystals was resumed at university research laboratories in Europe. George Gray (Fig. 1.10), a prominent researcher of liquid crystals, began investigating these materials in the late 1940s. His group synthesized many new materials that exhibited the liquid crystalline state

Fig. 1.9 Pierre-Gilles de Gennes



and developed a better understanding of how to design molecules that exhibit the state. His book [81] became a guidebook on the subject.

The discovery of Williams Domains [64–66] led George H. Heilmeier to perform research on a liquid crystal-based flat panel display to replace the cathode ray vacuum tube used in televisions. But the para-azoxyanisole that Williams and Heilmeier used exhibits the nematic liquid crystal state only above 116 °C, which made it impractical to use in a commercial display product. A material that could be operated at room temperature was clearly needed. In 1966, Joel E. Goldmacher and Joseph A. Castellano, research chemists in Heilmeier group at RCA, discovered that mixtures made exclusively of nematic compounds that differed only in the number of carbon atoms in the terminal side chains could yield room-temperature nematic liquid crystals. A ternary mixture of Schiff base compounds resulted in a material that had a nematic range of 22–105 °C [82]. Operation at room temperature enabled the first practical display device to be made [74]. The team then proceeded to prepare numerous

Fig. 1.10 George Gray



mixtures of nematic compounds many of which had much lower melting points. This technique of mixing nematic compounds to obtain wide operating temperature range eventually became the industry standard and is still used to tailor materials to meet specific applications.

In 1969, Hans Kelker succeeded in synthesizing a substance that had a nematic phase at room temperature, N-(4-methoxybenzylidene)-4-butylaniline (MBBA), which is one of the most popular subjects of liquid crystal research [83]. The next step to commercialization of liquid-crystal displays was the synthesis of further chemically stable substances (cyanobiphenyls) with low melting temperatures by Gray [84, 85]. That work with Ken Harrison and the UK MOD (RRE Malvern), in 1973, led to design of new materials resulting in rapid adoption of small area LCDs within electronic products. These molecules are rod-shaped, some created in the laboratory and some appearing spontaneously in nature. Sivaramakrishna Chandrasekhar (Fig. 1.11) [86] synthesized disc-shaped liquid crystal in 1977. The cone or bowl shaped liquid crystal [87, 88] predicted by Lin Lei or Lui Lam (Fig. 1.12) [89, 90], [91, pp. 21] was synthesized in 1985. In the 1970s, ferroelectric liquid crystals [92–94], which respond quickly to electric fields, were developed.

Fig. 1.11 Sivaramakrishna Chandrasekhar

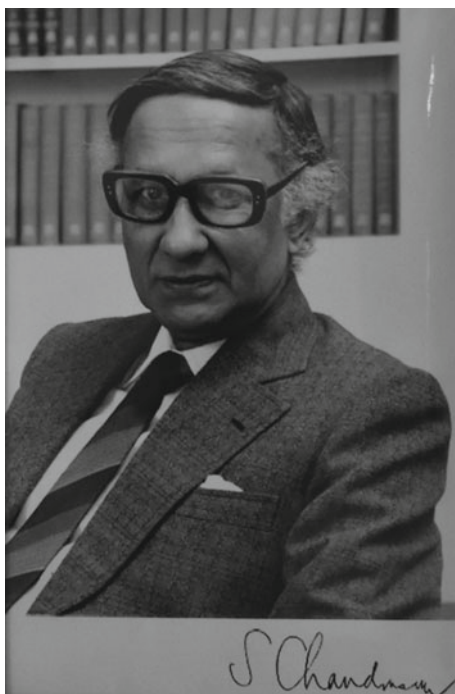


Fig. 1.12 Lui Lam

1.2.6 Applications

In 1911, Charles-Victor Mauguin (Fig. 1.13) first experimented with liquid crystals confined between plates in thin layers and discovered the twisted nematic field effect [76, 95–97]. In 1927, Vsevolod Frederiks (Fig. 1.14) devised the electrically switched light valve, called the Fréedericksz transition [98], the essential effect of all LCD technology [99]. In 1936, the Marconi Wireless Telegraph company patented the first practical application of the liquid crystal light valve technology [100–102].

In 1962, when Richard Williams applied an electric field to a thin layer of a nematic liquid crystal, he observed the formation of a regular pattern, the Williams Domains [64, 65], [67, pp. 17]. This discovery suggested that electric field ordering of a liquid crystal could be used in a display or light modulation device [66].

Fig. 1.13 Charles-Victor Mauguin

Fig. 1.14 Vsevolod Frederiks [28]



In 1964, George Heilmeier proposed to produce a color display by doping nematic liquid crystals with pleochroic dyes and discovered the guest–host effect [67, pp. 19–22], [69, 103] that color could be turned on and off with an electric field. This breakthrough demonstrated potential to fabricate a flat panel color television display.

Soon after the discovery of the guest–host effect, dynamic scattering [72–75], [67, pp. 23] was discovered. It offered yet another way to build a flat panel to display information in gray scale for not only television but also a variety of other practical applications. Heilmeier and his group fabricated and demonstrated the first working liquid crystal display [67, pp. 23] in December 1966. The concept of a thin-film transistor (TFT)-based liquid–crystal display (LCD) [67, pp. 41–42], [104–106] was demonstrated in 1968 with an 18×2 matrix dynamic scattering mode (DSM) LCD that used standard discrete MOSFETs. Active-matrix TFT liquid–crystal display panel was further developed in early 1970s [106–108], [109, pp. 74], [110, 111].

A big technology breakthrough in LCD technology that made LCD practical came about in 1970s when Martin Schadt and Wolfgang Helfrich (Fig. 1.15) invented the nematic liquid crystal twist cell display [112–117] based on the twisted nematic effect [95–97] and developed the first commercial room temperature nematic liquid crystal mixture used in the displays of the first Japanese digital TN-LCD watches [118, 119]. Coincidentally, James Fergason filed an identical patent US3731986 [120] in the United States on April 22, 1971. Schadt and Helfrich’s patent CH532261 [114] was licensed worldwide to electronics and watch industries. It changed the look of modern wristwatch and paved the way for liquid crystal readouts on calculators, thermometers, watches, clocks, and numerous other devices. Super twisted nematic display (Fig. 1.16) [121–127], [128, pp. 115–117] with superior characteristics was

invented at the Brown Boveri Research Center, Baden, Switzerland in 1983, allowing for more complex pictures.

The introduction of TN-effect displays led to their rapid expansion in the display field, quickly pushing out other common technologies like monolithic LEDs and cathode-ray-tube-based (CRT) for most electronics. By the 1990s, TN-effect LCDs were largely universal in portable electronics. In 2007, the image quality of LCD televisions surpassed that of CRT TVs [129] and LCD televisions surpassed CRT TVs in worldwide sales for the first time.

Fig. 1.15 Wolfgang Helfrich



Fig. 1.16 Pioneering super twisted Nematic display



The grayscale inversion from up to down and high response time drove development of alternatives to the TN-effect LCDs. In the 1990s, new technologies that could resolve these weaknesses were developed and applied to large computer monitor panels. Typical technologies include photoalignment [130–143], in-plane switching (IPS) [144–149], and vertical alignment (VA) [150–152].

The distinct double twist structure of blue phase LC gave rise to the first proposal of blue phase mode LCD [153] in 2007 for better display of moving images, reduced sensitivity to mechanical pressure, simplified manufacturing process, and reduced production costs. On May 14, 2008, Samsung Electronics announced that it has developed the world's first Blue Phase LCD panel offering more natural moving images with an unprecedented image-driving speed of 240 Hz.

Nowadays there is an unprecedented growth of interest for non-display applications [154–166], [167, pp. 321–336], [168] of LCs during the 1st decade of twenty-first century. Consequently, the research and development of LCs are moving rapidly beyond displays and evolving into entirely new scientific frontiers, opening broad avenues for versatile applications such as aerodynamic testing [169], lasers [170–173], photovoltaics, light-emitting diodes, field effect transistors, nonlinear optics, biosensors, switchable windows, 3D printing [174], communications [175–179], hyperspectral imaging [180], and nanophotonics. These fields, which gain extensive attentions of physicists, chemists, engineers, and biologists, are of a most engaging and challenging area of contemporary research, covering organic chemistry, materials science, bioscience, polymer science, chemical engineering, material engineering, electrical engineering, photonics, optoelectronics, nanotechnology, and renewable energy.

1.3 Classification of Liquid Crystals

As shown in Fig. 1.17, the liquid crystalline phase exists between the state of a crystalline solid and that of an isotropic liquid. LC materials may not always be in a liquid–crystal state of matter just as water may turn into ice or water vapor.

The molecules that can form LC mesophases are called mesogens. Mesogens can be rod-like, disc-like, amphiphilic, nonamphiphilic, metal containing, non-metal containing and low molecular weight or polymeric. The number of mesophases with different symmetries known today is large, with the count still ongoing.

Liquid crystals are classified in many ways [33, 98, 181–183]. It can be extended by employing the very general notion of broken symmetry [184–188]. All classification in terms of a single criterion only is incomplete. Boundaries between different liquid crystalline phases are not always easily determined [189, pp. 209]. Sometimes it is even hard to say if one is dealing with a mesophase or not.

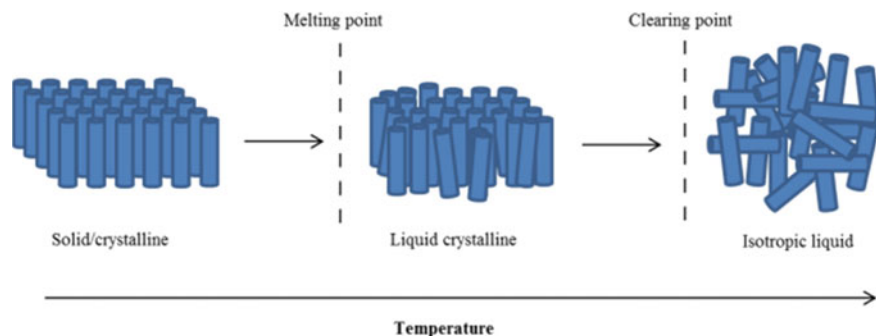


Fig. 1.17 Liquid crystal phase between solid and liquid phases

1.3.1 Physical Mechanisms for Self-organization

Under this criterion, liquid crystals can be divided into thermotropic [18, 190–198], lyotropic [197–204] and metallotropic phases [205]. Thermotropic and lyotropic liquid crystals consist mostly of organic molecules, although a few minerals are also known. Thermotropic LCs exhibit a phase transition into the liquid–crystal phase as temperature is changed. Lyotropic LCs exhibit phase transitions as a function of both temperature and concentration of the liquid–crystal molecules in a solvent (typically water). Metallotropic LCs are composed of both organic and inorganic molecules. Their liquid–crystal transition depends not only on temperature and concentration, but also on the inorganic–organic composition ratio.

1.3.1.1 Thermotropic Mesophases

Liquid crystal materials are mainly thermotropic. A liquid crystal phase is thermotropic if its order parameter is determined by temperature but insensitive to concentration. An example of a compound displaying thermotropic behavior is para-azoxyanisole [206]. Moreover, most thermotropic liquid crystals are composed of rod-like molecules, and admit nematic, smectic, or cholesteric phases.

Thermotropic phases occur only in a certain temperature range. In general, thermotropic mesophases occur because of anisotropic dispersion forces between the molecules and because of packing interactions. They are formed on heating a solid and/or cooling an isotropic liquid.

As temperature is changed, many thermotropic LCs exhibit a variety of phases with significant anisotropic orientational structure and short-range orientational order while still having an ability to flow [192, 207]. For instance, on heating a particular type of mesogen may exhibit various smectic phases followed by the nematic phase and finally the isotropic phase as temperature is increased (Fig. 1.18).

If the temperature rise is too high, most thermotropic liquid crystals will eventually become a conventional isotropic liquid characterized by random and isotropic

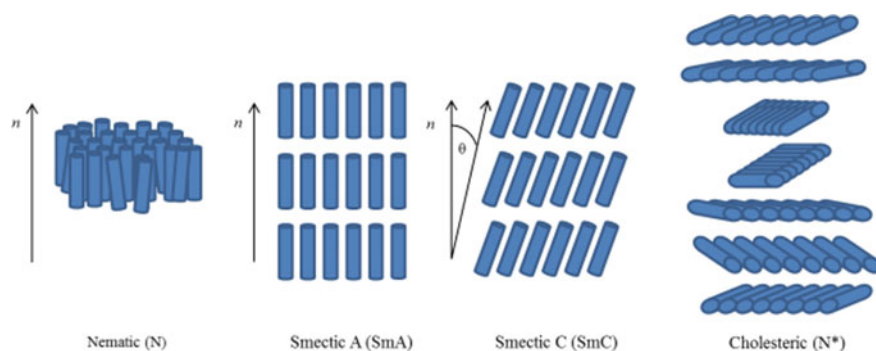


Fig. 1.18 Temperature-dependent liquid crystal phases

molecular ordering with little to no long-range order and fluid-like flow behavior. At too low temperatures, they will form a conventional crystal [192, 207].

Thermotropic phases are further subdivided into enantiotropic mesophases [208–210] and monotropic mesophases [209, 210]. Enantiotropic liquid crystals can be changed into the liquid crystal state from either lowering the temperature of a liquid or raising of the temperature of a solid. However, monotropic liquid crystals can only be changed into the liquid crystal state from either an increase in the temperature of a solid or a decrease in the temperature of a liquid, but not both. It is also observable in a metastable enantiotropic mesophase.

A low melting point is preferable in order to avoid metastable, monotropic liquid crystalline phases. Low-temperature mesomorphic behavior in general is technologically more useful, and alkyl terminal groups promote this.

1.3.1.2 Lyotropic Liquid Crystals

Lyotropic mesophases are obtained by dissolving an amphiphilic mesogen with immiscible hydrophilic head and hydrophobic tail within the same molecule in a suitable polar solvent. Many amphiphilic molecules show a wide range of lyotropic liquid-crystalline phases, for example the micellar or lamellar phase, depending on the volume balances between the hydrophilic part and hydrophobic part.

Lyotropic liquid-crystalline phases are abundant in living systems but can also be found in the mineral world as well as immiscible diblock copolymers. For example, many proteins and cell membranes are liquid crystals. Other well-known examples of liquid crystals are solutions of soap and various related detergents, as well as the tobacco mosaic virus, and some clays. Lyotropic liquid crystals are currently of great importance to the detergent and cosmetics industries.

A lyotropic liquid crystal consists of two or more components that exhibit liquid-crystalline properties in certain concentration ranges. In the lyotropic phases, solvent molecules fill the space around the compounds to provide fluidity to the system [202].

In contrast to thermotropic liquid crystals, these lyotropics have another degree of freedom of concentration that enables them to induce a variety of different phases.

The content of water or other solvent molecules changes the self-assembled structures. Similarly, as amphiphile concentration goes from low to high, lyotropic LCs will exhibit a generic progression of phases from micellar cubic phase, hexagonal columnar phase, lamellar phase, bicontinuous cubic phase, reverse hexagonal columnar phase, to inverse micellar phase. Even within the same phase, their self-assembled structures are tunable by the concentration. For example, in lamellar phases, the layer distances increase with the solvent volume.

At very low amphiphile concentration, the molecules will be dispersed randomly without any ordering. At slightly higher but still low concentration, amphiphilic molecules will spontaneously assemble into micelles or vesicles to hide the hydrophobic tail of the amphiphile inside the micelle core and expose a hydrophilic surface to aqueous solution. These spherical objects do not order themselves in solution, however. At higher concentration, the assemblies will become ordered. A typical phase is a hexagonal columnar phase, where the amphiphiles form long cylinders that arrange themselves into a roughly hexagonal lattice. This is called the middle soap phase. At still higher concentration, a lamellar phase may form, wherein extended sheets of amphiphiles are separated by thin layers of water. For some systems, a viscous isotropic phase may exist between the hexagonal and lamellar phases, wherein spheres are formed that create a dense cubic lattice. These spheres may also be connected to one another, forming a bicontinuous cubic phase.

The objects created by amphiphiles are usually spherical, but may also be disc-like, rod-like, or biaxial. These anisotropic self-assembled nano-structures can then order themselves in much the same way as thermotropic liquid crystals do, forming large-scale versions of all the thermotropic phases.

For some systems, at high concentrations, inverse phases are observed. That is, one may generate an inverse hexagonal columnar phase or an inverse micellar phase.

1.3.1.3 Metallotropic Liquid Crystals

Liquid crystal phases can also be based on low-melting inorganic phases like ZnCl_2 that have a structure formed of linked tetrahedra and easily form glasses. The addition of long chain soap-like molecules leads to a series of new phases that show a variety of liquid crystalline behavior both as a function of the inorganic–organic composition ratio and of temperature. This class of materials has been named metallotropic [205, 211–217], [218, pp. 193–247], [219, 220], [221, vol. 7, pp. 357–627], [222–225], [226, vol. 8, pp. 837–917], [227–231].

1.3.2 Shapes of Molecules in Liquid Crystals

A large number of chemical compounds are known to exhibit one or several liquid crystalline phases. Despite significant differences in chemical composition, these molecules have some common features in chemical and physical properties.

Vorländer [232] was one of the pioneers in liquid crystal who discovered that molecular shape was very important in the geometry of the mesophase. An extended, structurally rigid, highly anisotropic shape (Fig. 1.19), either rod [233, pp. 238] [234, 235], disc [233, pp. 238] [234, 235], sanidic [235], bent-core or banana (Fig. 1.20) [235–238], rice bowl, or board [233, pp. 238] [239], seems to be the main criterion for liquid crystalline behavior. The ordering of these molecules gives rise to anisotropy of the electric and optical properties.

1.3.2.1 Calamitic

Rod-shaped liquid crystal as shown in Fig. 1.21 is the most widely used liquid crystal material. Liquid crystal materials used in the display field and microwave communication are mainly rod-shaped structure compounds.

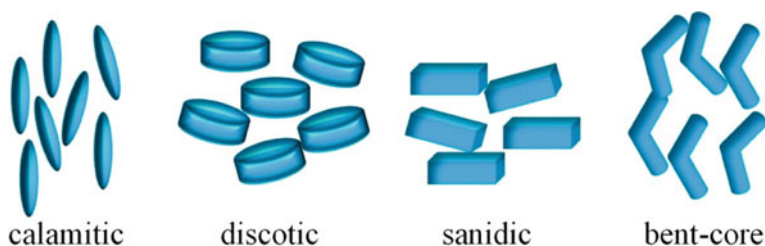


Fig. 1.19 Molecular shapes [235]

Fig. 1.20 Banana liquid crystals

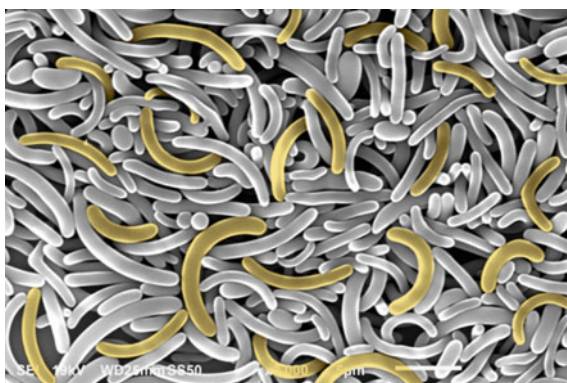
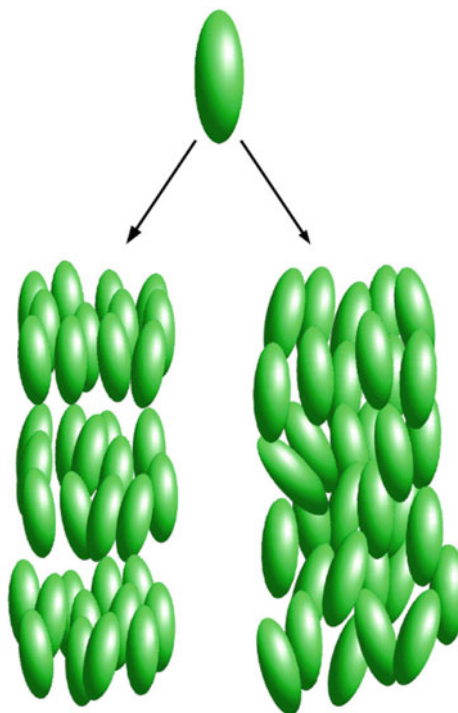


Fig. 1.21 Rod-like liquid crystal [234]

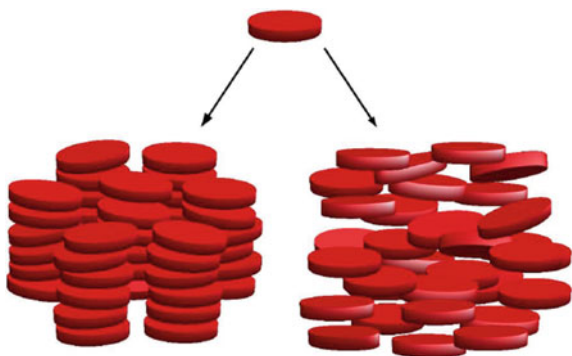


Rod-shaped molecules have an elongated, anisotropic geometry with aspect ratio greater than 4 allowing for preferential alignment along one spatial direction. The liquid crystal phase formation results from the interaction between the anisotropic shape of the rod-like molecules and the resulting anisotropic force. According to the order of liquid crystal molecular arrangement, rod-like liquid crystals are usually divided into smectic, nematics, and cholesterics phases. Furthermore, the rigid structure of rod-like liquid crystal molecules is not easy to bend [240].

1.3.2.2 Discotic

Discotics (Fig. 1.22) [234, 241, 242] are disc-like molecules consisting of a flat core of adjacent aromatic rings. Disk-shaped LC molecules can orient themselves in a layer-like fashion known as the discotic nematic phase. If the disks pack into stacks, the phase is called a discotic columnar. The columns themselves may be organized into rectangular or hexagonal arrays. Chiral discotic phases, similar to the chiral nematic phase, are also known.

Fig. 1.22 Discotic liquid crystal [234]



1.3.2.3 Bowlic

The core in a bowlic or conic LC (Fig. 1.23) [87–90, 243–252] such as triphenylenes is not flat, but is shaped like a rice bowl. This allows for two dimensional columnar ordering (Fig. 1.24) [252].



Fig. 1.23 Bowlic liquid crystal [252]

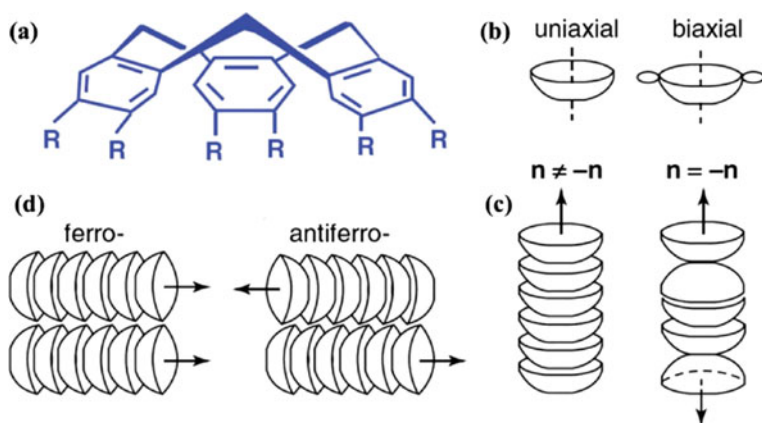


Fig. 1.24 Bowlic columnar ordering [252]

Conic LC molecules, like in discotics, can form columnar phases. Other phases, such as nonpolar nematic, polar nematic, stringbean, donut and onion phases, have been predicted. Conic phases, except nonpolar nematic, are polar phases [252].

1.3.3 Texture Ordering

Material properties of liquid crystals can be highly dependent on texture. The contrasting areas in the texture correspond to domains which may be on the order of micrometers. Within up to the entire domain, liquid-crystal molecules are well ordered. However, molecules present different ordering or symmetry breaking with respect to the isotropic liquid phase in different domains.

Texture ordering can be distinguished as positional and orientational order [253]. The orientational ordering might extend along only one dimension, with the material being essentially disordered in the other two directions [181, 182]. Moreover, order can be either short-range or long-range. Short-range order exists only between molecules close to each other while long-range ordering extends to larger, sometimes macroscopic, dimensions. Some techniques, such as the use of boundaries or an applied electric field, can be used to enforce a single ordered domain in a macroscopic scale.

Most liquid crystals change their molecular arrangement and orientation state with temperature as shown in Fig. 1.25. With the increase in temperature, the compound changes from crystal to smectic and then from smectic to nematic. The nematic phase is finally transformed into an isotropic liquid when the clearing point is reached.

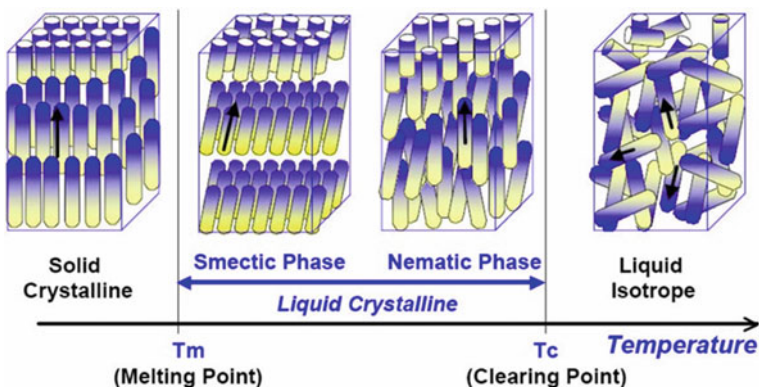


Fig. 1.25 Ordering of liquid crystal

1.3.3.1 Nematic Phase

One of the most common LC phases is the nematic [254–257] termed by Friedel’s daughter, Marie Friedel, after the Greek word for thread, νήμα (Greek: nema) [26, 258]. It is a state having one-dimensional long-range orientational order [255, 259]. Disclinations, the distinctive thread-like topological defects distinguish it from other liquid crystal phases.

Most nematics such as cyanobiphenyls are uniaxial. Calamitic organic molecules are represented by prolate spheroids with the long axes of neighboring molecules aligned approximately to one another as shown in Fig. 1.26. Molecules can rotate freely about their major axes and can be easily aligned by an external magnetic or electric field. Aligned nematics have the birefringent optical properties of uniaxial crystals which makes them extremely useful in liquid–crystal displays (LCD) [67]. Meanwhile, these same molecules have no particular position. They constantly readjust their position, and this positional disorder gives the fluid state.

The director $\hat{n}$ (Fig. 1.27), a dimensionless unit vector, is introduced to represent the direction of preferred orientation of molecules in the neighborhood of any point. If we define a unit vector to represent the long axis of each molecule, described by a distribution function $f(\theta, \phi)$, then the director is the statistical average of these unit vectors over a small volume element around a point. Because there is no physical polarity along the director axis, $\hat{n}$ and $-\hat{n}$ are fully equivalent [207].

On the other hand, some nematics are biaxial liquid crystals (Fig. 1.28) [193, 194, 239, 260] with three distinct optical axes. Nevertheless, a biaxial nematic is spatially homogeneous.

It is interesting to note that nematics do not necessarily exist in molecular systems [261–266]. Electrons can unite to flow together in high magnetic fields, to create an “electronic nematic” form of matter.

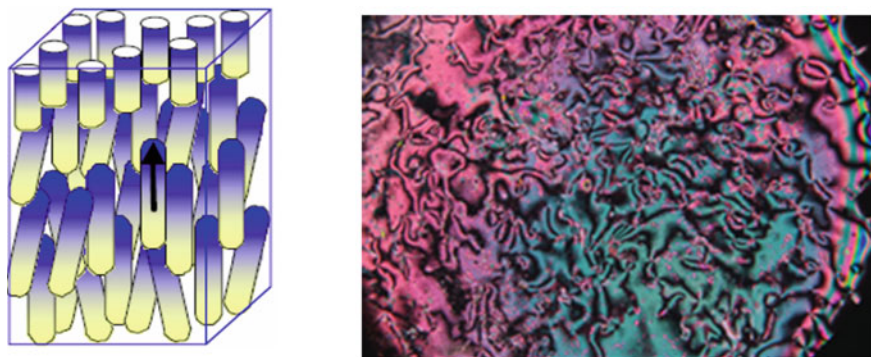
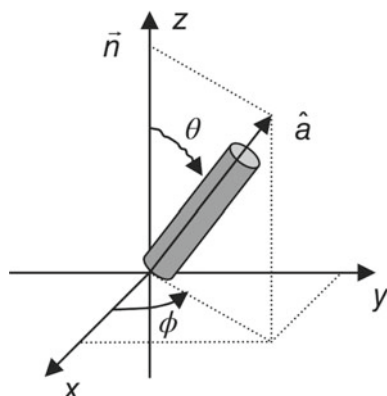


Fig. 1.26 Nematic liquid crystal

Fig. 1.27 Director

1.3.3.2 Smectic Phases

Smectic phases [267, 268] are found at lower temperatures than nematic. Many smectic compounds exhibit nematic phases at high temperatures.

Smectic materials were originally discovered from amphiphilic molecules. The word smectic originates from the Latin word smecticus, meaning cleaning, or having soap-like properties. Today, it is used for liquid crystals.

Unlike nematic materials, smectic materials show wax like properties. Rod-like molecules are organized in layers (Fig. 1.29) [269] with different molecular positioning in the layers. Stacked layers can slide over one another in a manner similar to that of soapy film but the stacked layers are not necessarily flat. Smectics are thus positionally ordered along one direction and accordingly also called a lamellar liquid crystal phase.

Molecules can be parallel or tilted with respect to the layer's normal axis [270]. Depending on the in layer ordering and the angle between the layer normal and the director, there is a very large number of distinct smectic phases [33, 192, 207, 271,

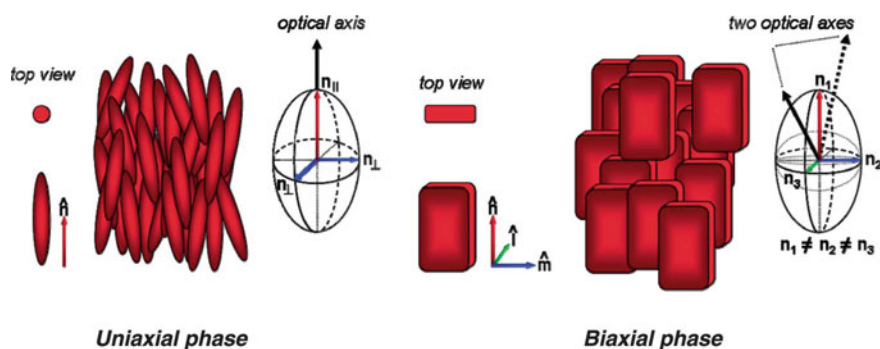
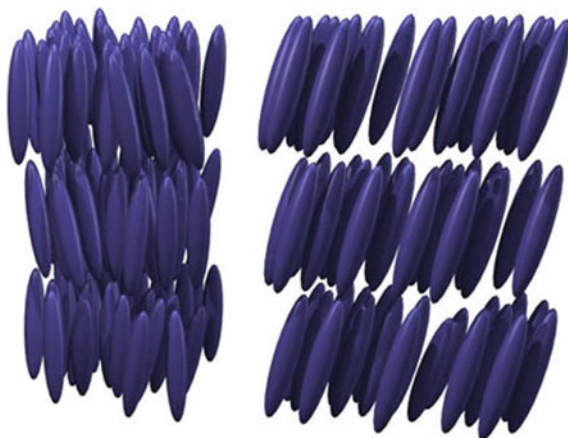
**Fig. 1.28** Biaxial phase [239]

Fig. 1.29 Smectic phase

272]. They are distinguished by letters according to the chronological sequence of their detection, SmA, SmB, SmC, etc., with SmA and SmC being the most common. Many compounds exhibit different smectic phases, but none can exhibit all smectic phases.

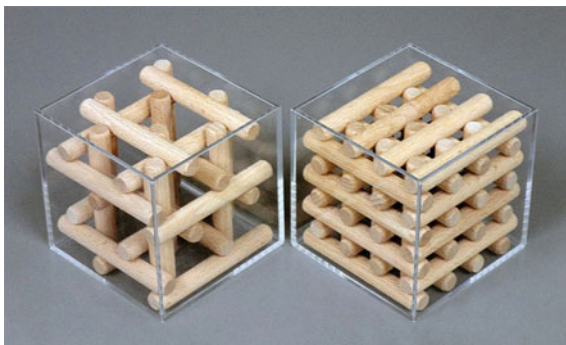
Beyond organic molecules, smectic ordering has also been reported to occur within colloidal suspensions of 2-D materials or nanosheets [14, 273].

1.3.3.3 Blue Phase

Blue phases [148, 149, 153, 274–286] are of interest for fast light modulators or tunable photonic crystals. Blue phases stabilized at room temperature allow electro-optical switching with response times of the order of 10^{-4} s [280].

The liquid crystalline phases Reinitzer observed include blue phases. They usually appear in very narrow temperature range between a chiral nematic phase and an isotropic liquid phase. In 2005, researchers discovered a class of blue-phase liquid crystals with a temperature range as wide as 16–60 °C [287, 288] which could be used for full-color displays [289].

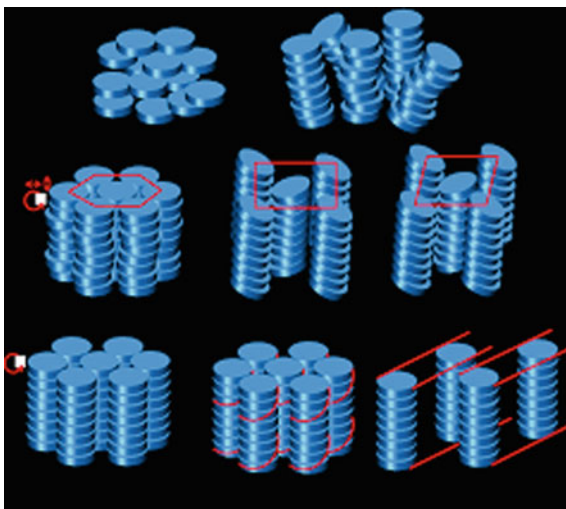
Blue phases have a regular three-dimensional cubic structure of defects with lattice periods of several hundred nanometers and a bandgap in the visible wavelength range (Fig. 1.30). Thus, they exhibit selective Bragg reflections in the wavelength range of visible light corresponding to the cubic lattice. It was theoretically predicted in 1981 that these phases can possess icosahedral symmetry similar to quasicrystals [274, 290].

Fig. 1.30 Blue phases

1.3.3.4 Columnar

The columnar phase [86, 245, 291] is a class of mesophases in which molecules, usually discoidal [241] or cone shaped [87, 88, 243, 244, 246], stack up to form infinitely long columns (Fig. 1.31). The molecules can be normal to the column axis or have a certain tilt angle. There is no positional correlation between the parallel one-dimensional columns that columns are free to slide with respect to each other. They can present various two-dimensional lattice [292–294], hexagonal, tetragonal, rectangular, or oblique.

Since the discovery of the first columnar liquid crystal in 1977 [86], a large number of columnar liquid crystals have been discovered in which triphenylene, porphyrin, phthalocyanine, coronene, and other aromatic molecules are involved. The typical columnar liquid-crystalline molecules have a π -electron-rich aromatic core attached by flexible alkyl chains. This structure is attracting particular attention for potential

Fig. 1.31 Columnar phase
[294, pp. 6]

molecular electronics in which aromatic parts transport electrons or holes and alkyl chains act as insulating parts.

1.3.4 Chirality

The chiral liquid crystal phase [255, 281, 295–301] exhibits chirality and thus responds differently from right- and left-handed circularly polarized light. They can therefore be used as polarization filters [302] and in many other interesting applications [303, 304].

There are three main types of chiral liquid crystals, formed by introducing chiral groups or adding chiral components into the liquid crystal molecules, or twisting the molecules. Chiral molecules can give rise to chiral phase. The names of chiral liquid crystal phases are thus formed by adding an asterisk behind the corresponding achiral mesophases. Due to the cooperative nature of liquid crystal ordering, chirality [301] can also be incorporated into a phase by adding a chiral dopant, which may not form LCs itself. A small amount of chiral dopant in an otherwise achiral mesophase is often enough to select out one domain handedness, making the system overall chiral. Twisted-nematic or super-twisted nematic mixtures [182] often contain a small amount of such dopants. Interestingly, achiral bent-core molecules have been shown to form chiral phases [236], either ferroelectric [256] or anti-ferroelectric.

Chiral phases usually have a helical twisting of the molecules. The helical pitch, generally about $0.2 \sim 100 \mu\text{m}$ or so, depends on the molecular structure and temperature changes. Typically, it changes when the temperature is altered or when other molecules are added to the LC host, allowing the pitch of a given material to be tuned accordingly. In some liquid crystal systems, the pitch is of the same order as the wavelength of visible light. This causes these systems to exhibit unique interesting optical interference effects, such as Bragg reflection and low-threshold laser emission [170], and these effects are exploited in a number of optical applications [21, 182].

1.3.4.1 Cholesteric

Cholesteric liquid crystal (Fig. 1.32), also called chiral nematic liquid crystal, is the first liquid crystal phase to be discovered [29, 44]. The term cholesteric came from discovery of this phase by Reinitzer in cholesterol esters. It is a special form of the nematic phase. Only chiral molecules can give rise to such a phase. It will disappear and return to a nematic liquid crystal state if chirality is cancelled by adding enantiomer molecules to the cholesteric phase liquid crystal.

In the cholesteric phase, molecules rely on the interaction of polar end groups to sequentially arrange in parallel into a flat layered state as shown in Fig. 1.33. The long axis of the molecule is on the layered plane. Due to the twist of the asymmetric carbon, the molecular director between adjacent layers changes at a certain angle

Fig. 1.32 Cholesteric phase

and twists together regularly. The finite twist angle between adjacent molecules is due to their asymmetric packing, which results in longer-range chiral order.

Due to the continuous and uniform rotation of the long axis of the molecule, the entire molecular structure exhibits a unique helical shape, leading to its unique optical properties [305] such as circular dichroism and optical rotation that the cholesteric

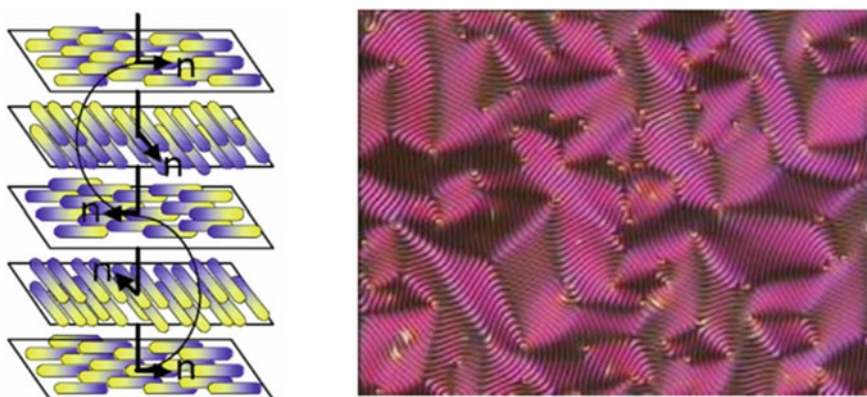
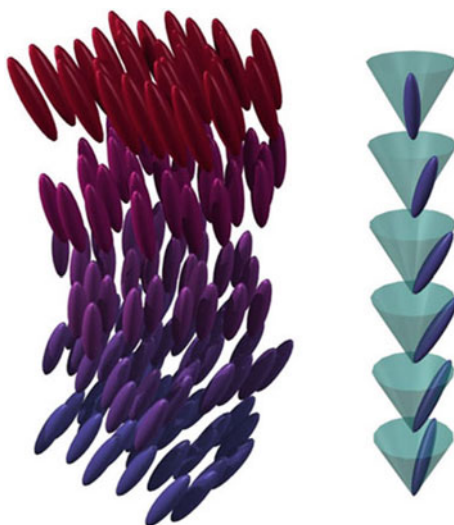
**Fig. 1.33** Helical twisting in cholesteric liquid crystals

Fig. 1.34 Chiral smectic phase



liquid crystal usually has a beautiful rainbow-like color. As such, sometimes, this phase is also called twisted nematics.

1.3.4.2 Chiral Smectic Phases

If an asymmetric carbon chiral group is introduced into the smectic phase molecules, the azimuthal angle θ between each molecule's director in the molecular layer and the Z axis will continue to change a constant angle from one layer to another. It results in a helical structure as shown in Fig. 1.34, forming chiral smectic phases SmC* [93, 181, 182, 207, 306], SmA*, twist-grain-boundary (TGB) [307, 308], and smectic blue phases [275–279, 309].

1.3.5 Molecular Mass

By molecular mass, liquid crystals can be divided into monomer liquid crystals (MLCs) and polymer liquid crystals (PLCs) [310]. Liquid crystal polymers (LCP) [91, 311–322], [323, pp. 557–558], [324–343] is polymers with the property of liquid crystal. It usually contains very large aromatic rings as mesogens of large molecular mass weight. In accordance, they exhibit unique electrical, mechanical, chemical, and thermal properties including stable dielectric constant and low loss tangent, low water absorption, good hermeticity, thermal actuation, anisotropic swelling, and soft elasticity besides toughness, high elasticity, viscoelasticity, and a tendency to form amorphous and semi-crystalline structures rather than crystals. As such,

LCP has advantages both in higher frequency operation and fabrication against the traditional uncompetitive printed circuit board materials for ever-growing applications at millimeter-wave (mmW) and terahertz (THz) frequencies. As a promising substrate and packing material, LCP has been both academically and industrially investigated for advanced wireless applications at such high frequencies over the last decade. In addition, the attractive properties of LCP films enable interesting applications in micro-electro-mechanical systems (MEMS), biomedical electronics, and microfluidics.

1.3.6 Mesogenes

Mesogens in most liquid crystals are neutral molecules, either organic or inorganic. However, mesogens in ionic liquid crystals (ILC) [261, 263–265, 344–348], [349, Chap. 4], [350–355] are anions and cations. ILC possesses properties characteristic of liquid crystals and ionic liquids [264], making them very interesting and useful for ion conduction [263, 265], electroluminescence, manufacturing of displays [356], spatial light modulators [357], optical connectors and switches [176], molecular sensors and detectors [358, 359].

1.4 Applications of Liquid Crystals

For a long time, liquid crystals were merely scientific curiosity [21]. The unique optical properties of liquid crystals together with the discovery of Williams Domains [64–66], [67, pp. 17] attracted Heilmeyer which led to the invention of practical liquid crystal display (LCD) [69, 73, 74]. It opened the door for massive applications of liquid crystals in the design of devices that combine the fluidity with the optical and dielectric anisotropy of liquid crystal materials.

Interests in liquid crystals quickly go beyond display. Intense and continuously growing research efforts are directed at diverse non-display applications in biology [196, 360], biomedicine [167, pp. 337–354], [174, 183, 361–363], chemistry [196, 364, 365], cosmetics, electromagnetics, information storage and processing [366–368], materials science [369–373], medicine [374], optics [298, 375–384], optoelectronics, pharmaceuticals [203, 385], photovoltaics [386], physics [33]. The list goes on and on.

One of the main reasons for industrial interest in liquid crystals lies with their anisotropic properties, molecular orientations and sensitivity to external stimuli, including light [387], temperature [388–392], mechanical shear, electric field [65, 144, 145, 291, 301, 376, 393, 394], magnetic field [395] and surface interactions with foreign molecules [172, 396–401]. The delicate and exquisite sensitivity is responsible for their applications as sensitive, fast-response and low-cost sensor materials [80, 190, 329, 357, 370, 402–412]. In recent decades, more and more properties of

liquid crystals such as phosphorescence and conductivity have been scrutinized to explore the potential for new technological application fields such as luminescent sensors, electric batteries and biomedicine [264].

In modern society, there must be very few whose lives have not been affected by the advent of liquid crystal technology. It is undoubtedly impossible to exhaustively present each and every application of liquid crystals when more and more unforeseen applications have been emerging. In this regard, here, we will only brief well-established, commercialized or even industrialized applications. Generally, hypothetical or exploratory applications up to prototyping will not be discussed. We would like to sincerely apologize for purposely omitting or unintentionally neglecting numerous great contributions.

1.4.1 Liquid Crystal Display

Liquid crystals are primarily known for their widespread use in displays [67, 76, 97, 117, 356, 407, 413–422]. LCD has revolutionized the worldwide information-display technology and given rise to nothing less than the creation of a new industry. It plays a key role in various technologies and dominates the huge international market for displays, in particular, digital clocks, mobile phones, digital watches, laptop computers, tablets, navigation with built-in GPS receiver showing position, flat-screen TVs, projection systems, smart car key. At present, liquid crystals are the only materials that can be used for low-power, low-profile, portable displays. Emerging civil and military trends include displays on silicon, plastic displays, etc.

1.4.2 Smart Glass

Smart glass [423–426] provides variable levels of transparency by adjusting the applied voltage. Polymer dispersed liquid crystals (PDLC) [336, pp. 195–250], [404, Chap. 14], [417, Chap. 16], [427–432], [433, pp. 62–79], [434–442], [443, Chap. 2], [444, 445] screens that change their transparency in response to an electrical impulse provide the technology behind. Randomly arranged liquid crystals in inactive PDLC screens block light that the smart glass appears milky. On the other hand, the applied voltage and accordingly the electrical field between electrodes causes the liquid crystals to align, allowing light to pass through and essentially turning the glass from translucent to transparent [439]. The degree of transparency can be controlled by the applied voltage.

Smart glass is perfect for commercial as well as household use as privacy screens or windows, in both interior and exterior environments for privacy control or as a temporary projection screen. Commercially available adhesive smart film in rolls can be added to existing windows and cut to size as required. Growing scenarios



Fig. 1.35 Smart glass

include architectural internal partitions for conference rooms (Fig. 1.35), intensive-care areas, bathroom/shower doors, fitting rooms, home cinemas where privacy are essential, interior of cars, airplanes such as the Boeing 787 Dreamliner. Large-scale installations were completed at the Prada Flagship store in New York City, the Guinness Storehouse in Dublin, the Nissan Micra CC in London using a four-sided glass box made up of 150 switchable glass panels which switched in sequence to create a striking outdoor display.

The same principle is applied in adaptive optics. Nano- or holographic PDLC is used to produce reconfigurable wavefront correction devices to modulate the optical phase of the transmitted light. Such phase-modulators have widespread applications in astronomy, line-of-sight communications and ophthalmics since they switch very fast.

1.4.3 Liquid Crystal Temperature Sensors

Heat-sensitive thermochromic liquid crystals change color as temperature changes [446]. This builds the essential principle behind liquid crystal temperature sensors [447, 448] which portray temperatures as colors. They can be used to follow temperature changes caused by heat flow by conduction, convection, and radiation.

Aquarium, pool, homebrewing and mood rings (Fig. 1.36) [388] make common use of liquid crystal color transitions. In medical thermography, a liquid crystal thermometer attached to the skin can safely read body temperature. It can even be useful in the detection of skin cancer, as tumors have different temperatures than surrounding tissues. Liquid crystal temperature sensors also find application in the electronics and semiconductor industry with the capability to pinpoint bad connections within a circuit board or detect electrically generated hot spots for failure analysis [389–392].

Fig. 1.36 Mood ring

1.4.4 Chemical Sensors and Biosensors

Liquid crystal-based chemical sensors and biosensors [196, 370, 399, 411, 412, 449–453] provide simple, fast, portable, wearable, visible and inexpensive manners to flag presence of label-free analyte in disease diagnosis, environmental analysis, and food safety. Concerned analyte can be polyelectrolytes, ions, molecules, explosives, industrial pollutants or even the chemical markers of disease in a patient's breath. Besides quantitative results, the sensors can also generate optical textures that are visible to the naked eye under crossed-polarizers.

One of the detection principles is the highly sensitive orientational response of LC molecules to minute changes in type, strength, and concentration of surfactants and/or polymers existing in the aqueous phase (Fig. 1.37) [196]. 4-Cyano-4'-pentylbiphenyl (5CB) nematic liquid crystal (Fig. 1.38) [84, 115, 454], [455, pp. 617–643], [456, 457] is commonly used for this purpose. The sensitive and selective orientation of LCs acts as an amplifier for local perturbations caused by foreign molecules adsorbed on the interface. Due to long-range orientation correlations, small amounts of analyte would disrupt the interactions of the liquid crystals with the surface, and throw the ordered arrangement into disarray. The presence of analyte can also be signaled by a dark to bright transition due to disruption of the pH-sensitive LC molecules during enzymatic reaction [458, 459]. This is the second mechanism for analyte detection.

Multifarious LC-based sensors have been developed for potential applications in fields such as chemistry, biomedicine, and environmental science. A host of different

Fig. 1.37 Sensitive orientational response of liquid crystal molecules [196]

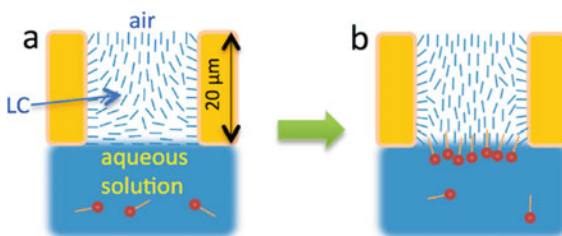
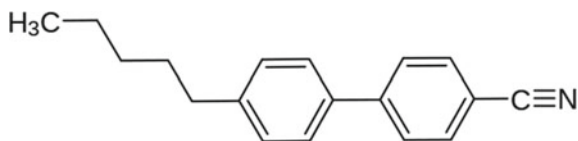


Fig. 1.38 5CB



analytes such as α chymotrypsinogen-A (ChTg) haemoglobin (Hb) and lysozyme [460], acetone, methanol and tetrahydrofuran (THF) [461], AchE-inhibiting pesticides [462], amino acids, DNA, and sugars [463], ammonia gas [451], asbovine serum albumin (BSA), hemoglobin (Hb), and chymotrypsinogen (ChTg) and [464], avidin [465], bisphenol A (BPA) [466], bovine serum albumin (BSA) [460, 467–471], butylamine vapour in air [472, 473], cadmium metal ion (Cd(II)) [474], carbon monoxide gas (CO) [475], carcinoembryonic antigen [476], cardiac troponin I (cTnI) [477], concanavalin A (Con A) [468, 471], Cyto, Hb and fibronectin (FibN) [471], dimethyl methylphosphonate (DMMP) [398, 478], Deoxyribonucleic acid (DNA) [463, 464, 479–481], glucose [463, 482–488], goat Immunoglobulin G (IgG) antigen [467, 489], human β -defensin-2 (HBD-2), a cysteine-rich cationic peptide with antimicrobial activity [490], hydrogen peroxide [488], lysozyme [468], melamine [491], molecular mimic of deadly sarin gas [364], nitrogen or synthetic air [300], nitrogen oxide (NO_2) [492], organophosphonate [493–495], toluene and acetone vapours [453], uranyl ion (UO_2^{2+}) [496] have been successfully detected.

It is expected that LC-based sensors, especially multiplex sensors integrated with multiple sensor units of distinctive sensing mechanisms for different types of analytes on the same sensing platform, will continue to grow. Foreseeable future convenient and fast sensing include freshness of fish or meat based on the presence of trace amounts of the foul-smelling molecule cadaverine, respiratory diseases based on analysis of small molecules such as nitric oxide in breath.

1.4.5 Electromagnetics

Liquid crystals are inherently useful in electromagnetic applications for its tunable electromagnetic anisotropy. As early as 1973, a liquid–crystal indicator was developed to visualize millimeter and submillimeter radiation [497].

At the end of last century, the phase modulation effect of liquid crystals was discovered [498–500]. By changing the external electric field or magnetic field, the phase of microwave can be well tuned. This opens the door to exploring the opportunities of liquid crystals in microwave, millimeter wave, and terahertz frequencies. Extensive and intensive researches have significantly advanced liquid crystals into one of the hot research frontiers for cutting-edge microwave, millimeter wave, and terahertz technologies.

With the arrival of 5G communications, the imperative need for compact, versatile, and lightweight microwave and millimeter wave devices for use in portable devices

and communication hubs makes liquid crystals extremely attractive. A variety of tunable devices and materials such as absorbers [501–507], phase shifters [178, 500, 508–532], reconfigurable antennas and metamaterials have been developed.

On account of the wide spread and great promising potential of liquid crystals in electromagnetics, a detailed retrospective topic review will be given in Chap. 3 of this book.

References

1. Kelker H (1973) History of liquid crystals. *Mol Cryst Liq Cryst* 21(1–2):1–48
2. Kelker H (1988) Survey of the early history of liquid crystals. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 165(1):1–43
3. Knoll PM, Kelker H (2012) Otto Lehmann: researcher of the liquid crystals, Books on Demand
4. Dunmur D, Sluckin T (2011) Soap, science, and flat-screen TVs: a history of liquid crystals. Oxford University Press
5. Friedel G (1922) Mesomorphic states of matter/Les états mésomorphes de la matière. *Annales de Physique* 9(18):273–474
6. Luzzati V, Mustacchi H, Skoulios A (1957) Structure of the liquid-crystal phases of the soap–water system: middle soap and neat soap. *Nature* 180(4586):600–601
7. Wensink HH, Dunkel J, Heidenreich S, Drescher K, Goldstein RE, Löwen H, Yeomans JM (2012) Meso-scale turbulence in living fluids. In: *Proceedings of the national academy of sciences of the United States of America*, vol 109, no 36, pp 14308–14313
8. Saw TB, Doostmohammadi A, Nier V, Kocgozlu L, Thampi S, Toyama Y, Marcq P, Lim CT, Yeomans JM, Ladoux B (2017) Topological defects in epithelia govern cell death and extrusion. *Nature* 544(7649):212–216
9. Zocher H (1925) Über freiwillige Strukturbildung in Solen (Eine neue Art anisotrop flüssiger Medien.). *Zeitschrift für anorganische und allgemeine Chemie* 147(1):91–110
10. Langmuir I (1938) The role of attractive and repulsive forces in the formation of tactoids, thixotropic gels, protein crystals and coacervates. *J Chem Phys* 6(12):873–896
11. Gabriel JC, Sanchez C, Davidson P (1996) Observation of nematic liquid-crystal textures in aqueous gels of smectite clays. *J Phys Chem* 100(26):11139–11143
12. Antonietti M (ed) (2003) Colloid chemistry I, series: topics in current chemistry, vol 226. Springer, Berlin, pp 119–172
13. Paineau E, Philippe AM, Antonova K, Bihannic I, Davidson P, Dozov I, Gabriel JCP, Impéror-Clerc M, Levitz P, Meneau F, Michot LJ (2013) Liquid–crystalline properties of aqueous suspensions of natural clay nanosheets. *Liq Cryst Rev* 1(2):110–126
14. Gabriel JC, Camerel F, Lemaire BJ, Desvaux H, Davidson P, Batail P (2001) Swollen liquid-crystalline lamellar phase based on extended solid-like sheets. *Nature* 413(6855):504–508
15. Däntl M, Ganter P, Szendrei-Temesi K, Jiménez-Solano A, Lotsch BV (2020) Customizing H3Sb3P2O14 nanosheet sensors by reversible vapor-phase amine intercalation. *Nanoscale Horiz* 5(4):74–81
16. Cladis PE (1988) A one hundred year perspective of the reentrant nematic phase. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 165(1):85–121
17. Demus D (1988) 100 years liquid crystal chemistry. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 165(1):45–84
18. Demus D (1989) Plenary lecture. One hundred years of liquid-crystal chemistry: Thermotropic liquid crystals with conventional and unconventional molecular structure. *Liq Cryst* 5(1):75–110
19. Kelker H, Knoll PM (1989) Plenary lecture. Some pictures of the history of liquid crystals. *Liq Cryst* 5(1):19–42

20. Stegemeyer H (1989) Centenary of the discovery of liquid crystals. *Liq Cryst* 5(1):5–6
21. Sluckin TJ, Dunmur DA, Stegemeyer H (2004) Crystals that flow: classic papers from the history of liquid crystals, series: liquid crystals book series. CRC Press, Boca Raton
22. Geelhaar T, Griesar K, Reckmann B (2013) 125 years of liquid crystals—a scientific revolution in the home. *Angewandte Chemie* 52(34):8789–8809
23. Lagerwall ST (2013) On some important chapters in the history of liquid crystals. *Liq Cryst* 40(12):1698–1729
24. Sluckin T (2013) Episodes from the history of liquid crystals. University of Southampton
25. Landgraf M (2014) 125 years of liquid crystal research, vol 131. Karlsruhe Institute of Technology Press Release
26. Mitov M (2014) Liquid-crystal science from 1888 to 1922: building a revolution. *ChemPhysChem* 15(7):1245–1250
27. Sparavigna AC (2019) The earliest researches on liquid crystals. Zenodo, art no 3365347
28. Chigrinov VG, Belyaev VV (1996) The life and times of Vsevolod Konstantinovich Frederiks: 1885–1944. *Liq Cryst Today* 6(4):11–12
29. Reinitzer F (1888) Beiträge zur Kenntniss des Cholesterins. *Monatshefte für Chemie—Chemical Monthly* 9(1):421–441
30. Grandjean F (1934) Georges Friedel 1865–1933 [note biographique]. *Bulletin de la Société française de Minéralogie* 57(3–6):144–183
31. Reinitzer F (1989) Contributions to the knowledge of cholesterol. *Liq Cryst* 5(1):7–18
32. Galerie VO (1840) Complete works of buffon. H. Fournier et Cie
33. Oswald P, Pieranski P (2005) (trans: Constantin D, Liquid crystals: concepts and physical properties illustrated by experiments), Series: liquid crystals book series. CRC Press, Boca Raton
34. Salit PW (1935) Phospholipid content of cataractous human lenses. *Br J Ophthalmol* 19(12):663–671
35. Salit PW, O'Brien CS (1935) Cholesterol content of cataractous human lenses. *Arch Ophthalmol* 13(2):227–237
36. Marmot M, Elliott P (eds) (2005) Coronary heart disease epidemiology: from aetiology to public health, 2nd edn. Oxford University Press
37. Borchman D, Yappert MC (2010) Lipids and the ocular lens. *J Lipid Res* 51(9):2473–2488
38. Virchow R (1854) Ueber das ausgebreitete Vorkommen einer dem Nervenmark analogen Substanz in den thierischen Geweben. *Virchows Archiv: European Journal of Pathology* 6(4):562–572
39. Planer J (1861) Notiz über das Cholestearin. *Annalen der Chemie und Pharmacie* 118(CXVIII): 25–27
40. Lisetski L (2010) What was observed by Julius Planer in 1861? *Condens Matt Phys* 13(3), art no 33604
41. Trokhymchuk A (2010) On Julius Planer's 1861 paper "Notiz über das Cholestearin" in *Annalen der Chemie und Pharmacie*. *Condens Matt Phys* 13(3), art no 37002
42. Shenderovskiy VA, Trokhymchuk AD, Lisetski LN, Kozhushko BV, Gvozдовskiy IA, Planer J (2018) A pioneer in the study of liquid crystals. *J Mol Liq* 267:560–563
43. Reinitzer F (1908) Zur Geschichte der flüssigen Kristalle. *Annalen der Physik* 332(11):213–224
44. Lehmann O (1889) Über fließende Krystalle. *Z Phys Chem* 4U(1):462–472
45. Lehmann O (1908) Zur Geschichte der flüssigen Kristalle. *Ann Phys* 330(5):852–860
46. Lehmann O (1908) Bemerkung zu den Abhandlungen von D. Vorländer und Ada Prins über flüssige Krystalle. *Berichte der Deutschen Chemischen Gesellschaft* 41(3):3774–3783
47. Lehmann O (1904) Flüssige Kristalle sowie Plastizität von Kristallen im allgemeinen, molekulare Umlagerungen und Aggregatzustandsänderungen. Wilhelm Engelmann, Leipzig
48. Lehmann O, Krystalle F (1901) Entgegnung auf die Bemerkungen des Hrn. G. Tammann. *Annalen der Physik* 310(5):236–239
49. Tammann G (1901) Ueber die sogenannten flüssigen Krystalle. *Ann Phys* 309(3):524–530

50. Wulff G (1901) XXV. Zur Frage der Geschwindigkeit des Wachstums und der Auflösung der Krystallflächen. *Zeitschrift für Kristallographie/Crystal Mater* 34(5–6):449–530
51. Gattermann L, Ritschke A (1890) Ueber Azoxyphenoläther. *Berichte der Deutschen Chemischen Gesellschaft* 23(1):1738–1750
52. Bredig G, Schukowsky GV (1904) Prüfung der Natur der flüssigen Krystalle mittels elektrischer Kataphorese. *Berichte der Deutschen Chemischen Gesellschaft* 37(3):3419–3425
53. Coehn A (1904) Über “Flüssige Kristalle.” *Zeitschrift für Elektrochemie und angewandte physikalische Chemie* 10(45):856–857
54. Meyer F, Dahlem K (1903) Azo- und Azoxybenzoesäureester. *Justus Liebigs Ann Chem* 326(3):331–346
55. Vorländer D (1907) Einfluß der molekularen Gestalt auf den krystallinisch-flüssigen Zustand. *Berichte der Deutschen Chemischen Gesellschaft* 40(2):1970–1972
56. Friedel G, Grandjean F (1910) Observations sur les « flüssige Kristalle » de M. O. Lehmann [article]. *Bulletin de la Société française de Minéralogie* 33(5–6):192–239
57. Lehmann O (1910) Cristaux liquides. Réponse à MM. G. Friedel et F. Grandjean [note critique]. *Bulletin de la Société française de Minéralogie* 33(7):300–317
58. Friedel G (1911) *Leçons de Cristallographie*. Librairie Scientifique A. Hermann et Fils, Paris
59. Friedel G, Friedel E (1931) Les propriétés physiques des stases mésomorphes en général et leur importance comme principe de classification. *Zeitschrift für Kristallographie/Cryst Mater* 79(1):1–60
60. Frank FC, van der Merwe JH (1949) One-dimensional dislocations. I. Static theory. *Proc Royal Soc A* 198(1053):205–216
61. Frank FC, van der Merwe JH (1949) One-dimensional dislocations. II. Misfitting monolayers and oriented overgrowth. *Proc Royal Soc A* 198(1053):216–225
62. Frank FC, van der Merwe JH (1949) One-dimensional dislocations. III. Influence of the second harmonic term in the potential representation, on the properties of the model. *Proc Royal Soc A* 200(1060):125–134
63. Brown GH, Shaw WG (1957) The mesomorphic state—liquid crystals. *Chem Rev* 57(6):1049–1157
64. Williams K (1963) Domains in liquid crystals. *J Chem Phys* 39(2):384–479
65. Williams K (1963) Liquid crystals in an electric field. *Nature* 199(4890):273–274
66. Williams W (1967) Electro-optical elements utilizing an organic nematic compound, Patent No. US3322485, RCA Corp
67. Castellano JA (2005) *Liquid gold: the story of liquid crystal displays and the creation of an industry*. World Scientific
68. Mandle RJ, Davis EJ, Archbold CT, Cowling SJ, Goodby JW (2014) Microscopy studies of the nematic NTB phase of 1,11-di-(1''-cyanobiphenyl-4-yl)undecane. *J Mater Chem C* 2(3):556–566
69. Heilmeyer GH, Zanoni LA (1968) Guest-host interactions in nematic liquid crystals, a new electro-optic effect. *Appl Phys Lett* 13(3):91–92
70. Nam SM, Oh SW, Kim SH, Huh JW, Lim E, Kim J, Yoon TH (2019) Parameter space design of a guest-host liquid crystal device for transmittance control. *Crystals* 9(2), art no 63
71. Sunil BN, Yam WS, Hegde C (2019) Photoresponsive behavior of hydrophilic/hydrophobic-based novel azobenzene mesogens: synthesis, characterization and their application in optical storage devices. *Royal Soc Chem (RSC) Adv* 9(69):40588–40606
72. Heilmeyer GH, Zanoni LA, Barton LA (1966) A flat liquid crystal reflective display based on dynamic scattering. RCA Laboratories Company Report
73. Heilmeyer GH, Zanoni LA, Barton LA (1968) Dynamic scattering in nematic liquid crystals. *Appl Phys Lett* 13(1):46–47
74. Heilmeyer GH, Zanoni LA, Barton LA (1968) Dynamic scattering: a new electrooptic effect in certain classes of nematic liquid crystals. *Proc IEEE* 56(7):1162–1171
75. Heilmeyer GH, Zanoni LA (1970) Electro-optical devices. Patent No. US3499112, RCA Corp
76. Gross B (2012) How RCA lost the LCD. *IEEE Spectr* 49(11):38–44
77. Stegemeyer H (ed) (1994) *Liquid crystals, series: topics in physical chemistry, vol 3*. Springer

78. de Gennes PG (1992) Soft matter (nobel lecture). *Angew Chem* 31(7):842–845
79. Weygand C, Vorländer D (1943) 11. 6. 1867–8. 6. 1941, *Berichte der Deutschen Chemischen Gesellschaft A* 76(6):41–58
80. Rabbi AR, Al Faysal J (2020) Preparation, characterization and applications of liquid crystals: a review. *IOSR J Appl Chem* 13(12):43–54
81. Gray GW (1962) Molecular structure and the properties of liquid crystals. Academic Press
82. Goldmacher JE, Castellano JA (1970) Electro-optical compositions and devices. Patent No. US3540796A, RCA Corp
83. Kelker H, Scheurle B (1969) A liquid-crystalline (Nematic) phase with a particularly low solidification point. *Angew Chem* 8(11):884–885
84. Gray GW, Harrison KJ, Nash JA (1973) New family of nematic liquid crystals for displays. *Electron Lett* 9(6):130–131
85. Shibaev V (2015) My way to George gray and liquid crystal polymers. *Liq Cryst* 42(5–6):623–642
86. Chandrasekhar S, Sadashiva BK, Suresh KA (1977) Liquid crystals of disc-like molecules. *Pramana* 9(5):471–480
87. Malthête J, Collet A (1985) *Nouveau journal de chimie/New J Chem* 9:151–153
88. Zimmermann H, Poupko R, Luz Z, Billard J (1985) Pyramidic mesophases. *Zeitschrift für Naturforschung A: J Phys Sci* 40(2):149–160
89. Lin L (1982) Liquid crystal phases and the “dimensionality” of molecules. *Physics* 11(3):171–178
90. Lin L (1983) Liquid Crystal Research in China: 1970–1982. *Mol Cryst Liq Cryst* 91(1–2):77–91
91. Collyer AA (ed) (1992) Liquid crystal polymers: from structures to applications, series: polymer liquid crystals series, vol 1. Springer (Elsevier Applied Science), Berlin
92. McMillan WL (1973) Simple molecular theory of the smectic C phase. *Phys Rev A* 8(4):1921–1929
93. Meyer RB, Liébert L, Strzelecki L, Keller P (1975) Ferroelectric liquid crystals. *Journal de Physique (Paris) Lettres* 36(3):L69–L71
94. Meyer RB (1977) Ferroelectric liquid crystals; a review. *Mol Cryst Liq Cryst* 40(1):33–48
95. Mauguin C (1911) Sur les cristaux liquides de Lehmann. *Bulletin de la Société française de Minéralogie* 34(3):71–117
96. Schadt M (1988) The twisted nematic effect: liquid crystal displays and liquid crystal materials. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 165(1):405–438
97. Yeh P, Gu C (1999) Optics of liquid crystal displays, series: wiley series in pure and applied optics. Wiley-Interscience
98. Sluckin TJ (2000) The liquid crystal phases: physics and technology. *Contemp Phys* 41(1):37–56
99. Fréedericksz V, Repiewa A (1927) Theoretisches und Experimentelles zur Frage nach der Natur der anisotropen Flüssigkeiten. *Z Phys* 42(7):532–546
100. Levin B, Levin N (1936) Improvements in or relating to light valves. British Patent GB441274, Marconis Wireless Telegraph Co Ltd
101. Jacobson AD, Beard TD, Bleha WP, Margerum JD, Wong SY (1973) The liquid crystal light valve, an optical-to-optical interface device. *Patents Recogn* 5(1):13–18
102. Cristaldi DJR, Pennisi S, Pulvirenti F (2009) Liquid crystal display drivers: techniques and circuits. Springer
103. Heilmeyer GH, Castellano JA, Zanoni LA (1969) Guest-host interactions in nematic liquid crystals. *Mol Cryst* 8(1):293–304
104. Lechner B, Marlowe F, Nester E, Tufts J (1969) Liquid crystal matrix displays. In: 1969 IEEE international solid-state circuits conference. Philadelphia, PA, pp 52–53
105. Lechner BJ, Marlowe FJ, Nester EO, Tufts J (1971) Liquid crystal matrix displays. *Proc IEEE* 59(11):1566–1579
106. Kawamoto H (2012) The inventors of TFT active-matrix LCD receive the 2011 IEEE Nishizawa Medal. *J Disp Technol* 8(1):3–4

107. Brody TP, Asars JA, Dixon GD (1973) A 6×6 inch 20 lines-per-inch liquid-crystal display panel. *IEEE Trans Electron Devices* 20(11):995–1001
108. Brody TP (1997) Birth of the active matrix. *Inf Display* 13(10):28–32
109. Brotherton SD (2013) Introduction to thin film transistors: physics and technology of TFTs. Springer
110. Kawamoto H (2012) The history of liquid-crystal display and its industry. In: 2012 3rd IEEE history of electro-technology conference (HISTELCON). Pavia, Italy, art no 6487587
111. Kuo Y (2013) Thin film transistor technology—past, present, and future. *Electrochem Soc Interface* 22(1):55–61
112. Williams DF, Schadt M (1971) Electroluminescent device with light emitting aromatic, hydrocarbon material. Patent No. US3621321A, Canadian Patents and Development Ltd
113. Boller A, Scherrer H, Schadt M, Wild P (1972) Low electrooptic threshold in new liquid crystals. *Proc IEEE* 60(8):1002–1003
114. Helfrich W, Schadt M (1973) Lichtsteuerzelle. Swiss Patent No. CH532261
115. Gray GW (1998) Reminiscences from a life with liquid crystals. *Liq Cryst* 24(1):5–14
116. Buntz GH (2005) (trans: Becker ME)., Twisted nematic liquid crystal displays (TN-LCDs), an invention from basel with global effects, information No. 118, Internationale Treuhand AG
117. Schadt M (2009) Milestone in the history of field-effect liquid crystal displays and materials. *Jpn J Appl Phys* 48(3S2), art no 03B001
118. Hama T, Nishimura I (1975) Driving arrangement for passive time indicating devices. Patent No. US3881311, Suwa Seikosha KK
119. Gray GW, Kelly SM (1999) Liquid crystals for twisted nematic display devices. *J Mater Chem* 9(9):2037–2050
120. Fergason JL (1973) Display devices utilizing liquid crystal light modulation. Patent No. US3731986, International Liquid Xtal Company
121. Amstutz H, Heimgartner D, Kaufmann M, Scheffer T (1983) LCD with twisted nematic crystal between support plates. Swiss Patent No. CH664027A5, Bbc Brown Boveri & Cie, filed on 12 July 1983
122. Amstutz H, Heimgartner D, Kaufmann M, Scheffer TJ (1983) Flüssigkristallanzeige, Swiss Patent No. CH665491, Bbc Brown Boveri & Cie, filed on 28 Oct 1983
123. Scheffer TJ, Nehring J (1984) A new, highly multiplexable liquid crystal display. *Appl Phys Lett* 45(10):1021–1023
124. H. Amstutz, D. Heimgartner, M. Kaufmann, and T. J. Scheffer, Liquid crystal display/Flüssigkristallanzeige, European Patent No. EP0131216, BBC Brown Boveri AG Switzerland
125. Amstutz H, Heimgartner D, Kaufmann M, Scheffer TJ (1987) Liquid crystal display. Patent No. US4634229, ABB Schweiz Holding AG
126. Welzen TL, De Vaan AJSM (1988) Low drive voltage display device. Patent No. US4783653, US Philips Corp
127. Welzen TL, De Vaan AJSM (1990) Liquid crystal display device. Patent No. US4902105, US Philips Corp
128. Kelly SM (2000) Flat Panel displays: advance organic materials monograph. Series: RSC Materials Monographs, Royal Society of Chemistry
129. De Vaan AJSM (2007) Competing display technologies for the best image performance. *J Soc Inform Display* 15(9):657–666
130. Ichimura K, Suzuki Y, Seki T, Hosoki A, Aoki K (1988) Reversible change in alignment mode of nematic liquid crystals regulated photochemically by command surfaces modified with an azobenzene monolayer. *Langmuir* 4(5):1214–1216
131. Gibbons WM, Shannon PJ, Sun ST, Swetlin BJ (1991) Surface-mediated alignment of nematic liquid crystals with polarized laser light. *Nature* 351(6321):49–50
132. Dyadyusha AG, Marusii TY, Reznikov YA, Khizhnyak AI, Reshetnyak VY (1992) Orientational effect due to a change in the anisotropy of the interaction between a liquid crystal and a bounding surface. *Sov J Exp Theor Phys Lett* 56(1):17–21
133. Schadt M, Schmitt K, Kozinkov V, Chigrinov V (1992) Surface-induced parallel alignment of liquid crystals by linearly polymerized photopolymers. *Jpn J Appl Phys Part 1: Regul Pap Short Notes* 31(7R):2155–2164

134. Chigrinov VG, Kozenkov VM, Novoseletsky NV, Reshetnyak VY, Reznikov YA, Schadt M, Schmitt K (1995) Process for making photopolymers having varying molecular orientation using light to orient and polymerize. Patent No. US5389698, State Scientific Center of Russian Federation "NIOPIK", Rolic Technologies Ltd Niopic Moscow Research and Production Association
135. Chigrinov VG, Kozenkov VM, Novoseletsky NV, Reshetnyak VY, Reznikov YA, Schadt M, Schmitt K (1998) Liquid crystal display cell. Patent No. US5838407, State Scientific Center of Russian Federation "NIOPIK", Rolic Technologies Ltd
136. Ichimura K (2000) Photoalignment of liquid-crystal systems. *Chem Rev* 100(5):1847–1874
137. Chigrinov VG, Kozenkov VM, Kwok HS (2008) Photoalignment of liquid crystalline materials: physics and applications, series: Wiley—SID series in display technology. John Wiley & Sons, New York
138. Yaroshchuk O, Reznikov Y (2012) Photoalignment of liquid crystals: basics and current trends. *J Mater Chem* 22(2):286–300
139. Seki T, Nagano S, Hara M (2013) Versatility of photoalignment techniques: from nematics to a wide range of functional materials. *Polymer* 54(22):6053–6072
140. Seki T (2014) New strategies and implications for the photoalignment of liquid crystalline polymers. *Polym J* 46(11):751–768
141. Ji W, Wei BY, Chen P, Hu W, Lu YQ (2017) Optical field control via liquid crystal photoalignment. *Mol Cryst Liq Cryst* 644(1):3–11
142. Murata M, Yokoyama R, Tanaka Y, Hosokawa T, Ogura K, Yanagihara Y, Kusafuka K, Matsumoto T (2018) 81–1: high transmittance and high contrast LCD for 3D head-up displays. *Soc Inf Disp Symp Dig Tech Pap* 49(1):1088–1091
143. Pan S, Ho JY, Chigrinov VG, Kwok HS (2018) Novel photoalignment method based on low-molecular-weight azobenzene dyes and its application for high-dichroic-ratio polarizers. *ACS Appl Mater Inter* 10(10):9032–9037
144. Soref R (1974) Liquid crystal electric field sensing measurement and display device. Patent No. US3834794, WALTER E HELLER WESTERN Inc, Babcock Display Products Inc
145. Baur G, Fehrenbach W, Staudacher BWN, Windscheid F, Kiefer R (1996) Liquid crystal switching elements having a parallel electric field and β_0 which is not 0° or 90° . Patent No. US5576867, Merck Patent GmbH
146. Hairston N (1996) Optical patterning. *Nature* 382(6593):666
147. Kondo K, Terao H, Abe H, Ohta M, Suzuki K, Sasaki T, Kawachi G, Ohwada J (1997) Liquid crystal display device. Patent No. US5598285, Panasonic Liquid Crystal Display Co Ltd
148. Ge Z, Gauza S, Jiao M, Xianyu H, Wu ST (2009) Electro-optics of polymer-stabilized blue phase liquid crystal displays. *Appl Phys Lett* 94(10), art no 101104
149. Ge Z, Rao L, Gauza S, Wu ST (2009) Modeling of blue phase liquid crystal displays. *J Disp Technol* 5(7):250–256
150. NXP Semiconductors (2013) Vertical alignment (VA) displays and NXP LCD Drivers, User Manual UM 10764 Rev 1
151. Schiesser T (2020) Display panel technology: TN versus VA versus IPS: what's the difference?
152. Schiesser T (2021) Display tech compared: TN versus VA versus IPS: what's the difference in 2021?
153. Kikuchi H, Higuchi H, Haseba Y, Iwata T (2007) Fast electro-optical switching in polymer-stabilized liquid crystalline blue phases for display application. *Soc Inf Disp Symp Dig Tech Pap* 38(1):1737–1740
154. Wiltshire MCK (1993) Non-display applications of liquid crystal devices. *GEC J Res* 10(2):119–125
155. Beresnev L, Haase W (1998) Ferroelectric liquid crystals: development of materials and fast electrooptical elements for non-display applications. *Opt Mater* 9(1–4):201–211
156. Haase W, Ganzke D, Pozhidaev EP (1999) Ferroelectric liquid crystals for non-display applications. *MRS Online Proc Libr* 559:15–26
157. Semenova Y, Panarin Y, Farrell G, Dovgalets S (2004) Liquid crystal based optical switches. *Mol Cryst Liq Cryst* 413(1):385–398

158. Pasechnik SV, Maksimochkin GI, Kravchuk AS, Lukin AV (2006) Liquid crystal emulsions: new system for display and non-display applications. In: 2006 Asian symposium on information display, New Delhi, India, pp 185–187
159. Wilkinson TD, Henderson C, Gil Leyva D, Ghannam R, Crossland WA (2006) Non-display applications and the next generation of liquid crystal over silicon technology. *Philos Trans Royal Soc London A* 364(1847):2721–2732
160. Yang FZ (2008) New directions in recent liquid crystal studies—the progress in foundational research of non-display application of liquid crystals. *Prog Phys* 28(2):107–129
161. Abdulhalim I (2011) Non-display bio-optic applications of liquid crystals. *Liq Cryst Today* 20(2):44–60
162. Garbovskiy Y, Reisman L, Celinski Z, Camley RE, Glushchenko A (2011) Metallic surfaces as alignment layers for nondisplay applications of liquid crystals. *Appl Phys Lett* 98(7), art no 073301
163. Lavrentovich OD (2012) Liquid crystals for optical non-display applications. *SPIE/Photon Innov Sol Comp Environ Syst* 8482, art no 84820D
164. Li Q (ed) (2012) Liquid crystals beyond displays: chemistry, physics, and applications. Wiley
165. Chaudhary A (2014) Influence of one-dimensional CdS nanoparticles on physical parameters of ferroelectric liquid crystal for display and non display applications. *Sustain Ind Proc Summit* 5:481–482
166. Bian Z (2015) The applications of low-cost liquid crystal display for light field modulation and multimodal microscopy imaging. Master Thesis, University of Connecticut
167. Lee CC (ed) (2015) The current trends of optics and photonics, series: topics in applied physics, vol 129. Springer, Berlin, pp 321–336, 337–354
168. Lu Y (2016) Liquid crystal for non-display photonic applications. In: 2016 Asia Pacific optical sensors conference, Shanghai, China, art no Tu1A.1
169. Bonnett P (1989) Applications of liquid crystals in aerodynamic testing. Ph.D. Dissertation, University of Oxford
170. Kopp VI, Fan B, Vithana HK, Genack AZ (1998) Low-threshold lasing at the edge of a photonic stop band in cholesteric liquid crystals. *Opt Lett* 23(21):1707–1709
171. Dolgaleva K, Wei SK, Lukishova SG, Chen SH, Schwartz K, Boyd RW (2008) Enhanced laser performance of cholesteric liquid crystals doped with oligofluorene dye. *J Opt Soc Am B* 25(9):1496–1504
172. Xiang J, Varanytsia A, Minkowski F, Paterson DA, Storey JMD, Imrie CT, Lavrentovich OD, Palffy-Muhoray P (2016) Electrically tunable laser based on oblique heliconical cholesteric liquid crystal. *Proc Nat Acad Sci United States Am* 113(46):12925–12928
173. Sakurai Y, Nishitaten M, Ito M, Takatoh K (2021) UV durable LCOS for laser processing. *Crystals* 11(9), art no 1047
174. Barnes M, Sajadi SM, Parekh S, Rahman MM, Ajayan PM, Verduzco R (2020) Reactive 3D printing of shape-programmable liquid crystal elastomer actuators. *ACS Appl Mater Interfaces* 12(25):28692–28699
175. Crossland WA, Clapp TV, Wilkinson TD, Manolis IG, Georgiou A, Robertson B (2004) Liquid crystals in telecommunications systems. *Mol Cryst Liq Cryst* 413(1):363–383
176. De Bougrenet de la Tocnaye JL (2004) Engineering liquid crystals for optimal uses in optical communication systems. *Liq Cryst* 31(2):241–269
177. Madhav BTP, Pisipati VGKM, Khan H, Prasad VGNS, Praveen Kumar K, Bhavani KVL, Ravi Kumar M (2011) Liquid crystal bow-tie microstrip antenna for wireless communication applications. *J Eng Sci Technol Rev* 4(2):131–134
178. Heunisch A, Schulz B, Rabe T, Strunck S, Follmann R, Manabe A (2012) LTCC antenna array with integrated liquid crystal phase shifter for satellite communication. In: 2012 International microelectronics assembly and packaging society (iMAPS) CICMT, Erfurt, Germany, pp 97–102
179. Zou J, Yang Z, Mao C, Wu ST (2021) Fast-response liquid crystals for 6G optical communications. *Crystals* 11(7), art no 797

180. Ciofani G, Menciassi A (eds) (2012) Piezoelectric nanomaterials for biomedical applications, series: nanomedicine and nanotoxicology. Springer, Berlin
181. Collings PJ, Hird M (1997) Introduction to liquid crystals: chemistry and physics, series: liquid crystals book series. CRC Press, Boca Raton
182. Dierking I (2003) Textures of liquid crystals. Wiley
183. Shirpur R (2019) Liquid crystals: a review. *Int J Creat Innov Res Stud* 1(12):119–129
184. Curie P (1895) Lois expérimentales du magnétisme. Propriétés magnétiques des corps à diverses températures/Magnetic properties of materials at various temperatures. *Annales de Chimie et de Physique* 7 5:289–405
185. Landau L, Lifchitz E (1969) Statistical physics, 2nd revised and enlarged Ed., Series: Course of theoretical physics, vol 5. Pergamon Press, Oxford
186. Anderson PW (1972) More is different. *Science* 177(4047):393–396
187. Landau L, Lifchitz E (1980) Statistical physics, 3rd revised and enlarged Ed., Series: course of theoretical physics, vol 5. Pergamon Press, Oxford
188. Anderson PW (1984) Basic notions of condensed matter physics, series: advanced books classics Westview Press/Addison-Wesley
189. Davies P (ed) (1989) The new physics. Cambridge University Press, Cambridge
190. Kovshev EI, Blinov LM, Titov VV (1977) Thermotropic liquid crystals and their applications. *Russ Chem Rev* 46(5):395–419
191. Vertogen G, Jeu WH (1988) Thermotropic liquid crystals, fundamentals, series: springer series in chemical physics, vol 45. Springer, Berlin
192. Chandrasekhar S (1992) Liquid crystals, 2nd edn. Cambridge University Press, Cambridge University Press
193. Madsen LA, Dingemans TJ, Nakata M, Samulski ET (2004) Thermotropic biaxial nematic liquid crystals. *Phys Rev Lett* 92(14), art no 145505
194. Prasad V, Kang SW, Suresh KA, Joshi L, Wang Q, Kumar S (2005) Thermotropic uniaxial and biaxial nematic and smectic phases in bent-core mesogens. *J Am Chem Soc* 127(49):17224–17227
195. Ramamoorthy A (2007) Thermotropic liquid crystals: recent advances. Springer
196. Popov N, Honaker LW, Popova M, Usol'tseva N, Mann K, Jákli A, Popov P (2018) Thermotropic liquid crystal-assisted chemical and biological sensors. *Materials* 11(1), art no 20
197. Pieranski P, Godinho MH (eds) (2021) Liquid crystals: new perspectives. *Sciences: Physics of Soft Matter: Lyotropic and Thermotropic Liquid Crystals*, iSTE
198. Wilson MR, Yu G, Potter TD, Walker M, Gray SJ, Li J, Boyd NJ (2022) Molecular simulation approaches to the study of thermotropic and lyotropic liquid crystals. *Crystals* 12(5), art no 685
199. Khetrapal CL, Kunwar AC, Tracey AS, Diehl P (1975) Nuclear magnetic resonance studies in lyotropic liquid crystals, series: NMR basic principles and progress, vol 9. Springer-Verlag, New York
200. Vroege GJ, Lekkerkerker HN (1992) Phase transitions in lyotropic colloidal and polymer liquid crystals. *Rep Prog Phys* 55(8):1241–1309
201. Figueiredo Neto AM, Salinas SRA (2005) The physics of lyotropic liquid crystals: phase transitions and structural properties, series: monographs on the physics and chemistry of materials. Oxford University Press
202. Liang Q, Liu P, Liu C, Jian X, Hong D, Li Y (2005) Synthesis and properties of lyotropic liquid crystalline copolyamides containing phthalazinone moieties and ether linkages. *Polymer* 46(16):6258–6265
203. Kim DH, Jahn A, Cho SJ, Kim JS, Ki MH, Kim DH (2015) Lyotropic liquid crystal systems in drug delivery: a review. *J Pharm Investig* 45(1):1–11
204. Wang X, Zhang Y, Gui S, Huang J, Cao J, Li Z, Li Q, Chu X (2018) Characterization of lipid-based lyotropic liquid crystal and effects of guest molecules on its microstructure: a systematic review. *AAPS PharmSciTech* 19(5):2023–2040

205. Martin JD, Keary CL, Thornton TA, Novotnak MP, Knutson JW, Folmer JCW (2006) Metal-lotropic liquid crystals formed by surfactant templating of molten metal halides. *Nat Mater* 5(4), art no 1610, pp 271–275
206. Shao Y, Zerda TW (1998) Phase transitions of liquid crystal PAA in confined geometries. *J Phys Chem B* 102(18):3387–3394
207. De Gennes PG, Prost J (1993) The physics of liquid crystals, series: the international series of monographs on physics, vol 83. Oxford University Press, Oxford
208. Chen HH, Lin HA, Lai YH, Lin SY, Chiang CH, Hsu HF, Shih TL, Lee JJ, Lai CC, Kuo TS (2012) Enantiotropic nematics from cross-like 1,2,4,5-tetrakis(4'-alkyl-4-ethynylbiphenyl)benzenes and their biaxiality studies. *Chem Euro J* 18(31):9543–9551
209. Gold V (2012) International union of pure and applied chemistry: compendium of chemical terminology: gold book, Version 2.3.1. Blackwell Scientific Publications
210. Carletta A (2015) Solid-state investigation of polymorphism and tautomerism of phenylthiazole-thione: a combined crystallographic, calorimetric, and theoretical survey. *Cryst Growth Des* 15(5):2461–2473
211. Maitlis PM, Bruce DW, Dhillon R, Dunmur DA, Fanizzi FP, Hunt SE, Lelagadec R, Lalinde E, Orr R, Rourke JP, Salt NJS, Stacey JP, Styring P (1990) Metallomesogens—organometallic and coordination-complexes with liquid-crystalline properties. *New J Chem* 14(6–7):549–551
212. Rourke JP, Fanizzi FP, Bruce DW, Dunmur DA, Maitlis PM (1992) Synthesis and properties of (±)trans-(h₂-alkene)(2-alkyloxy-4-stilbazole)-dichloroplatinum: a very remarkable family of organometallic mesogens. *J Chem Soc Dalton Trans* 20:3009–3014
213. Bruce DW (1994) High coordination number calamitic metallomesogens. *Adv Mater* 6(9):699–701
214. Ghedini M, Morrone S, Francescangeli O, Bartolino R (1994) Metallomesogens. synthesis and mesomorphic properties of 2-Hydroxy-4-n-Alkoxy-4'-n-alkylazobenzenes palladium(II) complexes. *ACS Chem Mater* 6(11):1971–1977
215. Galyametdinov YG, Ivanova G, Ovchinnikov I, Prosvirina A, Guillon D, Heinrich B, Dunmur DA, Bruce DW (1996) X-ray and magnetic birefringence studies of some lanthanide metallomesogens with Schiff's base ligands. *Liq Cryst* 20(6):831–833
216. Serrano JL (ed) (1996) Metallomesogens: synthesis, properties, and applications. VCH, Weinheim
217. Liu XH, Nurul Abser M, Bruce DW (1998) Synthesis and characterisation of rod-like metallomesogens of Mn(I) based on Schiff base ligands. *J Organomet Chem* 551(1–2):271–280
218. Mingos DMP (ed) (1999) Liquid crystals II, series: structure and bonding, vol 95. Springer, Berlin
219. Mironov VS (2000) On the magnetic anisotropy of lanthanide-containing metallomesogens. *J Chem Phys* 113(22):10293–10303
220. Date RW, Fernandez Iglesias E, Rowe KE, Elliott JM, Bruce DW (2003) Metallomesogens by ligand design. *Dalton Trans* 10:1914–1931
221. McCleverty JA, Meyer TJ (eds) (2003) Comprehensive coordination chemistry II: from biology to nanotechnology volume 7: from the molecular to the nanoscale: synthesis, structure, and properties. Elsevier
222. Smirnova AI, Fazio D, Iglesias EF, Hall CG, Guillon D, Donnio B, Bruce DW (2003) Polycatenar metallomesogens—from layers to columns and so on cubics. *Mol Cryst Liq Cryst* 396(1):227–240
223. Crispini A, Ghedini M, Pucci D (2009) Functional properties of metallomesogens modulated by molecular and supramolecular exotic arrangements. *Beilstein J Organic Chem* 5, art no 54
224. Menon SK, Patel RKV, Panchal JG, Mistry BR, Rana VA (2011) Dielectric study of novel liquid crystals based on calix[4]arene Schiff bases. *Liq Cryst* 38(2):123–134
225. Santoro A, Prokhorov AM, Kozhevnikov VN, Whitwood AC, Donnio B, Williams JA, Bruce DW (2011) Emissive metallomesogens based on 2-phenylpyridine complexes of iridium(III). *J Am Chem Soc* 133(14):5248–5251
226. Reedijk J, Poeppelemeier K (eds) (2013) Comprehensive inorganic chemistry II: from elements to applications volume 8: coordination and organometallic chemistry, 2nd edn. Elsevier

227. Iliş M, Micutz M, Cîrcu V (2017) Luminescent palladium(II) metallomesogens based on cyclometalated Schiff bases and N-benzoyl thiourea derivatives as co-ligands. *J Organometal Chem* 836–837:81–89
228. Iliş M, Cîrcu V (2018) Discotic liquid crystals based on Cu(I) complexes with benzoylthiourea derivatives containing a perfluoroalkyl chain. *J Chem*, art no 7943763
229. Wu X, Zhu M, Bruce DW, Zhu W, Wang Y (2018) An overview of phosphorescent metallomesogens based on platinum and iridium. *J Mater Chem C* 6(37):9848–9860
230. Andelesc AA, Heinrich B, Spirache MA, Voirin E, Deda ML, Maio GD, Szerb EI, Donnio B, Costisor O (2020) Playing with PtII and ZnII coordination to obtain luminescent metallomesogens. *Chem Euro J* 26(21):4850–4860
231. Cuerva C, Cano M, Lodeiro C (2021) Advanced functional luminescent metallomesogens: the key role of the metal center. *Chem Rev* 121(20):12966–13010
232. Vorländer D (1923) Die Erforschung der molekularen Gestalt mit Hilfe der kristallinen Flüssigkeiten. *Z Phys Chem* 105U(1):211–254
233. Dvornic PR, Owen MJ (eds) (2009) Silicon-containing dendritic polymers, series: advances in silicon science, vol 2. Springer
234. Mazza MG, Schoen M (2011) Structure and dynamics of reentrant nematics: any open questions after almost 40 years? *Int J Mol Sci* 12(8):5352–5372
235. Shen Y, Dierking I (2019) Perspectives in liquid-crystal-aided nanotechnology and nanoscience. *Appl Sci* 9(12), art no 2512
236. Achard MF, Bedel JP, Marcerou JP, Nguyen HT, Rouillon JC (2003) Switching of banana liquid crystal mesophases under field. *Euro Phys J E: Appl Phys* 10(2):129–134
237. Blanca Ros M, Serrano JL, Rosario de la Fuente M, Folcia CL (2005) Banana-shaped liquid crystals: a new field to explore. *J Mater Chem* 15(48):5093–5098
238. Fernández-Rico C, Chiappini M, Yanagishima T, de Sousa H, Aarts DGAL, Dijkstra M, Dullens RPA (2020) Shaping colloidal bananas to reveal biaxial, splay-bend nematic, and smectic phases. *Science* 369(6506):950–955
239. Lehmann M (2009) The dawn in the area of thermotropic biaxial nematics. *Liq Cryst Today* 18(1):31–34
240. Greco C, Marini A, Frezza E, Ferrarini A (2014) From the molecular structure to spectroscopic and material properties: computational investigation of a bent-core nematic liquid crystal. *ChemPhysChem* 15(7):1336–1344
241. Destrade C, Nguyen HT, Gasparoux H, Malthête J, Levelut AM (1981) Disc-like mesogens: a classification. *Mol Cryst Liq Cryst* 71(1–2):111–135
242. Simpson CD, Wu J, Watson MD, Müllen K (2004) From graphite molecules to columnar superstructures—an exercise in nanoscience. *J Mater Chem* 14(4):494–504
243. Levelut AM, Malthête J, Collet A (1986) X-ray structural study of the mesophases of some cone-shaped molecules. *J Phys Paris* 47(2):351–358
244. Zimmermann H, Poupkov R, Luz Z, Billard J (1986) Temperature dependent sign reversal of the optical anisotropy in pyramidal mesophases. *Zeitschrift für Naturforschung A: J Phys Sci* 41(9):1137–1138
245. Lin L (1987) Bowlic liquid crystals. *Mol Cryst Liq Cryst* 146(1):41–54
246. Malthête J, Collet A (1987) Inversion of the cyclotriphenylene cone in a columnar mesophase: a potential way to ferroelectric materials. *J Am Chem Soc* 109(24):7544–7545
247. Lam L (1988) Bowlic and polar liquid crystal polymers. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 155(1):531–538
248. Xu B, Swager TM (1993) Rigid bowlic liquid crystals based on Tungsten-Oxo calix[4]arenes: host-guest effects and head-to-tail organization. *J Am Chem Soc* 115(3):1159–1160
249. Shibaev VP, Lam L (1994) Liquid crystalline and mesomorphic polymers, series: partially ordered systems. Springer
250. Lin L (2000) *Physics* 29(8):497–498
251. Dierking I (2017) Editorial. *Liq Cryst Today* 26(4):75–111
252. Wang L, Huang D, Lam L, Cheng Z (2017) Bowlics: history, advances and applications. *Liq Cryst Today* 26(4):85–111

253. Ericksen JL (1991) Liquid crystals with variable degree of orientation. *Arch Ration Mech Anal* 113(2):97–120
254. Géza T, Denniston C, Yeomans JM (2002) Hydrodynamics of topological defects in nematic liquid crystals. *Phys Rev Lett* 88(10), art no 105504
255. Rego JA, Harvey JA, MacKinnon AL, Gatdula E (2010) Asymmetric synthesis of a highly soluble ‘trimeric’ analogue of the chiral nematic liquid crystal twist agent Merck S1011. *Liq Cryst* 37(1):37–43
256. Lavrentovich OD (2020) Ferroelectric nematic liquid crystal, a century in waiting. *Proc Nat Acad Sci United States Am* 117(26):14629–14631
257. van der Schoot P (2022) Molecular theory of nematic (and other) liquid crystals: an introduction, series: Springer Briefs in physics. Springer, Berlin
258. Mitov M (2012) (trans: Weiss G), Sensitive matter: foams, gels, liquid crystals, and other miracles. Harvard University Press
259. Géza T, Denniston C, Yeomans JM (2003) Hydrodynamics of domain growth in nematic liquid crystals. *Phys Rev E* 67(5), art no 051705
260. Bates M, Luckhurst G (2005) Biaxial nematic phases and V-shaped molecules: a Monte Carlo simulation study. *Phys Rev E* 72(5), art no 051702
261. Knight GA, Shaw BD (1938) Long-chain alkylpyridines and their derivatives New examples of liquid crystals. *J Chem Soc* 121:682–683
262. Kivelson SA, Fradkin E, Emery VJ (1998) Electronic liquid-crystal phases of a doped Mott insulator. *Nature* 393(6685):550–553
263. Kato T (2002) Self-assembly of phase-segregated liquid crystal structures. *Science* 295(5564):2414–2418
264. Binnemans K (2005) Ionic liquid crystals. *Chem Rev* 105(11):4148–4204
265. Yoshio M, Kagata T, Hoshino K, Mukai T, Ohno H, Kato T (2006) One-dimensional ion-conductive polymer films: alignment and fixation of ionic channels formed by self-organization of polymerizable columnar liquid crystals. *J Am Chem Soc* 128(16):5570–5577
266. Fradkin E, Kivelson SA, Lawler MJ, Eisenstein JP, Mackenzie AP (2010) Nematic Fermi fluids in condensed matter physics. *Ann Rev Condens Matter Phys* 1:153–178
267. Gray GW, Goodby JW (1984) Smectic liquid crystals. Textures and structures. Leonard Hill
268. Sackmann H (1989) Plenary lecture. Smectic liquid crystals. A historical review. *Liq Cryst* 5(1):43–55
269. Jakli A, Saupe A (2006) One- and two-dimensional fluids: properties of smectic, lamellar and columnar liquid crystals, series: series in condensed matter physics. CRC Press
270. Pershan PS (1988) Structure of liquid crystal phases, series: world scientific lecture notes in physics, vol 23. World Scientific, Singapore
271. Barón M (2001) Definitions of basic terms relating to low-molar-mass and polymer liquid crystals. *Pure Appl Chem* 73(5):607–621
272. Chen B, Zeng XB, Baumeister U, Diele S, Ungar G, Tschierske C (2004) Liquid crystals with complex superstructures. *Angewandte Chemie* 43(35):4621–4625
273. Davidson P, Penisson C, Constantin D, Gabriel JP (2018) Isotropic, nematic, and lamellar phases in colloidal suspensions of nanosheets. *Proc Nat Acad Sci United States Am* 115(26):6662–6667
274. Seideman T (1990) The liquid-crystalline blue phases. *Rep Prog Phys* 53(6):659–705
275. Li MH, Lause V, Nguyen HT, Sigaud G, Barois P, Isaert N (1997) Blue phases and twist grain boundary phases (TGBA and TGBC) in a series of fluoro-substituted chiral tolane derivatives. *Liq Cryst* 23(3):389–408
276. Pansu B, Li MH, Nguyen HT (1997) Structural measurements in blue phases with smectic ordering. *Journal de Physique II France* 7(5):751–764
277. Pansu B, Grelet E, Li MH, Nguyen HT (2000) Hexagonal symmetry for smectic blue phases. *Phys Rev E* 62(1):658–665
278. Grelet E, Pansu B, Li MH, Nguyen HT (2001) Structural investigations on smectic blue phases. *Phys Rev Lett* 86(17):3791–3794

279. Grelet E, Pansu B, Nguyen HT (2001) Influence of the molecular tilt on the structure of smectic blue phases. *Phys Rev E* 64(1), art no 010703
280. Kikuchi H, Yokota M, Hisakado Y, Yang H, Kajiyama T (2002) Polymer-stabilized liquid crystal blue phases. *Nat Mater* 1(1):64–68, art no 712
281. Haseba Y, Kikuchi H (2006) Electro-optic effects of the optically isotropic state induced by the incorporative effects of a polymer network and the chirality of liquid crystal. *J Soc Inform Displ* 14(6):551–556
282. Rao L, Ge Z, Wu ST, Lee SH (2009) Low voltage blue-phase liquid crystal displays. *Appl Phys Lett* 95(23), art no 231101
283. Rao L, Yan J, Wu ST, Yamamoto SI, Haseba Y (2011) A large Kerr constant polymer-stabilized blue phase liquid crystal. *Appl Phys Lett* 98(8), art no 081109
284. Oton E, Netter E, Nakano T, Katayama Y-D, Inoue F (2017) Monodomain blue phase liquid crystal layers for phase modulation. *Sci Rep* 7, art no 44575
285. Yang J, Zhao W, He W, Yang Z, Wang D, Cao H (2019) Liquid crystalline blue phase materials with three-dimensional nanostructures. *J Mater Chem C* 7(43):13352–13366
286. Otón E, Yoshida H, Morawiak P, Strzeżysz O, Kula P, Ozaki M, Piecek W (2020) Orientation control of ideal blue phase photonic crystals. *Sci Rep* 10, art no 10148
287. Coles HJ, Pivnenko MN (2005) Liquid crystal ‘blue phases’ with a wide temperature range. *Nature* 436(7053):997–1000
288. Castles F, Morris SM, Terentjev EM, Coles HJ (2010) Thermodynamically stable blue phases. *Phys Rev Lett* 104(15), art no 157801
289. Yamamoto J, Nishiyama I, Inoue M, Yokoyama H (2005) Optical isotropy and iridescence in a smectic ‘blue phase’. *Nature* 437(7058):525–528
290. Kleinert H, Maki K (1981) Lattice textures in cholesteric liquid crystals. *Fortschr Phys* 29(5):219–259
291. Sato K, Itoh Y, Aida T (2011) Columnarly assembled liquid-crystalline peptidic macrocycles unidirectionally orientable over a large area by an electric field. *J Am Chem Soc* 133(35):13767–13769
292. Levelut AM, Oswald P, Ghanem A, Malthête J (1984) Structure of the two columnar phases of a chiral triphenylene ester/Structure des deux phases colonnaires d’un ester de triphénylène chiral. *J Phys Paris* 45(4):745–754
293. Malthête J, Levelut AM, Nguyen HT (1985) Phasmids: a new class of liquid crystals. *Journal de Physique (Paris) Lettres* 46(18):L-875–L-880
294. Panchatcharam UC (2015) Ordering properties of oligomeric columnar discotic liquid crystals. Ph. D. Dissertation, Wageningen University
295. Kitzerow H, Bahr C, Chandrasekhar S (2001) Chirality in liquid crystals, series: partially ordered systems. Springer
296. Görtz V, Goodby JW (2005) Enantioselective segregation in achiral nematic liquid crystals. *Chem Commun* 26:3262–3264
297. Dierkinig I (2014) Chiral liquid crystals: structures, phases, effects. *Symmetry* 6(2):444–472
298. Popov P, Honaker LW, Mirheydari M, Mann EK, Jáklí A (2017) Chiral nematic liquid crystal microlenses. *Sci Rep* 7, art no 1603
299. Tomczyk W, Marzec M, Jusztyńska-Gałązka E, Węglowska D (2017) Mesomorphic and physicochemical properties of liquid crystal mixture composed of chiral molecules with perfluorinated terminal chains. *J Mol Struct* 1130:503–510
300. Pschyklenk L, Wagner T, Lorenz A, Kaul P (2020) Optical gas sensing with encapsulated chiral-nematic liquid crystals. *ACS Appl Polymer Mater* 2(5):1925–1932
301. Concellón A, Lu RQ, Yoshinaga K, Hsu HF, Swager TM (2021) Electric-field-induced chirality in columnar liquid crystals. *J Am Chem Soc* 143(24):9260–9266
302. Fujikake H, Takizawa K, Aida T, Negishi T, Kobayashi M (1998) Video camera system using liquid-crystal polarizing filter to reduce reflected light. *IEEE Trans Broadcast* 44(4):419–426
303. Baus M, Colot JL (1989) Ferroelectric nematic liquid-crystal phases of dipolar hard ellipsoids. *Phys Rev A* 40(9):5444–5446

304. Uehara H, Hatano J (2002) Pressure-temperature phase diagrams of ferroelectric liquid crystals. *J Phys Soc Jpn* 71(2):509–3491
305. Priestley EB, Wojtowicz PJ, Sheng P (eds) (1975) *Introduction to liquid crystals*. Plenum Press, New York
306. Clark NA, Lagerwall ST (1980) Submicrosecond bistable electro-optic switching in liquid crystals. *Appl Phys Lett* 36(11):899–901
307. de Gennes PG (1972) An analogy between superconductors and smectics A. *Solid State Commun* 10(9):753–756
308. Goodby JW, Waugh MA, Stein SM, Chin E, Pindak R, Patel JS (1989) Characterization of a new helical smectic liquid crystal. *Nature* 337(6206):449–452
309. Kamien R (1997) Smectic order in double-twist cylinders. *Journal de Physique II France* 7(5):743–750
310. Samulski ET (1985) Macromolecular structure and liquid crystallinity. *Faraday Discuss Chem Soc* 79(1):7–20
311. Lawrence Chapoy L (1985) *Recent advances in liquid crystalline polymers*. Elsevier
312. McArdle CB (ed) (1989) *Side chain liquid crystal polymers*. Chapman and Hall
313. Takeda M, Limura K, Koide N, Platé N (1989) Preface: special issue on applied liquid crystal polymer research. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 169(1):v
314. Brostow W (1990) Properties of polymer liquid crystals: choosing molecular structures and blending. *Polymer* 31(6):979–995
315. National Materials Advisory Board (1990) *Liquid crystalline polymers: report of the committee on liquid crystalline polymers*. National Academic Press
316. Weiss RA, Ober CK (eds) (1990) *Liquid-crystalline polymers*, series: ACS symposium series, vol 435. American Chemical Society
317. Thompson DC, Tantot O, Jallageas H, Ponchak GE, Tentzeris MM, Papapolymerou J (2004) Characterization of liquid crystal polymer (LCP) material and transmission lines on LCP substrates from 30 to 110 GHz. *IEEE Trans Microw Theory Tech* 52(4):1343–1352
318. Wang XJ, Zhou QF (2004) *Liquid crystalline polymers*. World Scientific
319. Dejean G, Bairavasubramanian R, Thompson D, Ponchak GE, Tentzeris MM, Papapolymerou J (2005) Liquid crystal polymer (LCP): a new organic material for the development of multi-layer dual-frequency/dualpolarization flexible antenna arrays. *IEEE Antennas Wirel Propag Lett* 4:22–26
320. Donald AM, Windle AH, Hanna S (2005) *Liquid crystalline polymers*, cambridge solid state science series. Cambridge University Press
321. Nikolaou S, Ponchak GE, Papapolymerou J, Tentzeris MM (2006) Conformal double exponentially tapered slot antenna (DE TSA) on LCP for UWB applications. *IEEE Trans Antennas Propag* 54(5):1663–1669
322. Bairavasubramanian R (2007) *Development of microwave/millimeter-wave antennas and passive components on multilayer liquid crystal polymer (LCP) technology*. Ph. D. Dissertation, Georgia Institute of Technology
323. Callister WD, Rethwish DG (2007) *Materials science and engineering: an introduction*, 7th edn. Wiley
324. Vyas R, Rida A, Bhattacharya S, Tentzeris MM (2007) Liquid crystal polymer (LCP): the ultimate solution for low-cost RF flexible electronics and antennas. In: 2007 IEEE antennas and propagation society international symposium, Honolulu, HI, pp 1729–1732
325. Khan J (2008) *Design of microstrip patch antenna on liquid crystal polymer (LCP) for applications at 70 GHz*. Master Thesis, University of Gävle
326. Kingsley N, Ponchak GE, Papapolymerou J (2008) Reconfigurable RF MEMS phased array antenna integrated within a liquid crystal polymer (LCP) system-on-package. *IEEE Trans Antennas Propag* 56(1):108–118
327. Ganicz T, Stańczyk W (2009) Side-chain liquid crystal polymers (SCLCP): methods and materials. an overview. *Materials* 2(1):95–128
328. Ha D, Kim BG, Lin TY, Ouyang Y, Irazoqui PP, Chappell WJ (2010) 3D packaging technique on liquid crystal polymer (LCP) for miniature wireless biomedical sensor. In: 2010 IEEE MTT-S international microwave symposium, Anaheim, CA, pp 612–615

329. Lee DY, Seo JM, Khan W, Kornfield JA, Kurji Z, Park SY (2010) pH-responsive aqueous/LC interfaces using SGLCP-b-polyacrylic acid block copolymers. *Soft Matter* 6(9):1964–1970
330. Marnat L, Shamim A (2012) Liquid crystal polymer (LCP) based antenna for flexible system on package (SoP) applications. In: 2012 15th international symposium on antenna technology and applied electromagnetics, Toulouse, art no 6262403
331. Kotamraju SK, Rama Krishna TV, Madhav BTP, Khan H, Bhavani KVL (2013) Exponential multiband serrated microstrip antenna on LCP substrate. In: 2013 international conference on advanced research in engineering and technology, Andhra Pradesh, India, pp 732–736
332. Callister WD, Rethwisch DG (2014) *Materials science and engineering: an introduction*, 9th edn. Wiley
333. Liu D, Broer DJ (2014) Liquid crystal polymer networks: preparation, properties, and applications of films with patterned molecular alignment. *Langmuir* 30(45):13499–13509
334. Thakur VK, Kessler MR (eds) (2015) *Liquid crystalline polymers: volume 2--processing and applications*. Springer
335. White TJ, Broer DJ (2015) Programmable and adaptive mechanics with liquid crystal polymer networks and elastomers. *Nat Mater* 14(11):1087–1098
336. Thakur VK, Kessler MR (eds) (2016) *Liquid crystalline polymers: volume 1--structure and chemistry*. Springer
337. Hosono R, Uemichi Y, Hasegawa Y, Nakatani Y, Kobayashi K, Guan N (2017) Development of millimeter-wave devices based on liquid crystal polymer (LCP) substrate. *IEICE Electron Exp* 14(20):1–13, art no 2001
338. Callister WD, Rethwisch DG (2018) *Materials science and engineering: an introduction*, 10th edn. Wiley
339. De Kort GW, Leoné N, Stellamanns E, Auhl D, Wilsens CHRM, Rastogi S (2018) Effect of shear rate on the orientation and relaxation of a vanillic acid based liquid crystalline polymer. *Polymers* 10(9), art no 935
340. Hosono R, Uemichi Y, Hasegawa Y, Kobayashi K, Nakatani Y, Guan N (2018) Development for LCP-based millimeter-wave devices. *Fujikura Tech Rev* 48:23–27
341. Kato T, Uchida J, Ichikawa T, Soberats B (2018) Functional liquid-crystalline polymers and supramolecular liquid crystals. *Polym J* 50(1):149–166
342. Ji Y, Bai Y, Liu X, Jia K (2020) Progress of liquid crystal polyester (LCP) for 5G application. *Adv Ind Eng Poly Res* 3(4):160–174
343. Zhu L, Li CY, (eds) (2020) *Liquid crystalline polymers, series: power polymers and polymeric composites*. Springer
344. Yamanaka N, Kawano R, Kubo W, Kitamura T, Wada Y, Watanabe M, Yanagida S (2005) Ionic liquid crystal as a hole transport layer of dye-sensitized solar cells. *Chem Commun* 6:740–742
345. Hu W, Zhao H, Song L, Yang Z, Cao H, Cheng Z, Liu Q, Yang H (2010) Electrically controllable selective reflection of chiral nematic liquid crystal/chiral ionic liquid composites. *Adv Mater* 22(4):468–472
346. Kondrat S, Bier M, Harnau L (2010) Phase behavior of ionic liquid crystals. *J Chem Phys* 132(18), art no 184901
347. Axenov KV, Laschat S (2011) Thermotropic ionic liquid crystals. *Materials* 4(1):206–259
348. Kokorin A (ed) (2011) *Ionic liquids: theory, properties, new approaches*. Intech
349. Mohammad A, Inamuddin (eds) (2012) *Green solvents II: properties and applications of ionic liquids*. Springer
350. Kadokawa JI (ed) (2013) *Ionic liquids: new aspects for the future*. Intech
351. Sakuda J, Yoshio M, Ichikawa T, Ohno H, Kato T (2015) 2D assemblies of ionic liquid crystals based on imidazolium moieties: formation of ion-conductive layers. *New J Chem* 39(6):4471–4477
352. Fernandez AA, Kouwer PHJ (2016) Key developments in ionic liquid crystals. *Int J Mol Sci* 17(5), art no 731
353. Goossens K, Lava K, Bielawski CW, Binnemans K (2016) Ionic liquid crystals: versatile materials. *Chem Rev* 116(8):4643–4807

- 354. Handy S (ed) (2017) Progress and developments in ionic liquids. Intech
- 355. Kapernaum N, Lange A, Ebert M, Grunwald MA, Haege C, Marino S, Zens A, Taubert A, Giesselmann F, Laschat S (2022) Current topics in ionic liquid crystals. *ChenPlusChem* 87(1), art no e202100397
- 356. Karim MA (1992) Electro-optical displays, series: optical science and engineering. CRC Press, Boca Raton
- 357. Bahadur B (ed) (1992) Liquid crystals—applications and uses, vol 3. World Scientific
- 358. Hussain A, Pina AS, Roque ACA (2009) Bio-recognition and detection using liquid crystals. *Biosens Bioelectron* 25(1):1–8
- 359. Ohm C, Brehmer M, Zentel R (2010) Liquid crystalline elastomers as actuators and sensors. *Adv Mater* 22(31):3366–3387
- 360. Lowe AM, Abbott NL (2012) Liquid crystalline materials for biological applications. *ACS Chem Mater* 24(5):746–758
- 361. Woltman SJ, Jay GD, Crawford GP (eds) (2007) Liquid crystals frontiers in biomedical applications. World Scientific
- 362. Woltman SJ, Jay GD, Crawford GP (2007) Liquid-crystal materials find a new order in biomedical applications. *Nat Mater* 6(12):929–938, art no 2010
- 363. Cuerva C, Fernández-Lodeiro J, Cano M, Capelo-Martínez JL, Lodeiro C (2021) Water-soluble hollow nanocrystals from self-assembly of AIEE-active Pt(II) metallomesogens. *Nano Res* 14(1):245–254
- 364. Roling LT, Scaranto J, Herron JA, Yu H, Choi S, Abbott NL, Mavrikakis M (2016) Towards first-principles molecular design of liquid crystal-based chemoresponsive systems. *Nat Commun* 7, art no 13338
- 365. Mahmood N, Al-Qraawy WKN, Almosawy MGAA (2021) Review on liquid crystals and their chemical applications. *Int J Chem-Inf Res* 7(1):8–15
- 366. Silva MC, Sotomayor J, Figueirinhas J (2015) Effect of an additive on the permanent memory effect of polymer dispersed liquid crystal films. *J Chem Technol Biotechnol* 90(9):1565–1569
- 367. da Silva MC, Figueirinhas JL, Sotomayor JC (2016) Improvement of permanent memory effect in PDLC films using TX-100 as an additive. *Liq Cryst* 43(1):124–130
- 368. Kos Ž, Dunkel J (2022) Nematic bits and universal logic gates. *Sci Adv* 8(33), art no eabp8371
- 369. Zakerhamidi MS, Shahrabi S (2013) Solvatochromic solvent polarity parameters for the characterisation of some cyanobiphenyl nematic liquid crystals. *Liq Cryst* 40(9):1195–1201
- 370. Hussain Z, Qazi F, Ahmed MI, Usman A, Riaz A, Abbasi AD (2016) Liquid crystals based sensing platform-technical aspects. *Biosens Bioelectron* 85:110–127
- 371. Bendahou A, Khoubi Z, Benabdallah T, Maschke U (2018) Mesophase study of pure and doped cyanobiphenyl liquid crystals with salen-type systems. *Liq Cryst* 45(9):1312–1323
- 372. Pushpavathi N, Sandhya KL (2019) Photoluminescence study of liquid crystal-ZnO nanocomposites. *J Mol Liq* 274:724–729
- 373. Oladepo SA (2021) Temperature-dependent fluorescence emission of 4-cyano-4'-pentylbiphenyl and 4-cyano-4'-hexylbiphenyl liquid crystals and their bulk phase transitions. *J Mol Liq* 323:114590
- 374. Stasiek J, Jewartowski M, Kowalewski TA (2014) The use of liquid crystal thermography in selected technical and medical applications—recent development. *J Crystal Proc Technol* 4(1), art no 42466
- 375. Sato S (1979) Liquid-crystal lens-cells with variable focal length. *Jpn J Appl Phys* 18(9):1679–1684
- 376. Lin HC, Chen MS, Lin YH (2011) A review of electrically tunable focusing liquid crystal lenses. *Trans Electr Electron Mater* 12(6):234–240
- 377. Maasch M, Roig M, Damm C, Jakoby R (2014) Realization of a voltage tunable gradient-index fishnet loaded with liquid crystal. In: 2014 8th international congress on advanced electromagnetic materials in microwaves and optics, Copenhagen, Denmark, art no 6948644, pp 196–198
- 378. Maasch M, Roig M, Damm C, Jakoby R (2014) Voltage-tunable artificial gradient-index lens based on a liquid crystal loaded fishnet metamaterial. *IEEE Antennas Wirel Propag Lett* 13:1581–1584

379. Lin YH, Wang YJ, Reshetnyak V (2017) Liquid crystal lenses with tunable focal length. *Liq Cryst Rev* 5(2):111–143
380. Nose T, Ohno S, Masaka M, Ito K, Ito R, Honma M (2017) Basic performance of a liquid crystal millimeter wave Fresnel lens fabricated using machinable porous polymethylmethacrylate materials. *Mol Cryst Liq Cryst* 647(1):341–350
381. Reese R, Jost M, Polat E, Tesmer H, Strobl J, Schuster C, Nickel M, Jakoby R, Maune H (2019) A millimeter-wave beam-steering lens antenna with reconfigurable aperture using liquid crystal. *IEEE Trans Antennas Propag* 67(8):5313–5324
382. Shen Z, Zhou S, Ge S, Duan W, Ma L, Lu Y, Hu W (2019) Liquid crystal tunable terahertz lens with spin-selected focusing property. *Opt Exp* 27(6):8800–8807
383. Cai WF, Li YF, Jiang HD, Luo D, Liu YJ (2020) Research progress of liquid crystal microlens arrays. *Chin J Liq Cryst Displ* 35(7):749–761
384. Wang YJ, Lin YH, Cakmakci O, Reshetnyak V (2020) Phase modulators with tunability in wavefronts and optical axes originating from anisotropic molecular tilts under symmetric electric field II: experiments. *Opt Exp* 28(6):8985–9001
385. Tadwee I, Shahi S, Ramteke V, Syed I (2012) Liquid crystals pharmaceutical application: a review. *Int J Pharm Res Allied Sci* 1(2):6–11
386. Choudhury PK, Ibrahim ABMA (eds) (2022) *Liquid crystals*. Intech
387. Zheng M, Zeng M, Chen X, Yuan J (2021) Structures and applications of photo-responsive shape-changing liquid crystal polymers. *Prog Chem* 33(6):914–925
388. Gregory Plimpton R (1988) Pool thermometer, Patent No. US4738549
389. Lin H, Khan M, Giao T (1994) Dynamic liquid crystal hot spot examination of functional failures on production testers. In: 1994 20th international symposium for testing and failure analysis, Materials Park, OH, pp 81
390. Ferrier S (1997) Thermal and optical enhancements to liquid crystal hot spot detection methods. In: 1997 23rd international symposium for testing and failure analysis, Materials Park, OH, pp 57
391. Burgess D (1999) Liquid crystal: best ideas from 15 years. *Electron Device Fail Anal News* 1(2):7–10
392. Burgess D (1999) Liquid crystals detect hot defects
393. Heilmeyer GH, Goldmacher JE (1969) A new electric field controlled reflective optical storage effect in mixed liquid crystal systems. *Proc IEEE* 57(1):34–38
394. Yaghmaee P, Karabey OH, Bates B, Fumeaux C, Jakoby R (2013) Electrically tuned microwave devices using liquid crystal technology. *Int J Anten Propag*, art no 824214
395. Candau S, Le Roy P, Debeauvais F (1973) Magnetic field effects in nematic and cholesteric droplets suspended in a isotropic liquid. *Mol Cryst Liq Cryst* 23(3–4):283–297
396. Shah RR, Abbott NL (2003) Orientational transitions of liquid crystals driven by binding of organoamines to carboxylic acids presented at surfaces with nanometer-scale topography. *Langmuir* 19(2):275–284
397. Xu H, Bi X, Ngo X, Yang KL (2009) Principles of detecting vaporous thiols using liquid crystals and metal ion microarrays. *Analyst* 134(5):911–915
398. Wang PH, Yu JH, Zhao YB, Li ZJ, Li GQ (2011) A novel liquid crystal-based sensor for the real-time identification of organophosphonate vapors. *Sens Actuators B: Chem* 160(1):929–935
399. Carlton RJ, Hunter JT, Miller DS, Abbasi R, Mushenheim PC, Tan LN, Abbott NL (2013) Chemical and biological sensing using liquid crystals. *Liq Cryst Rev* 1(1):29–51
400. Wani OM, Zeng H, Priimagi A (2017) A light-driven artificial flytrap. *Nat Commun* 8, art no 15546
401. Brannum MT, Steele AM, Venetos MC, Korley LTJ, Wnek GE, White TJ (2019) Light control with liquid crystalline elastomers. *Adv Opt Mater* 7(6), art no 1801683
402. Meier G, Sackmann E, Grubmaier JG (1975) *Applications of liquid crystals*. Springer
403. Ericksen JL, Kinderlehrer D (eds) (1987) *Theory and applications of liquid crystals, series: the IMA volumes in mathematics and its applications*, vol 5. Springer, New York
404. Bahadur B (ed) (1990) *Liquid crystals: applications and uses*, vol 1. World Scientific

405. Bahadur B (ed) (1991) Liquid crystals—applications and uses, vol 2, World Scientific
406. Takato K, Hasegawa M, Koden M, Itoh N, Hasegawa R, Sakamoto M (2005) Alignment technologies and applications of liquid crystal devices, series: liquid crystals book series. CRC Press, Boca Raton
407. Atkuri HM, Leong ESP, Hwang J, Palermo G, Si G, Wong JM, Chien LC, Ma J, Zhou K, Liu YJ, Sio LD (2015) Developing novel liquid crystal technologies for display and photonic applications. *Displays* 36(6):21–29
408. Shibaev PV, Wenzlick M, Murray J, Tantillo A, Howard-Jennings J (2015) Rebirth of liquid crystals for sensoric applications: environmental and gas sensors. *Adv Condens Matter Phys*, art no 729186
409. Esteves C, Ramou E, Porteira ARP, Barbosa AJM, Roque ACA (2020) Seeing the unseen: the role of liquid crystals in gas-sensing technologies. *Adv Opt Mater* 8(11), art no 1902117
410. Kumar S, Verma R (2021) Liquid crystal polymers: novel applications. *Poly Sci: Peer Rev J* 1(5), art no 525
411. Wang Z, Xu T, Noel A, Chen YC, Liu T (2021) Applications of liquid crystals in biosensing. *Soft Matter* 17(18):4675–4702
412. Oladepo SA (2022) Development and application of liquid crystals as stimuli-responsive sensors. *Molecules* 27(4), art no 1453
413. Schadt M, Helfrich W (1971) Voltage-dependent optical activity of a twisted nematic liquid crystal. *Appl Phys Lett* 18(4):127–128
414. Schadt M (1989) Plenary lecture. The history of the liquid crystal display and liquid crystal material technology. *Liq Cryst* 5(1):57–71
415. Schadt M, Seiberle H, Schuster A (1996) Optical patterning of multi-domain liquid-crystal displays with wide viewing angles. *Nature* 381(6579):212–215
416. Kawamoto H (2002) The history of liquid-crystal displays. *Proc IEEE* 90(4):460–500
417. Crawford G (ed) (2005) Flexible flat panel displays, series: wiley—SID series in display technology. John Wiley & Sons, New York
418. Smith CA (2008) A review of liquid crystal display technologies, electronic interconnection and failure analysis. *Circ World* 34(1):35–41
419. Cliff Jones J (2018) The fiftieth anniversary of the liquid crystal display. *Liq Cryst Today* 27(3):44–70
420. Gross B (2018) The TVs of tomorrow: how RCA's flat-screen dreams led to the first LCDs, series: synthesis. University of Chicago Press
421. Ishihara S, Kobayashi S, Ukai Y (eds) (2019) High quality liquid crystal displays and smart devices, volume 1: development, display applications and components, series: IET materials, circuits and devices series, vol 68. The Institution of Engineering and Technology
422. Ishihara S, Kobayashi S, Ukai Y (eds) (2019) High quality liquid crystal displays and smart devices, volume 2: surface alignment, new technologies and smart device applications, series: iet materials, circuits and devices series, vol 68. The Institution of Engineering and Technology
423. Geng Y, Brogueira P, Figueirinhas JL, Godinho MH, Almeida PL (2013) Light shutters from nanocrystalline cellulose rods in a nematic liquid crystal. *Liq Cryst* 40(6):769–773
424. Nasir N, Hong H, Rehman MA, Kumara S, Seo Y (2020) Polymer-dispersed liquid-crystal-based switchable glazing fabricated via vacuum glass coupling. *Royal Soc Chem (RSC) Adv* 10(53):32225–32231
425. Kamal W, Li M, Lin JD, Parry E, Jin Y, Elston SJ, Castrejón-Pita AA, Morris SM (2022) Spatially patterned polymer dispersed liquid crystals for image-integrated smart windows. *Adv Opt Mater* 10(3), art no 2101748
426. Li Y, Wang M, Zhang C, Wang CC, Xu W, Gao S, Zhou Y, Wang CT, Wang Z (2022) A fully self-powered cholesteric smart window actuated by droplet-based electricity generator. *Adv Opt Mater* 10(7), art no 2102274
427. Fergason JL (1984) Encapsulated liquid crystal and method. Patent No. US4435047, Manchester R&D Partnership
428. Fergason JL (1985) Polymer encapsulated nematic liquid crystals for display and light control applications. *Soc Inf Displ Symp Dig Tech Pap* 16(1):68–70

429. Doane JW, Vaz NA, Wu BG, Zumer S (1986) Field controlled light scattering from nematic microdroplets. *Appl Phys Lett* 48(4):269–271
430. Drzaic PS (1986) Polymer dispersed nematic liquid crystal for large area displays and light valves. *J Appl Phys* 60(6):2142–2148
431. Doane JW, Golemme A, West JL, Whitehead JB Jr, Wu BG (1988) Polymer dispersed liquid crystals for display application. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 165(1):511–532
432. Drzaic PS (1988) Reorientation dynamics of polymer dispersed nematic liquid crystal films. *Liq Cryst* 3(11):1543–1559
433. Friedman A (1990) Mathematics in industrial problems part 3, series: the IMA volumes in mathematics and its applications, vol 31. Springer, New York, pp 62–79
434. Coates D (1993) Normal and reverse mode polymer dispersed liquid crystal devices. *Displays* 14(2):94–103
435. Ferguson JL, Fan NS, Rearlman KN (1993) Encapsulated liquid crystal having a smectic phase. European Patent No. EP0204537A3, Raychem Corp
436. Pearlman KN, Ferguson JL, Fan NS (1993) Encapsulated liquid crystal having a smectic phase. Patent No. US5216530A, Tyco International Ltd Bermuda TE Connectivity Corp Tyco International PA Inc
437. Coates D (1995) Polymer-dispersed liquid crystals. *J Mater Chem* 5(12):2063–2072
438. Takei J (1996) Polymer dispersed liquid crystal display device having encapsulated liquid crystal surrounded by polymer matrix liquid crystal and method of manufacturing the same. Patent No. US5530567, Battelle Memorial Institute Inc, Casio Computer Co Ltd
439. Drzaic P, Drzaic PS (2006) Putting liquid crystal droplets to work: a short history of polymer dispersed liquid crystals. *Liq Cryst* 33(11–12):1281–1296
440. Kopčanský P, Timko M, Mitrova Z, Zavisova V, Koneracká M, Tomašovičová N, Tomčo L, Gornitska OP, Kovalchuk OV, Bykov VM, Kovalchuk TM, Studenýak IP (2010) Morphology and dielectric properties of polymer dispersed liquid crystal with magnetic nanoparticles. *Semiconductor Phys Q Electron Optoelectron* 13(4):343–347
441. Kopcansky P, Timko M, Mitrova Z, Zavisova V, Koneracka M, Tomasovicova N, Tomco L, Kovalchuk OV, Bykov VM, Kovalchuk TM, Lad AI (2013) Effect of magnetic nanoparticles with various geometrical shapes on morphology and dielectric properties of nanodispersions of nematic liquid crystal in polymer matrix. *Semiconductor Phys Q Electron Optoelectron* 16(3):253–258
442. Sparavigna AC (2019) Polymer dispersed liquid crystals and related electro-optical devices— an overview. Zenodo, art no 3361600
443. Ghamisari MS, Carlescu I (eds) (2020) Liquid crystals and display technology. Intech
444. Pozhidaev EP, Kaznacheev AV, Torgova SI, Kesaev VV, Barbashov VA (2020) Polymer dispersed liquid crystals with electrically controlled light scattering in the visible and near-infrared ranges. *Opt Mater Exp* 10(12):3030–3040
445. Saeed MH, Zhang S, Cao Y, Zhou L, Hu J, Muhammad I, Xiao J, Zhang L, Yang H (2020) Recent advances in the polymer dispersed liquid crystal composite and its applications. *Molecules* 25(23), art no 5510
446. Ferguson JL, Vogl TP, Max G (1963) Thermal imaging devices utilizing a cholesteric liquid crystalline phase material. Patent No. US3114836, CBS Corp
447. Witonsky RJ, Scarantino JW (2001) Liquid crystal thermometer, Patent No. US6257759, Medical Indicators Inc
448. Sparavigna AC (2013) James Ferguson, a pioneer in advancing of liquid crystal technology, arXiv, art no 1310.7569v1
449. Manna U, Zayas-Gonzalez YM, Carlton RJ, Caruso F, Abbott NL, Lynn DM (2013) Liquid crystal chemical sensors that cells can wear. *Angewandte Chemie* 52(52):14011–14015
450. Wang D, Park SY, Kang IK (2015) Liquid crystals: emerging materials for use in real-time detection applications. *J Mater Chem C* 3(35):9038–9047
451. Niu X, Zhong Y, Chen R, Wang F, Luo D (2017) Highly sensitive and selective liquid crystal optical sensor for detection of ammonia. *Opt Exp* 25(12):13549–13556

452. Schenning APHJ, Crawford GP, Broer DJ (2018) Liquid crystal sensors, series: liquid crystals book series. CRC Press, Boca Raton
453. Wang J, Jákli A, West JL (2018) Liquid crystal/polymer fiber mats as sensitive chemical sensors. *J Mol Liq* 267:490–495
454. Ashford A, Constant J, Kirton J, Raynes EP (1973) Electro-optic performance of a new room-temperature nematic liquid crystal. *Electron Lett* 9(5):118–120
455. Johnson JF, Porter RS (eds) (1974) Liquid crystals and ordered fluids, vol 2. Springer
456. Seo DS, Matsuda H, Oh-ide T, Kobayashi S (1993) Alignment of nematic liquid crystal(5CB) on the treated substrates: characterization of orientation films, generation of pretilt angles, and surface anchoring strength. *Mol Cryst Liq Cryst Sci Technol. Section A. Mol Cryst Liq Cryst* 224(1):13–31
457. Vill V (1998) Grey levels in the history of liquid crystals. *Liq Cryst* 24(1):21–24
458. Kwon JY, Khan M, Park SY (2016) pH-Responsive liquid crystal double emulsion droplets prepared using microfluidics. *Royal Soc Chem (RSC) Adv* 6(61):55976–55983
459. Jang HJ, Park YS (2017) PH-responsive cholesteric liquid crystal double emulsion droplets prepared by microfluidics. *Sens Actuators, B Chem* 241:636–643
460. Omer M, Islam MT, Khan M, Kim YK, Lee JH, Kang IK, Park SY (2014) Liquid crystal-based biosensors using a strong polyelectrolyte-containing block copolymer, poly(4-cyanobiphenyl-4'-oxyundecylacrylate)-b-poly(sodium styrene sulfonate). *Macromol Res* 22(8):888–894
461. Tang J, Fang J, Liang Y, Zhang B, Luo Y, Liu X, Li Z, Cai X, Xian J, Lin H, Zhu W, Guan H, Lu H, Zhang J, Yu J, Chen Z (2018) All-fiber-optic VOC gas sensor based on side-polished fiber wavelength selectively coupled with cholesteric liquid crystal film. *Sens Actuators B: Chem* 273:1816–1826
462. Wang Y, Hu Q, Tian T, Yu L (2017) Simple and sensitive detection of pesticides using the liquid crystal droplet patterns platform. *Sens Actuators, B Chem* 238:676–682
463. Ailincal D, Pamfil D, Marin L (2018) Multiple bio-responsive polymer dispersed liquid crystal composites for sensing applications. *J Mol Liq* 272:572–582
464. Omer M, Khan M, Kim YK, Lee JH, Kang IK, Park SY (2014) Biosensor utilizing a liquid crystal/water interface functionalized with poly(4-cyanobiphenyl-4'-oxyundecylacrylate-b-((2-dimethyl amino) ethyl methacrylate)). *Colloids Surfaces B: Biointerfaces* 121:400–408
465. Khan M, Park SY (2015) Specific detection of avidin–biotin binding using liquid crystal droplets. *Colloids Surf B: Biointerfaces* 127:241–246
466. Ren H, An Z, Jang CH (2019) Liquid crystal-based aptamer sensor for sensitive detection of bisphenol A. *Microchem J* 146:1064–1071
467. Tingey ML, Wilyana S, Snodgrass EJ, Abbott NL (2004) Imaging of affinity microcontact printed proteins by using liquid crystals. *Langmuir* 20(16):6818–6826
468. Wang Y, Hu Q, Tian T, Gao Y, Yu L (2016) A nonionic surfactant-decorated liquid crystal sensor for sensitive and selective detection of proteins. *Analytica Chimica Acta* 937:119–126
469. Tian T, Kang Q, Wang T, Xiao J, Yu L (2018) Alignment of nematic liquid crystals decorated with gemini surfactants and interaction of proteins with gemini surfactants at fluid interfaces. *J Colloid Interface Sci* 518:111–121
470. Wu PC, Karn A, Lee MJ, Lee W, Chen CY (2018) Dye-liquid-crystal-based biosensing for quantitative protein assay. *Dyes Pigm* 150:73–78
471. Verma I, Selvakumar SLV, Pal SK (2020) Surfactin-laden aqueous–liquid crystal interface enabled identification of secondary structure of proteins. *J Phys Chem C* 124(1):780–788
472. Ding X, Yang KL (2012) Liquid crystal based optical sensor for detection of vaporous butylamine in air. *Sens Actuators, B Chem* 173:607–613
473. Dadoenkova MR, Bentivegna FF, Svetukhin VV, Zhukov AV, Petrov R, Bichurin MR (2017) Controlling optical beam shifts upon reflection from a magneto-electric liquid-crystal-based system for applications to chemical vapor sensing. *Appl Phys B: Lasers Opt* 123(4), art no 107
474. Wang N, Kanhere E, Miao J, Triantafyllou MS (2018) Nanoparticles-modified chemical sensor fabricated on a flexible polymer substrate for cadmium(II) detection. *Polymers* 10(7), art no 694

475. Vistak M, Sushynsky IO, Mykytyuk Z, Aksimentyeva O, Semenova Y (2015) Sensing of carbon monoxide with porous Al₂O₃ intercalated with Fe₃O₄ nanoparticles-doped liquid crystal. *Sens Actuators, A* 235:165–170
476. Ren H, Jang CH (2019) A simple liquid crystal-based aptasensor using a hairpin-shaped aptamer for the bare-eye detection of carcinoembryonic antigen. *BioChip J* 13(4):352–361
477. Xia C, Zhou D, Su Y, Zhou G, Yao L, Sun W, Liu Y (2020) A liquid-crystal-based immunosensor for the detection of cardiac troponin I. *Analyst* 145(13):4569–4575
478. Hunter JT, Abbott NL (2013) Dynamics of the chemo-optical response of supported films of nematic liquid crystals. *Sens Actuators B: Chem* 183:71–80
479. Tan H, Li X, Liao S, Yu R, Wu Z (2014) Highly-sensitive liquid crystal biosensor based on DNA dendrimers-mediated optical reorientation. *Biosens Bioelectron* 62:84–89
480. Liu Y, Yang KL (2015) Applications of metal ions and liquid crystals for multiplex detection of DNA. *J Colloid Interface Sci* 439:149–153
481. Kim HJ, Jang CH (2018) Imaging DNA single-strand breaks generated by reactive oxygen species using a liquid crystal-based sensor. *Anal Biochem* 556:1–6
482. Rowinski P, Rowinska M, Heller A (2008) Liquid crystal membranes for serum-compatible diabetes management-assisting subcutaneously implanted amperometric glucose sensors. *Anal Chem* 80(5):1746–1755
483. Kim J, Khan M, Park SY (2013) Glucose sensor using liquid-crystal droplets made by microfluidics. *ACS Appl Mater Interfaces* 5(24):13135–13139
484. Zhong S, Jang CH (2014) Highly sensitive and selective glucose sensor based on ultraviolet-treated nematic liquid crystals. *Biosens Bioelectron* 59:293–299
485. Khan M, Park SY (2015) Liquid crystal-based glucose biosensor functionalized with mixed PAA and QP4VP brushes. *Biosens Bioelectron* 68:404–412
486. Khan M, Park SY (2017) Liquid crystal-based biosensor with backscattering interferometry: a quantitative approach. *Biosens Bioelectron* 87:976–983
487. Munir S, Park SY (2018) Liquid-crystal droplets functionalized with a non-enzymatic moiety for glucose sensing. *Sens Actuators, B Chem* 257:579–585
488. Qi L, Hu Q, Kang Q, Yu L (2018) Fabrication of liquid-crystal-based optical sensing platform for detection of hydrogen peroxide and blood glucose. *Anal Chem* 90(19):11607–11613
489. Popov P, Honaker L, Kooijman EE, Mann E, Jákli AI (2016) A liquid crystal biosensor for specific detection of antigens. *Sens Bio-Sens Res* 8:31–35
490. Su X, Huo W, Yang D, Luan C, Xu J (2019) Label-free liquid crystal immunosensor for detection of HBD-2. *Talanta* 203:203–209
491. Chuang HY, Chen CH (2019) Developing liquid crystal-based immunoassay for melamine detection. *Res Chem Intermed* 45(1):91–102
492. Sen A, Kupcho KA, Grinwald BA, Van Treeck HJ, Acharya BR (2013) Liquid crystal-based sensors for selective and quantitative detection of nitrogen dioxide. *Sens Actuators B: Chem* 178:222–227
493. Bungabong ML, Bin Ong P, Yang KL (2010) Using copper perchlorate doped liquid crystals for the detection of organophosphonate vapor. *Sens Actuators B: Chem* 148(2):420–426
494. Chen CH, Yang KL (2013) A liquid crystal biosensor for detecting organophosphates through the localized pH changes induced by their hydrolytic products. *Sens Actuators, B Chem* 181:368–374
495. Zhou L, Hu Q, Kang Q, Yu L (2018) Construction of liquid crystal droplet-based sensing platform for sensitive detection of organophosphate pesticide. *Talanta* 190:375–381
496. Hu C, Li P, Wu Z, Fan F, Qian D, Yi Y, Yang S, Xiao F (2021) A novel liquid crystal sensing platform for highly selective UO₂²⁺ detection based on a UO₂²⁺-specific DNAzyme. *Anal Meth* 13(40):4732–4738
497. Tolmachev AV, Govorun EY, Kuz'Michev VM (1973) Visualization of radiation in the millimeter and submillimeter range by means of liquid crystals. *Soviet Phys J Exp Theo Phys* 36(2):309–310
498. Lim KC, Margerum JD (1992) Liquid-crystal optical properties and applications in the millimeter-wave range. *SPIE/Display Technol* 1815:99–105

499. Lim KC, Margerum JD, Lackner AM, Miller LJ (1992) Microwave phase modulation with liquid crystals. European Patent No. EP0472403A2, Raytheon Co
500. Lim KC, Margerum JC, Lackner AM, Miller LJ, Sherman E, Smith WH Jr (1993) Liquid crystal birefringence for millimeter wave radar. *Liq Cryst* 14(2):327–337
501. Shrekenhamer D, Chen WC, Padilla WJ (2013) Liquid crystal tunable metamaterial absorber. *Phys Rev Lett* 110(17), art no 177403
502. Isić G, Vasić B, Zografopoulos DC, Beccherelli R, Gajić R (2015) Electrically tunable critically coupled terahertz metamaterial absorber based on nematic liquid crystals. *Phys Rev Appl* 3(6), art no 064007
503. Wang L, Ge S, Chen Z, Hu W, Lu Y (2016) Liquid crystal based tunable terahertz metamaterial absorbers. In: 2016 conference COMSOL conference. Shanghai
504. Wang L, Ge S, Chen Z, Hu W, Lu Y (2016) Bridging the terahertz near-field and far-field observations of liquid crystal based metamaterial absorbers. *Chin Phys B* 25(9), art no 094222
505. Yin Z, Wan C, Deng G, Zheng A, Wang P, Yang Y, Gao S, Yang J, Cai F, Li Z, Lu H (2018) Fast-tunable terahertz metamaterial absorber based on polymer network liquid crystal. *Appl Sci* 8(12), art no 2454
506. Zhou S, Shen Z, Kang R, Ge S, Hu W (2018) Liquid crystal tunable dielectric metamaterial absorber in the terahertz range. *Appl Sci* 8(11), art no 2211
507. Kuznetsov SA, Nikolaev NA, Trashkeev SI, Lazorskiy PA, Arzhannikov AV (2019) Application of the concept of ultra-thin resonant absorbers for controlling millimeter-wave radiation by means of liquid crystals. *Siberian J Phys* 14(2):86–102
508. Dolfi D, Labeyrie M, Joffre P, Huignard JP (1993) Liquid crystal microwave phase shifter. *Electron Lett* 29(10):926–928
509. Dolfi D, Labeyrie M, Joffre P, Huignard JP (1994) Liquid-crystal microwave phase shifter. *SPIE/Optoelectron Sig Proc Phased-Array Antennas IV* 2155:420–425
510. Vogel W, Berroth M (2001) Polarisation independent liquid crystal 360° phase shifter for optically generated RF-signals. In: 2001 31st European microwave conference, London, England, vol 3, pp 31–34
511. Belyaev BA, Leksikov AA, Serzhantov AM, Shabanov VF (2008) Controllable liquid-crystal microwave phase shifter. *Tech Phys Lett* 34(6):463–466
512. Goelden F, Gaebler A, Goebel M, Manabe A, Mueller S, Jakoby R (2009) Tunable liquid crystal phase shifter for microwave frequencies. *Electron Lett* 45(13):686–687
513. Nozokido T, Maede S, Miyasaka N, Okada H, Nose T, Murai T (2010) A millimeter-wave quasi-optical grid phase shifter using liquid crystal. *IEICE Electron Exp* 7(2):67–72
514. Kamei T, Yokota M, Ozaki R, Moritake H, Onodera N (2011) Microstrip array antenna with liquid crystals loaded phase shifter. *Mol Cryst Liq Cryst* 542(1):167–175
515. Garbovskiy Y, Zagorodnii V, Krivosik P, Lovejoy J, Camley RE, Celinski Z, Glushchenko A, Dziaduszek J, Dąbrowski R (2012) Liquid crystal phase shifters at millimeter wave frequencies. *J Appl Phys* 111(5), art no 054504
516. Wu Y, Ruan X, Chen CH, Shin YJ, Lee Y, Niu J, Liu J, Chen Y, Yang KL, Zhang X, Ahn JH, Yang H (2013) Graphene/liquid crystal based terahertz phase shifters. *Opt Exp* 21(18):21395–21402
517. Deo P, Mirshekar-Syahkal D, Seddon L, Day SE, Fernandez FA (2014) Beam steering 60 GHz slot antenna array using liquid crystal phase shifter. In: 2014 8th European conference on antennas and propagation, The Hague, The Netherlands, pp 1005–1007
518. Yang CS, Tang TT, Pan RP, Yu P, Pan CL (2014) Liquid crystal terahertz phase shifters with functional indium-tin-oxide nanostructures for biasing and alignment. *Appl Phys Lett* 104(14), art no 141106
519. Attoui A, Boualleg H (2015) External command study of the phase shifter for applications to array antenna with nematic liquid crystal. *Metall Min Ind* 7:134–140
520. Du Y, Tian H, Cui X, Wang H, Zhou ZX (2016) Electrically tunable liquid crystal terahertz phase shifter driven by transparent polymer electrodes. *J Mater Chem C* 4(19):4138–4142
521. Weickhmann CJM (2017) Liquid crystals towards terahertz: characterisation and tunable waveguide phase shifters for millimetre-wave and terahertz beamsteering antennas. Ph. D. Dissertation, Technischen Universität Darmstadt

- 522. Bui VB, Inoue Y, Higuchi H, Kikuchi H, Moritake H (2018) Response improvement of microstrip line microwave and milliwave phase shifter utilizing polymer stabilized nematic liquid crystal with UV polymerization. *Electron Commun Jpn* 101(3):49–57
- 523. Gao S, Yang J, Wang P, Zheng A, Lu H, Deng G, Lai W, Yin Z (2018) Tunable liquid crystal based phase shifter with a slot unit cell for reconfigurable reflect arrays in F-band. *Appl Sci* 8(12), art no 2528
- 524. Li J (2018) Structure and optimisation of liquid crystal based phase shifter for millimetre-wave applications. University of Cambridge, Ph. D. Dissertation
- 525. Yang J, Cai C, Yin Z, Xia T, Jing S, Lu H, Deng G (2018) Reflective liquid crystal terahertz phase shifter with tuning range of over 360°. *IET Microw Antennas Propag* 12(9):1466–1469
- 526. Yang J, Xia T, Jing S, Deng G, Lu H, Fang Y, Yin Z (2018) Electrically tunable reflective terahertz phase shifter based on liquid crystal. *J Infrared, Millimeter, Terahertz Waves* 39(5):439–446
- 527. Ji Y, Fan F, Xu S, Yu J, Chang S (2019) Manipulation enhancement of terahertz liquid crystal phase shifter magnetically induced by ferromagnetic nanoparticles. *Nanoscale* 11(11):4933–4941
- 528. Sahoo AK, Yang CS, Wada O, Pan CL (2019) Twisted nematic liquid crystal based terahertz phase shifter with crossed indium tin oxide finger type electrodes. *IEEE Trans Terahertz Sci Technol* 9(4):399–408
- 529. Sahoo AK, Yang CS, Yen CL, Lin HC, Wang YJ, Lin YH, Wada O, Pan CL (2019) Twisted nematic liquid-crystal-based terahertz phase shifter using pristine PEDOT: PSS transparent conducting electrodes. *Appl Sci* 9(4), art no 761
- 530. Yang CS, Kuo C, Chen PH, Wu WT, Pan RP, Yu P, Pan CL (2019) High-transmittance 2π electrically tunable terahertz phase shifter with CMOS-compatible driving voltage enabled by liquid crystals. *Appl Sci* 9(2), art no 271
- 531. Nickel M, Jiménez-Sáez A, Agrawal P, Gadallah A, Malignaggi A, Schuster C, Reese R, Tesmer H, Polat E, Wang D, Schumacher P, Jakoby R, Kissinger D, Maune H (2020) Ridge gap waveguide based liquid crystal phase shifter. *IEEE Access* 8:77833–77842
- 532. Oh-e M, Zheng DY (2022) Newly discovered dimensional effects of electrodes on liquid crystal THz phase shifters enable novel switching between in-plane and out-of-plane. *Sci Rep* 12, art no 5482

Chapter 2

Elementary Liquid Crystal Physics



Liquid crystal is an intermediate state of matter ubiquitous in modern life with physical properties intermediate between those of conventional crystalline solids and conventional amorphous liquids. A large number of organic and inorganic compounds are known to go through several discrete liquid crystal phases when it is cooled from the isotropic liquid state to the anisotropic solid crystalline state [1, pp. 1]. Nematic liquid crystals are the simplest liquid crystalline phase as well as the most widely used in applications.

The performance of liquid crystal is dependent on a variety of internal and external factors. A crucial step in the industrial applications of liquid crystal is the theoretical understanding of the liquid crystal phases for controlling, predicting and even engineering liquid crystal properties. Of key importance is the underlying microscopic structure that is often poorly understood. In fact, systematic mechanisms for transferring information between microscopic and macroscopic scales is of fundamental scientific interest and recognized to be a major challenge for modern liquid crystal science. It is an intricate interdisciplinary science involving cutting-edge problems in diverse branches of mathematics, thermodynamics, statistical physics, chemistry, fluid mechanics, materials science, electrodynamics, and optics [2, pp. 5].

In this chapter, elements of liquid crystal physics are briefed. Attention is focused on nematic liquid crystal. More importantly, in consistency with the featured applications of liquid crystal in microwave, millimeter wave and terahertz frequencies, electromagnetic properties critical for such electromagnetic applications as well as effect of electromagnetic fields on liquid crystals are given more concerns.

2.1 Mesogen Model

Strong anisotropy of liquid crystals is a property not observed in other fluids. It has been pointed out in Chap. 1 of this book that an extended, structurally rigid, highly anisotropic molecule seems to be one of the critical origins for liquid crystal phases, regardless of chemical composition [3, pp. 59]. It is because of the anisotropic nature of the mesogens in liquid crystals that ordering in the following section as well as fluid flow must be considered when describing liquid crystal materials.

Known anisotropic molecules giving rise to liquid crystal phases can be either rod, disc, sanidic, bent-core or banana, rice bowl, or board, among which rod-shaped liquid crystal is the most widely used liquid crystal material, especially in the display field and microwave communication. A rigid elongated liquid crystal molecule has a rigid core, a flexible head and a flexible tail. With balanced rigid and flexible parts, the molecule exhibits liquid crystal phases. Three axes can be attached to it to describe its orientation. One is the long molecular axis $\hat{a}$ and the other two axes are perpendicular to the long molecular axis.

Usually the mesogen rotates fast around the long molecular axis $\hat{a}$. Although a real calamitic liquid crystal molecule is not exactly cylindrical, it can be regarded as a uniaxial cylinder because of the fast rotation on the order of 10^{-9} s around the long molecule axis due to thermal motion if there is no hindrance in the rotation. There is no preferred direction for the short axes. In addition, in non-ferroelectric liquid crystal phases, the head and tail are the same, even if the molecule has a permanent dipole moment, because the dipole has equal probability of pointing up or down.

On account of the rarity of lyotropic biaxial liquid crystals and the controversy about thermotropic biaxial liquid crystals, in this book, we concentrate on uniaxial nematic liquid crystals consisting of calamitic molecules unless otherwise specified. From the point of view of physical behavior, the theoretical model of a calamitic mesogen of length L and diameter D is shown in Fig. 2.1. Typical values of L and D for 40-n-Pentyl-4-cyano-biphenyl (5CB) are 2 nm and 0.5 nm, respectively.

Mesogens swivels due to thermal motion. Accordingly, the long molecular axis $\hat{a}$ of a calamitic mesogen is described by a distribution function $f(\theta, \phi)$. Nevertheless, $\langle \hat{a} \rangle$, the statistical average of $\hat{a}$ over a small volume element around a point, is well defined and is the same for all the molecules at macroscopic scale. Such a preferred direction as shown in Fig. 2.2 is defined as the director of liquid crystal and is denoted as $\hat{n}$. Because there is no physical polarity along the director axis, $\hat{n}$ and $-\hat{n}$ are fully

Fig. 2.1 Cylindrical molecular model for nematic liquid crystal

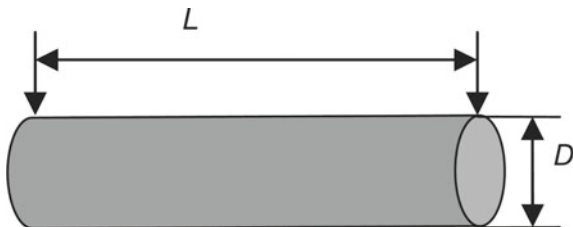
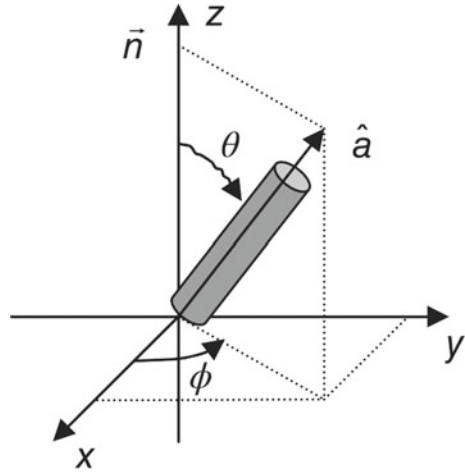


Fig. 2.2 Director of nematic liquid crystal



equivalent [4]. Furthermore, the vibration of the mesogenic mass center is ignored because of lack of positional order in nematic liquid crystal.

2.2 Theories of Liquid Crystal Phase Transitions

The theoretical description of a phase transition, or equivalently, determination of the corresponding free energy density function, is extremely difficult. Theoretical analysis and numerical simulation of liquid crystal phases can become much more complicated, owing to the non-negligible strong interactions, hard-core repulsions, and many-body correlations [5–16]. In particular, since lyotropic liquid crystals rely on a subtle balance of intermolecular interactions, it is more difficult to analyze their structures and properties than those of thermotropic liquid crystals.

There are a hierarchy of liquid crystal theories [3], [17, pp. 1403–1429], [18, pp. 2021–2051], [19], ranging from the most detailed atomistic theories to the least detailed macroscopic ones. Besides introducing well-established theories from other fields such as the Rayleigh-Gans theory [20], scaling theory of phase transitions [21–27], and renormalization group theory [28–32], [33, pp. 327–404], [34–36], since the 1920s, the liquid crystal community has also worked out numerous indigenous theories of liquid crystals of different complexities [5, 7, 20, 37–78], [79, Chap. 3], [80–108], among which a number of fairly simple theories can at least predict the general behavior of the meosphase transitions in liquid crystal systems. Very often, mathematical techniques such as calculus of variations, or the variational principle [5, 38, 40, 65, 77, 102, 109–119], are applied, especially when the interactions in the system are not trivial, e.g., at the presence of defects commonly observed in experiments on liquid crystals [111].

2.2.1 *Swarm Theory*

The swarm theory [40, 120–122] for nematics and cholesterics proposed by E. Bose in 1909 [5, pp. 9], [123] is so named because of the swarms dispersed in an isotropic melt. The swarm formation is basically attributed to the unsymmetrical shape of mesogens.

The swarm theory can easily explain the cloudy appearance of thick layers of nematic liquid crystals due to inhomogeneously oriented swarms. The strong light scattering [124] behind is one of the experimental evidences in its favor. Another experiment support for the swarm theory comes from the alignment by a magnetic field.

2.2.2 *Oseen-Frank Theory*

The Oseen-Frank theory [2, Chap. 1], [38, 40, 45, 89, 125–131], or the elastic continuum theory [3, Chap. 8], [14, 54, 58, 62, 73, 74, 83, 86, 121, 132–136], is one of the most prevalent theoretical models in the physics and mathematics literature for nematic liquid crystals. Its immediate premise, the distortion theory [5, pp. 10], [109, 123, 137], was laid down by Hans Zocher in 1927. It is a convenient tool for large-scale liquid–crystal phenomena involving the response of bulk liquid–crystal samples to external disturbances, e.g., modeling liquid crystal devices and lipid bilayers [74, 138]. It is very successful in explaining various magnetic and electric field-induced effects.

The elastic continuum theory ignores molecular details of a liquid crystal material but regards it as a continuous medium with a set of elastic constants corresponding to splay, twist, and bend distortions of the bulk liquid crystal to external disturbances. The response of the material can then be characterized by the energy penalty incurred by the distortions and is commonly quantified by the Oseen-Frank or simply Frank free energy density [2]. Different terms in the free energy density corresponds to different distortions based on the elastic constants.

2.2.3 *Landau-de Gennes Theory*

The Oseen-Frank theory fails to describe several characteristic features of nematic liquid crystals, including the isotropic-nematic phase transition, non-orientability of the director field, and the fine structure of defects [131]. The more difficult Landau-de Gennes theory [3, Chap. 10], [4, 61, 64, 67, 75, 76, 87–90, 97, 99–101], [139, pp. 193–216], [140–147] accounts for these features by incorporating additional degrees of freedom and provides a semi-quantitative description of the specific heat, the order parameter, and the entropy in the vicinity of a second-order phase transition.

A physical system in which phase transitions can occur is usually characterized by the free energy density $f(\vec{r}, T, S)$ as a function of spatial position $\vec{r}$, temperature T , and scalar order parameter S and its spatial derivatives [4, 10, 111, 148]. When the system transforms from one phase to the other, the equilibrium value of the scalar order parameter $S_{eq}(\vec{r}, T)$ changes either continuously or discontinuously.

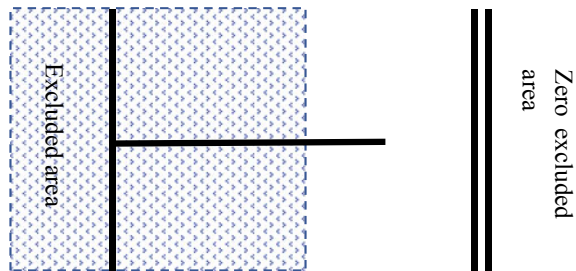
The crucial idea of the Landau-de Gennes theory lies with the elegant and far-reaching speculation about the functional dependence of the free energy density on the order parameter and its spatial derivatives near a second-order phase transition point Landau made in 1937 [139, pp. 193–216]. It is speculated that near a second-order transition the free energy density function can be expanded as a power series in the scalar order parameter and its spatial derivatives, with temperature dependent coefficients. The inclusion of spatial variations of the scalar order parameter gives it a new dimension not found in mean field theory. However, the Landau-de Gennes theory contains more phenomenological parameters that make it somewhat less satisfying. It is further assumed that, sufficiently close to the transition, only the leading terms of the series are important, so that the expansion of the free energy density function becomes a simple low-order polynomial. This assumption unfortunately further limits its applicability in a limited temperature range close to the transition point only. de Gennes successfully generalized Landau theory of second-order phase transitions to include first-order phase transitions [140].

2.2.4 Onsager Virial Theory

The Onsager virial theory or the hard-rod model [3, Chap. 5], [39, 66, 69, 149–159] explains lyotropic transition from an isotropic state to an ordered nematic phase above a critical concentration in a solution of hard rods without any forces between them. The key idea here is the steric effect that is due to the impenetrability of long thin hard rods as shown in Fig. 2.3. Onsager intuitively recognized that the steric effect can lead to the first-order phase transition as the density of hard rods is increased.

Taking the entropy of the hard rod system as the degree of freedom corresponding to the volume excluded from the center-of-mass of one idealized cylinder as it approaches another, Onsager identified two competing contributions to entropy.

Fig. 2.3 Two-dimensional steric effect



Whilst parallel arrangements of anisotropic hard rods lead to a decrease in orientational entropy, there is an increase in translational entropy. On the other hand, angular arrangement sees a decrease in the translational entropy but an increase in orientational entropy. In another word, the increase of translational entropy is compensated by the decrease of orientational entropy, and vice versa. Therefore, from the point of view of excluded volume, a competition exists between the tendency to maximize the translational entropy and the tendency to maximize the orientational entropy. At very low concentration there is very little gain in entropy by reducing the excluded volume via parallel alignments that the orientational entropy wins. However, at very high concentration it is clear that a perfectly aligned system is the most favorable because the excluded volume is effectively zero. Thus at some intermediate point a transition must take place between the isotropic and nematic phases, although this kind of general argument cannot tell us whether the transition is smooth or abrupt.

The orientational degrees of freedom was assumed continuous in the original Onsager virial theory. A simplified approach of Zwanzig [150] allows only three different orientations. This simplification proves to be quite advantageous for the mathematical analysis as it permits a more accurate calculation of the virial coefficients while the original Onsager virial theory involves non-linear integral equations.

2.2.5 Maier–Saupe Theory

Alfred Saupe and Wilhelm Maier developed the mesoscopic Maier-Saupe theory [41–43] based on the orientation distribution function and the mean field theory (MFT) [2], [3, Chap. 4], [160–163], [164, Chap. 4], [165–168] for interacting systems with many degrees of freedom which are generally very challenging to solve exactly or compute in closed, analytic form. MFT perfectly fits liquid crystals because of the high dimensionality of extended mesogens in liquid crystals. The curse of dimensionality makes it too expensive to enumerate all the possible microstates and solve by brute force.

In physical essence MFT or self-consistent field theory in physics and probability theory approximates a high-dimensional stochastic many-body problem into a zeroth-order effective one-body problem by replacing all interactions to any one body with a mean effective interaction. In other words, MFT makes the hard original solvable at a lower computational cost by naively assuming that every single particle in the original stochastic system only experiences the mean effective field due to the remaining particles. Nevertheless, MFT can obtain some meaningful qualitative insight into the physical mechanisms of the interacting system, e.g., a phase transition between ferromagnetic and paramagnetic behavior, and in some cases may give very accurate analytic solution with relative ease. Because of the central limit theorem of statistics, the effect of randomness becomes weaker and weaker that MFT solution gets closer and closer to the truth as the dimensionality or the number of

interacting particles increases. Quite often, MFT provides a convenient launch point for studying higher-order fluctuations that correct the mean-field approximation.

The Maier-Saupe theory considers anisotropic van der Waals attraction that stabilizes parallel alignment of neighboring nonpolar molecules. The orientation-dependent interaction is assumed independent of the configuration of the centers of mass. Adjacent rod-like liquid crystal molecules induce a dipole moment in terms of a pairwise intermolecular attractive potential which can be expanded in a series of appropriate spherical harmonics and averaged to obtain the single-molecule potential function in the mean field approximation [3, Chap. 4]. The Maier-Saupe theory will result from the retention of only the first term in the potential.

The Maier-Saupe theory predicts thermotropic nematic-isotropic phase transitions, consistent with experiment. A notable extension took place in 1971 when William proposed the McMillan's model [51], [169, Chap. 12] to describe the phase transition of a liquid crystal from nematic to smectic A. It is further extended to high molecular weight liquid crystals by incorporating the bending stiffness of the molecules and using the method of path integrals in polymer science [170].

2.2.6 Ericksen-Leslie Theory

The Ericksen-Leslie theory [46, 47, 171, 172] by Frank Leslie (left) and Jerald Ericksen [173] is the first accepted dynamic continuum theory for the dynamics of nematic liquid crystals. It is based on the conservation laws for mass, linear and angular momentums as well as on constitutive relations. It has many precedents, both static [40, 45, 125, 132, 174, 175] and dynamic [38, 176].

The Ericksen-Leslie theory is characterized by using a macroscopic director field for needle-shaped molecules with totally relaxed internal degrees of freedom and is only valid when all molecules are locally totally aligned or when they form a time-independent global planar phase. Ericksen and Leslie's pioneering theory models nematic liquid crystal flow from a hydrodynamical point of view and describes the evolution of the underlying system under the influence of the velocity of the fluid and the orientation configuration of rod-like liquid crystals. Theoretical analysis agrees well with experimental measurements [177–179] and provides reasonable explanations for some phenomena such as “adsorption layer” and variations in apparent viscosity at low rates of shear.

The Ericksen-Leslie theory continues to be of significant interest to mathematicians, physicists, chemists, material scientists and engineers in the liquid crystal community. Many thermodynamically consistent proposals of Ericksen-Leslie type [86, 93, 115, 180–185], [186, pp. 433–459], [187, pp. 1075–1134], [188–191] dealing with the non-isothermal situation follow up, even in the case of compressible fluids. More importantly, the Ericksen-Leslie theory has been being so influential to the development of the liquid crystal technology that at least one liquid crystal device that we use daily has been developed or optimized for the best possible performance with the aid of Ericksen-Leslie theory over the decades.

2.2.7 *Eringen Theory*

Liquid crystals belong to a general class of polar fluids with microstructure, namely, micropolar fluids [192], [193, pp. xi], [194]. The Ericksen–Leslie theory for the dynamics of nematic liquid crystals no longer holds in the presence of disclinations or defects in the orientation of director [1, pp. 117–144], [40, 195] in liquid crystals. Nevertheless, defects typically populated in liquid crystal play a crucial role in physical phenomena.

Eringen theory, or the theory of micropolar fluids [73, 196–198], [199, pp. 315–330], [200, pp. 443–474], [201–206] incorporates molecular shape effects into a microinertia tensor and describes disclination dynamics by using the wryness tensor. It relies on a consistent use of the complete spin balance and the concept of the conservation of microinertia [194].

Interestingly, the theory of micropolar fluids has long been regarded distinct and competing with the Ericksen–Leslie director theory but proved equivalent while describing nematic liquid crystal dynamics [195]. Moreover, as a matter of fact, the Ericksen–Leslie theory, the Maier–Sauper theory and the Eringer theory are all special cases of theories of generalized continua [207–210].

2.2.8 *Doi Theory*

Doi theory [211–220] in molecular theory is presented for the dynamics of rod-like polymers in concentrated solutions. The theory describes the rotational motion of rods in both isotropic and liquid crystalline phases. Combined with the molecular expression of the stress tensor it also gives a unified rheological constitutive equation, which predicts the nonlinear viscoelasticity in both phases.

2.2.9 *Gay-Berne Model*

Dealing with liquid crystals is difficult as the intermolecular interactions in these materials are so complicated. Analytical methods are often not sufficient to solve problems involving soft matter. There has been a growing interest in computer simulations of liquid crystalline systems [221, 222] since 1970s. Analytically tractable and computationally efficient multiscale numerical methodologies capable of capturing the microscopic origins of macroscopic behaviour constitute additional sound theoretical foundation for understanding the effect of the structure and material properties.

The Gay-Berne model [223], an anisotropic form of the Lennard–Jones potential [224–226] in place of computationally inefficient double sum of Lennard–Jones

potential over the respective sites of the two molecules [227–230], has been extensively used. The phases of calamitic nematic and smectic [231–235] and nematic discotic and columnar phases [236] have been observed. A notable extension to biaxial [237] was reported in 1995. A more accurate and computationally efficient variant [238] was proposed in 2012.

2.3 Ordering

A liquid crystal may flow like a liquid, but have the anisotropic mesogens in the liquid arranged in a crystal-like way. When viewed under a microscope using a polarized light source, each liquid crystal phase has its own distinct ordering with respect to the isotropic liquid phase. Molecules in different texture domains present different ordering or anisotropy. Upon a transition during the cooling process the newly created liquid crystal phase has an abrupt increase in order and an associated reduction in isotropy. The ordering of the anisotropic mesogens is critical for the liquid crystal phases and is essentially responsible for the unique anisotropy of liquid crystal materials.

Generally speaking, there are three types of order: positional order, orientational order, and bond orientational order. Mesophases of crystalline solids can occur by either losing orientational order in the molecular distribution while maintaining translational order, or vice versa.

The rigid core of an anisotropic mesogen favors both orientational and positional order while the flexible head and tail disfavor them. Nevertheless, neither the positional order nor the bond orientational order requires anisotropic constituent particles. As such, the positional order and the bond orientational order will only be briefly discussed.

2.3.1 Positional Order

Positional order [239, 240] gives regular distances between molecules. Many crystals show a transition from a strongly-ordered state to a plastic crystal phase where each molecule commutes between several equivalent orientations, thus positional order is kept while orientational ordering is sacrificed [241].

The positional correlations decay exponentially. A positional order parameter [4, 169] can be used to describe the ordering of liquid crystals. It is characterized by the variation of the density of the center of mass of the liquid crystal molecules along a given vector. Usually, it can be expressed as a polar complex number or a real trigonometric series.

2.3.2 Bond Orientational Order

Bond orientational order [1, pp. 360], [239, 240, 242–247] refers to the extent to which the local axes of the nearest neighbors along the bond persists over macroscopic distances. The bond here is a line joining the centers of nearest-neighbor molecules sitting on average at some preferred distance from each other without a regular spacing along that line. The bond-orientational correlations decay algebraically.

Landau and Peierls [242, pp. 9] might have been aware of bond orientational order as early as in the 1930s. It was rediscovered by Mermin in 1968 [248] while studying two-dimensional melting [249–254] of hexatic phase. The KTHNY theory [255–267] was accordingly developed. In addition, the hexatic B phase, a mesophase with three-dimensional sixfold bond-orientational order, was predicted [268] and experimentally confirmed [269, 270] on free standing films.

2.3.3 Orientational Order

As pointed out in Chap. 1, highly geometrically anisotropic molecules are essential in liquid crystal [1, pp. 1]. Anisotropic mesogens in liquid crystals tend to point along a single preferred direction, called the liquid crystal director. This characteristic orientational order of the liquid crystal state distinguishes it from both traditional solid and liquid phases. Such tendency leads to anisotropy not observed in other fluids. If the average alignment is strong, the material is very anisotropic. Similarly, if the average alignment is weak, the material is almost isotropic. The anisotropic nature of liquid crystals is critical for its unique properties.

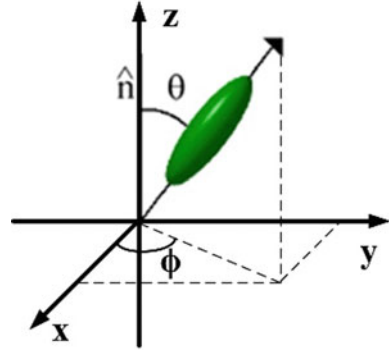
The calamitic nematic phase is the most common and simplest liquid crystal phase, where the long axes of the constituent rod-shaped molecules tend to align parallel to each other along a single preferred axis referred to as the anisotropic axis. If we define a unit vector $\hat{a}_i$ as shown in Fig. 2.4 to represent the long axis of each molecule in the neighborhood of any point with an angular statistical distribution, the director $\hat{n}$ is then the average direction of the long molecular axis,

$$\hat{n} = \langle \hat{a}_i(\theta, \phi) \rangle = \frac{\int_0^\pi \int_0^{2\pi} \hat{a}_i f(\theta, \phi) d\phi \sin \theta d\theta}{\int_0^\pi \int_0^{2\pi} f(\theta, \phi) d\phi \sin \theta d\theta} \quad (2.1)$$

where the angular brackets $\langle \cdot \rangle$ represents both a temporal and spatial statistical average, θ is the elevation angle and ϕ is the azimuthal angle of $\hat{a}_i$ with respect to $\hat{n}$, $f(\theta, \phi)$ describes the angular statistical distribution of liquid crystal molecules in the whole sample.

Due to rotational symmetry, we have

$$\hat{n} = \langle \hat{a}_i(\theta) \rangle = \frac{\int_0^\pi \hat{a}_i f(\theta) \sin \theta d\theta}{\int_0^\pi f(\theta) \sin \theta d\theta} \quad (2.2)$$

Fig. 2.4 Director

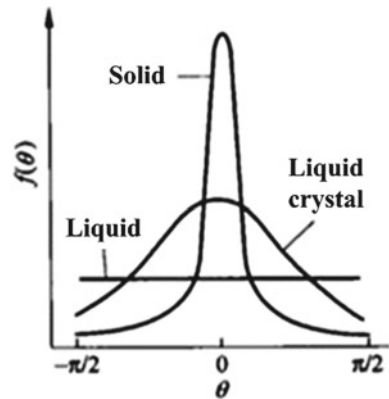
Some demonstrative angular statistical distribution $f(\theta)$ of liquid crystal molecules are shown in Fig. 2.5. When the rod-shaped molecule is in the solid state,

$$f(\theta) = \begin{cases} 1 & \theta = 0 \text{ or } \pi \\ 0 & \text{otherwise} \end{cases} \quad (2.3)$$

the molecules are all aligned parallel to one another and can only vibrate around the crystal axis. Meanwhile, if the rod-shaped molecule is in the isotropic liquid state, the orientation is completely random that all orientations are possible. Hence,

$$f(\theta) = \frac{1}{\pi} \quad 0 \leq \theta \leq \pi \quad (2.4)$$

Orientational order parameter represents a measure of the tendency of the molecules to align along the director $\hat{n}$ on a long-range basis. It can be experimentally measured in a number of ways [169], for example diamagnetism, optical birefringence Raman scattering, nuclear magnetic resonance (NMR) and electron paramagnetic resonance (EPR).

Fig. 2.5 Liquid crystal molecular orientation distribution

2.3.3.1 Scalar Order Parameter

The majority of liquid crystal phases are uniaxial nematic, with a single degree of rotational symmetry about the director. To quantitatively describe their orientational order, a scalar orientational order parameter [3, Chap. 6], [63], [164, pp. 168], [169] is usually defined as

$$S = \langle P_2(\cos \theta) \rangle = \frac{\int_0^\pi \frac{1}{2}(3\cos^2\theta - 1)f(\theta) \sin \theta d\theta}{\int_0^\pi f(\theta) \sin \theta d\theta} \quad (2.5)$$

where $P_2(x) = \frac{1}{2}(3x^2 - 1)$ is the second-order Legendre polynomial.

It is very easy to prove that $S = 1$ when the rod-shaped molecule is in the solid state and $S = 0$ if it is in the isotropic liquid state. Meanwhile, the mesogenic liquid crystal phase between the solid and liquid phases has a certain ordered orientation. Generally, the order parameter takes intermediate value that typically ranges from 0.4–0.8.

Most liquid crystals change their molecular arrangement and orientation state with temperature. Naturally, the order parameter varies with temperature [169]. The order parameter of 4-methoxybenzylidene-4'-butylaniline (MBBA) is shown in Fig. 2.6 as an example of such temperature dependence.

The structure of liquid crystal molecules further complicates the order parameter which has been confirmed by a large number of experiments. The order parameter is proportional to rigidity of molecules but inversely proportional to molecular polarization and the length of the terminal alkyl chain.

It has to be pointed out that the above scalar orientational order parameter does not always give reasonable result. For example, $S = \frac{-1}{2}$ if $f(\theta)$ is peaked at $\theta = \frac{\pi}{2}$. However, this corresponds to the unlikely situation where a collection of rods favors perpendicular alignment. In addition, it is not injective. In particular, the isotropic state is not the only molecular configuration that can give the state of minimum order parameter. If the molecules are arranged in a cone about the director with a specific

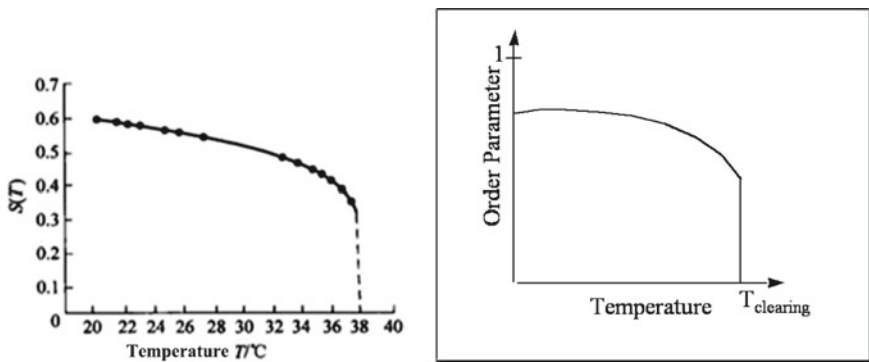


Fig. 2.6 Sequence parameter with temperature (MBBA)

angle, S can equal zero [5, pp. 17]. Additional order parameters in terms of higher even order Legendre polynomials can remove this ambiguity and yield additional information about molecular ordering but will inevitably complicate the analysis and be more difficult to measure [1].

2.3.3.2 Order Tensor

Uniaxial nematic has a single preferred axis, around which the system is rotationally symmetric. On the contrary, the most general biaxial liquid crystals [221, 271–287] based on bent-core mesogens or mixtures of classical rod-like mesogens and disk-like discotic mesogens [288] have three distinct optical axes. Both short and long axis of uniaxial or biaxial molecules can possess orientational order. Furthermore, biaxial liquid crystal can be induced from uniaxial mesogens by an applied electric field or by constrained geometries, where there are two directions in which the long axes of the molecules tend to align. It is then necessary to account for the directional dependence. A second rank order parameter tensor, or the Q-tensor [289], [290, pp. 313–382], [107], is therefore more instructive and appropriate.

According to the alignment tensor theory [4, 291–297], [298, pp. 47–67], [299, 300], the second rank symmetric traceless tensor order parameter is [5, pp. 17]

$$\overline{\overline{Q}} = \lambda_1 \hat{e}_1 \otimes \hat{e}_1 + \lambda_2 \hat{e}_2 \otimes \hat{e}_2 + \lambda_3 \hat{e}_3 \otimes \hat{e}_3 \quad (2.6)$$

where λ_1, λ_2 and λ_3 are the eigenvalues of $\overline{\overline{Q}}$ and $\hat{e}_1, \hat{e}_2$ and $\hat{e}_3$ are the corresponding eigenvectors, and $\otimes$ is the tensor product operator [5, pp. 49], [1]. In particular,

$$\lambda_3 = -(\lambda_1 + \lambda_2) \quad (2.7)$$

The liquid crystal is uniaxial when $\lambda_1 = \lambda_2$. In this case

$$\overline{\overline{Q}} = -3\lambda_1 \left(\hat{e}_3 \otimes \hat{e}_3 - \frac{\overline{\overline{I}}}{3} \right) \quad (2.8)$$

Otherwise, it is biaxial if $\lambda_1 \neq \lambda_2$ and the second rank symmetric traceless tensor order parameter is

$$\overline{\overline{Q}} = (2\lambda_1 + \lambda_2) \hat{e}_1 \otimes \hat{e}_1 + (\lambda_1 + 2\lambda_2) \hat{e}_2 \otimes \hat{e}_2 - (\lambda_1 + \lambda_2) \overline{\overline{I}} \quad (2.9)$$

The isotropic state occurs when all the eigenvalues are identically zero.

2.4 Dielectric Properties of Liquid Crystal

Like any ordinary materials, liquid crystal materials are also characterized by numerous materials properties [301, 302] including acoustical properties, atomic properties, chemical properties, electrical properties [303], magnetic properties, mechanical properties, optical properties [304–306], radiological properties, thermal properties, etc. These properties are essential in solving different physical problems governed by physical laws and constitutive equations. They may also be used as quantitative metric by which the benefits of one material versus another can be compared, thereby aiding in materials selection for a specific application.

On the other hand, liquid crystal materials present unique intermediate properties found in neither liquids nor solids [305]. More importantly, macroscopic properties of liquid crystals can be changed significantly by various stimuli, such as temperature, electric and magnetic fields [133, 135, 307–311], [312, Chap. 13], [146], light [313]. This sensitivity, combined with the self-assembling behaviour of makes liquid crystals extremely interesting and fascinating for chemists, physicists, and engineers in a variety of applications.

Microwave, millimeter wave, and terahertz wave are all covered under the general umbrella electromagnetic waves. From the electromagnetic point of view, liquid crystal materials are in nature anisotropic dielectric materials [314]. The anisotropic complex permittivity $\vec{\epsilon}_r$ and permeability $\vec{\mu}_r$ are thus the constitutive parameters crucial for applications of liquid crystal materials in microwave, millimeter wave, and terahertz range. Both electric and magnetic fields can be used to induce changes.

2.4.1 Permittivity

Just like any other dielectric materials, liquid crystal materials are polarizable. In the absence of an external field, the director of a liquid crystal is free to point in any direction. It is possible, however, to force the director to point in a specific direction by introducing an external field. In other words, when an electric field is applied to a liquid crystal, its molecules realign and become polarized. It will induce dipole moments and store electric energy in the liquid crystal. Such an effect of electromagnetic field is right behind the Fredericks transition [3, pp. 115], [37, 109, 315, 316] fundamental to the operation of many liquid crystal displays.

There are three different induced polarizations, electronic, ionic, and dipolar. The dipolar polarization is only present in material consisting of polar molecules. It comes from the reorientation of the permanent dipole of polar molecules and can only contribute up to a frequency of the order of MHz. On the contrary, both ionic and electronic polarizations are universal in both polar and non-polar materials. The ionic polarization is attributed to the relative displacement of the atoms constituting

the molecule and can contribute up to the frequency of infrared light. The electronic polarization comes from the slight deformation of the electron clouds of the constituting atoms of the molecule and can contribute up to the frequency of UV light.

Permittivity describes the polarizability of a liquid crystal material. Generally, speaking, permittivity is a thermodynamic function of frequency, magnitude, and direction of the applied field.

2.4.1.1 Non-polar Liquid Crystal

Dielectric Tensor in Molecular Frame

In liquid crystal, each and every mesogen is exposed to a local molecular electric field $\vec{E}_m$ which is produced by the external source and the dipole moments of all other molecules. The macroscopic field $\vec{E}$ is the sum of the field $\vec{E}_s$ produced by the dipole moment of the molecule itself and the local field $\vec{E}_m$,

$$\vec{E} = \vec{E}_s + \vec{E}_m \quad (2.10)$$

The local molecular electric field $\vec{E}_m$ differ from the macroscopic electric field $\vec{E}$ because of the strong dipole–dipole interactions between liquid crystal molecules. Without loss of generality, the local molecular electric field $\vec{E}_m$ and the macroscopic electric field $\vec{E}$ are related to each other by

$$\vec{E}_m = \overset{\leftrightarrow}{K}_m \cdot \vec{E} \quad (2.11)$$

where $\overset{\leftrightarrow}{K}_m$ is the tensorial internal field constant.

The induced dipole moment $\vec{p}_i$ of a liquid crystal molecule is

$$\vec{p}_i = \overset{\leftrightarrow}{\alpha}_m \cdot \vec{E}_m = \overset{\leftrightarrow}{\alpha}_m \cdot \overset{\leftrightarrow}{K}_m \cdot \vec{E} \quad (2.12)$$

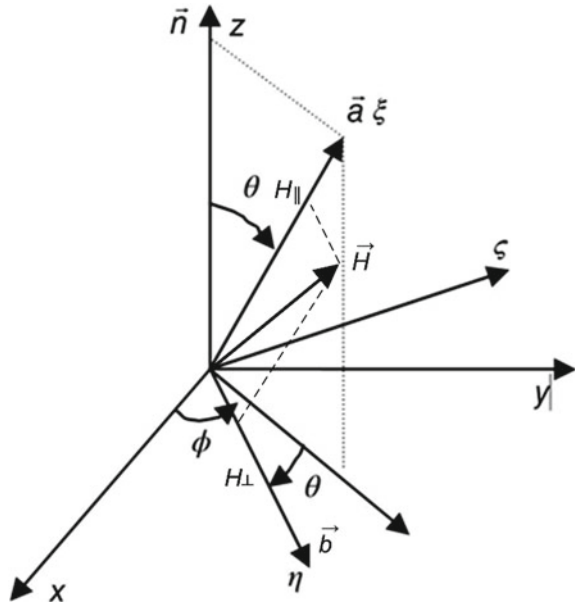
where $\overset{\leftrightarrow}{\alpha}_m$ is the molecular polarizability tensor.

The dipole moment per unit volume is therefore

$$\vec{P}_i = N \vec{p}_i = N \overset{\leftrightarrow}{\alpha}_m \cdot \vec{E}_m = N \overset{\leftrightarrow}{\alpha}_m \cdot \overset{\leftrightarrow}{K}_m \cdot \vec{E} = \overset{\leftrightarrow}{\chi}_e \cdot \vec{E} \quad (2.13)$$

where N is molecular number density and $\overset{\leftrightarrow}{\chi}_e = N \overset{\leftrightarrow}{\alpha}_m \cdot \overset{\leftrightarrow}{K}_m$ is the electric susceptibility tensor.

Fig. 2.7 Schematic diagram showing the transformation between the molecular principal frame $\eta\zeta\xi$ and the lab frame xyz and local molecular field and its decomposition into the components parallel to and perpendicular to the long molecular axis. $\hat{a}$: unit vector parallel to the long molecular axis, $\hat{b}$: unit vector perpendicular to the long molecular axis



The total displacement flux $\vec{D}$ is

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P}_i = \varepsilon_0 \left(\vec{I} + \frac{\vec{\chi}_e}{\varepsilon_0} \right) \cdot \vec{E} = \varepsilon_0 \vec{\varepsilon}_r \cdot \vec{E} \quad (2.14)$$

where $\varepsilon_0 = 9.95 \times 10^{-12}$ F/m is the permittivity of free space,

$$\vec{\varepsilon}_r = \vec{I} + \frac{\vec{\chi}_e}{\varepsilon_0} = \vec{I} + \frac{N \vec{\alpha}_m \cdot \vec{K}_m}{\varepsilon_0} \quad (2.15)$$

In the molecular principal frame $\eta\zeta\xi$ of a uniaxial liquid crystal with the ξ axis parallel to the long molecular axis $\hat{a}$ as shown in Fig. 2.7,

$$\vec{\alpha}_m = \begin{bmatrix} \alpha_{\perp} & 0 & 0 \\ 0 & \alpha_{\perp} & 0 \\ 0 & 0 & \alpha_{\parallel} \end{bmatrix} \quad (2.16)$$

$$\vec{K}_m = \frac{1}{1 - \frac{N \vec{\alpha}_m}{3 \varepsilon_0}} = \begin{bmatrix} K_{\perp} & 0 & 0 \\ 0 & K_{\perp} & 0 \\ 0 & 0 & K_{\parallel} \end{bmatrix} \quad (2.17)$$

where the subscripts $\parallel$ and $\perp$ indicate components of the corresponding quantity parallel and perpendicular to the long molecular axis $\hat{a}$.

Accordingly, the dipole moment per unit volume can be alternatively given by

$$\vec{P}_i = N\alpha_{\parallel}E_{\parallel}\hat{a} + N\alpha_{\perp}E_{\perp}\hat{b} \quad (2.18)$$

where

$$E_{\parallel} = \hat{a} \cdot \vec{E}_m \quad (2.19)$$

and

$$E_{\perp} = \hat{b} \cdot \vec{E}_m \quad (2.20)$$

as shown in Fig. 2.7 are the components of the local molecular electric field $\vec{E}_m$ parallel and perpendicular to $\hat{a}$, respectively.

Note

$$E_{\perp}\hat{b} = \vec{E}_m - \hat{a} \cdot \vec{E}_m \quad (2.21)$$

we have

$$\vec{P}_i = N\alpha_{\perp}\vec{E}_m + N\Delta\alpha(\hat{a} \cdot \vec{E}_m)\hat{a} \quad (2.22)$$

where $\Delta\alpha = \alpha_{\parallel} - \alpha_{\perp}$.

It is very easy to reformulate the dipole moment per unit volume as

$$\vec{P}_i = N\alpha_{\perp}\vec{E}_m + N\Delta\alpha(\hat{a}\hat{a}) \cdot \vec{E}_m \quad (2.23)$$

Substituting (2.11) into (2.23) leads to

$$\vec{P}_i = N\left[\alpha_{\perp}\vec{\hat{K}}_m + \Delta\alpha(\hat{a}\hat{a}) \cdot \vec{\hat{K}}_m\right] \cdot \vec{E} \quad (2.24)$$

Accordingly, the dielectric permittivity tensor in molecular frame is

$$\vec{\epsilon}_r = \vec{I} + \frac{N}{\epsilon_0}\left[\alpha_{\perp}\vec{\hat{K}}_m + \Delta\alpha(\hat{a}\hat{a}) \cdot \vec{\hat{K}}_m\right] \quad (2.25)$$

Dielectric Tensor in Lab Frame

Apparently, the local molecular principal frame $\eta\xi\zeta$ of a uniaxial liquid crystal with the ξ axis parallel to the long molecular axis $\hat{a}$ is inconvenient to analyze the collective dielectric tensor of a liquid crystal. Instead, the lab frame xyz with the z axis parallel to the liquid crystal director $\vec{n}$ is more appropriate.

In the lab frame,

$$\hat{a} = \begin{bmatrix} \sin \theta \cos \phi \hat{x} \\ \sin \theta \sin \phi \hat{y} \\ \cos \theta \hat{z} \end{bmatrix} \quad (2.26)$$

$$\hat{a}\hat{a} = \begin{bmatrix} \sin^2 \theta \cos^2 \phi & \sin^2 \theta \cos \phi \sin \phi & \sin \theta \cos \theta \cos \phi \\ \sin^2 \theta \cos \phi \sin \phi & \sin^2 \theta \sin^2 \phi & \sin \theta \cos \theta \sin \phi \\ \sin \theta \cos \theta \cos \phi & \sin \theta \cos \theta \sin \phi & \cos^2 \theta \end{bmatrix} \quad (2.27)$$

The local molecular frame $\eta\zeta\xi$ is achieved by first rotating the frame xyz around the z axis by the angle ϕ and then rotating the frame around the ζ axis by the angle θ . The rotation matrix is

$$\vec{R} = \begin{bmatrix} \cos \theta \cos \phi & -\sin \phi \sin \theta \cos \phi \\ \cos \theta \sin \phi & \cos \phi \sin \theta \sin \phi \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \quad (2.28)$$

The reverse rotation matrix is

$$\vec{R}^{-1} = \begin{bmatrix} \cos \theta \cos \phi \cos \theta \sin \phi & -\sin \theta \\ -\sin \phi & \cos \phi & 0 \\ \sin \theta \cos \phi & \sin \theta \sin \phi & \cos \theta \end{bmatrix} \quad (2.29)$$

In the lab frame, we have

$$\vec{K}_L = \vec{R} \cdot \vec{K}_m \cdot \vec{R}^{-1} = K_{\perp} \vec{I} + \Delta K \hat{a}\hat{a} \quad (2.30)$$

where $\Delta K = K_{\parallel} - K_{\perp}$.

It is very easy to prove

$$(\hat{a}\hat{a}) \cdot \vec{K}_L = K_{\parallel} \hat{a}\hat{a} \quad (2.31)$$

Therefore, the dielectric permittivity tensor in the lab frame is

$$\vec{\epsilon}_r = \vec{I} + \frac{N}{\epsilon_0} \left[\alpha_{\perp} K_{\perp} \vec{I} + (\alpha_{\perp} \Delta K + \Delta \alpha K_{\parallel}) \hat{a}\hat{a} \right] \quad (2.32)$$

Dielectric Tensor in Terms of Scalar Order Parameter

The molecule swivels because of thermal motion. Consequently, the macroscopic dielectric tensor is

$$\vec{\epsilon}_r = \vec{I} + \frac{N}{\epsilon_0} \left[\alpha_{\perp} K_{\perp} \vec{I} + (\alpha_{\perp} \Delta K + \Delta \alpha K_{\parallel}) \hat{a}\hat{a} \right] \quad (2.33)$$

For a uniaxial liquid crystal, we have

$$\langle \cos^2 \theta \rangle = \frac{2S + 1}{3} \quad (2.34)$$

$$\langle \sin^2 \theta \rangle = \frac{2 - 2S}{3} \quad (2.35)$$

$$\langle \sin^2 \phi \rangle = \langle \cos^2 \phi \rangle = \frac{1}{2} \quad (2.36)$$

$$\langle \sin \phi \cos \phi \rangle = 0 \quad (2.37)$$

Therefore

$$\langle \hat{a} \hat{a} \rangle = \begin{bmatrix} \frac{1-S}{3} & 0 & 0 \\ 0 & \frac{1-S}{3} & 0 \\ 0 & 0 & \frac{2S+1}{3} \end{bmatrix} \quad (2.38)$$

Finally,

$$\overset{\leftrightarrow}{\varepsilon}_r = \begin{bmatrix} \varepsilon_{r\perp} & 0 & 0 \\ 0 & \varepsilon_{r\perp} & 0 \\ 0 & 0 & \varepsilon_{r\parallel} \end{bmatrix} \quad (2.39)$$

where

$$\varepsilon_{r\perp} = 1 + \frac{N}{3\varepsilon_0} [\alpha_{\perp} K_{\perp} (2 + S) + \alpha_{\parallel} K_{\parallel} (1 - S)] \quad (2.40)$$

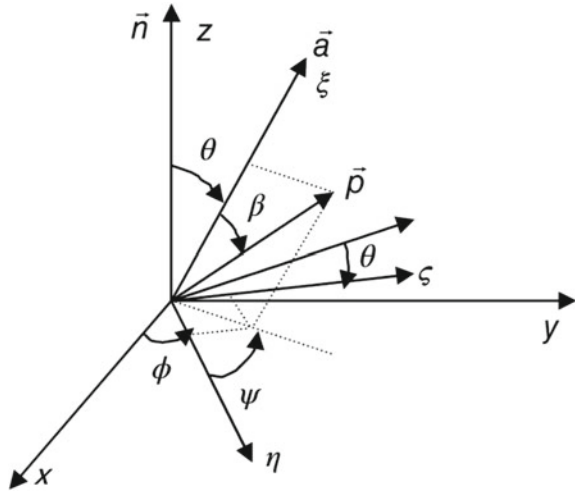
$$\varepsilon_{r\parallel} = 1 + \frac{N}{3\varepsilon_0} [\alpha_{\perp} K_{\perp} (2 - 2S) + \alpha_{\parallel} K_{\parallel} (1 + 2S)] \quad (2.41)$$

As a result of the uniaxial symmetry, the dielectric constants along and perpendicular to the director differ. Correspondingly, the dielectric anisotropy, or the difference between the parallel and perpendicular dielectric constants is

$$\Delta \varepsilon_r = \varepsilon_{r\parallel} - \varepsilon_{r\perp} = \frac{N}{\varepsilon_0} [\alpha_{\parallel} K_{\parallel} - \alpha_{\perp} K_{\perp}] S \quad (2.42)$$

The dielectric anisotropy is thus linearly proportional to the order parameter S and can be either positive or negative. When an electric field is applied to a liquid crystal with a positive dielectric anisotropy, the induced dipole moment of the molecules creates a net torque which tends to align the molecules along the direction of the electric field. On the other hand, vortices might emerge in liquid crystal with a negative dielectric anisotropy [317].

Fig. 2.8 The permanent dipole $\vec{p}_p$ in the molecular principal frame $\eta\zeta\xi$ and the lab frame xyz



5CB and E7 liquid crystal mixture are two $\Delta\epsilon > 0$ commercial liquid crystals commonly used. MBBA is a common $\Delta\epsilon < 0$ commercial liquid crystal. In particular, all microwave and millimeter wave liquid crystals reported in literature exhibit positive dielectric anisotropy.

The scalar order parameter is strongly dependent on temperature. As such, the dielectric tensor changes with temperature as S .

2.4.1.2 Polar Liquid Crystals

Polar Liquid Crystal Molecule

Permanent electric dipoles result when one end of a molecule has a net positive charge while the other end has a net negative charge. Consider a polar liquid crystal molecule with a permanent dipole moment $\vec{p}_p$ making the angle β with the long molecular axis $\hat{a}$ as shown in Fig. 2.8. When an external electric field is applied to the liquid crystal, the dipole molecules tend to orient themselves along the direction of the field [318] due to the electric nature of the molecules.

In the directing electric field $\vec{E}_d$, the energy associated with the permanent dipole is

$$u = -\vec{p}_p \cdot \vec{E}_d \quad (2.43)$$

As an approximation, it is assumed that the directing field

$$\vec{E}_d = d\vec{E} \quad (2.44)$$

where d is a constant.

The corresponding angular distribution function of the polar liquid crystal molecule is therefore

$$f(\beta, \psi) = f(\theta, \phi, \psi) \propto e^{-\frac{u}{k_B T}} \quad (2.45)$$

where $k_B = 1.381 \times 10^{-23}$ Joule/Kelvin is the Boltzmann constant and T is temperature.

Permanent Dipole Moment in Lab System

In the molecular frame $\eta\xi\xi$,

$$\vec{p}_p = p_p \begin{bmatrix} \sin \beta \cos \psi \hat{\eta} \\ \sin \beta \sin \psi \hat{\xi} \\ \cos \beta \hat{\xi} \end{bmatrix} \quad (2.46)$$

Using the rotation matrix in (2.28), $\vec{p}_p$ in the lab frame xyz can be computed as

$$\vec{p}_p^L = \vec{R} \cdot \vec{p}_p = p_p \begin{bmatrix} p_x \hat{x} \\ p_y \hat{y} \\ p_z \hat{z} \end{bmatrix} \quad (2.47)$$

where

$$p_x = \sin \beta \cos \psi \cos \phi - \sin \beta \sin \psi \cos \theta \sin \phi - \cos \beta \sin \theta \sin \phi \quad (2.48)$$

$$p_y = \sin \beta \cos \psi \sin \phi + \sin \beta \sin \psi \cos \theta \cos \phi + \cos \beta \sin \theta \cos \phi \quad (2.49)$$

$$p_z = \cos \beta \cos \theta - \sin \beta \sin \psi \sin \theta \quad (2.50)$$

Additional Dielectric Anisotropy

When the applied field is parallel to $\vec{n}$, $\vec{E} = E_{\parallel} \hat{z}$, the projection of the dipole $\vec{p}_p^L$ along the applied field is

$$p_{\parallel} = p_p p_z \quad (2.51)$$

and the associated energy is

$$u = -dp_p p_z E_{\parallel} \quad (2.52)$$

The average value of the projection is

$$\langle p_{\parallel} \rangle = \left\langle p_p p_z e^{-\frac{u}{k_B T}} \right\rangle \quad (2.53)$$

where the terms $e^{-\frac{u}{k_B T}}$ is the perturbation to the angular distribution function of the polar liquid crystal molecule

Usually, $-u \ll k_B T$, then

$$e^{-\frac{u}{k_B T}} \approx 1 - \frac{u}{k_B T} \quad (2.54)$$

In accordance,

$$\langle p_{\parallel} \rangle = p_p \langle p_z \rangle + \frac{dE_{\parallel} p_p^2}{k_B T} \langle p_z^2 \rangle \quad (2.55)$$

It is easy to prove that

$$\langle p_z \rangle = 0 \quad (2.56)$$

$$\langle p_z^2 \rangle = \cos^2 \beta \frac{2S+1}{3} + \sin^2 \beta \frac{1-S}{3} \quad (2.57)$$

Therefore,

$$\langle p_{\parallel} \rangle = \frac{dE_{\parallel} p_p^2}{3k_B T} [\cos^2 \beta (2S+1) + \sin^2 \beta (1-S)] \quad (2.58)$$

An additional term should therefore be included in $\varepsilon_{\parallel}$ as

$$\varepsilon_{r\parallel p} = \frac{N d p_p^2}{3\varepsilon_0 k_B T} [\cos^2 \beta (2S+1) + \sin^2 \beta (1-S)] \quad (2.59)$$

Similarly, we have

$$\varepsilon_{r\perp p} = \frac{N d p_p^2}{\varepsilon_0 k_B T} \left[\frac{\sin^2 \beta}{4} + \frac{\sin^2 \beta}{4} \frac{2S+1}{3} + \cos^2 \beta \frac{1-S}{3} \right] \quad (2.60)$$

Therefore, the additional dielectric anisotropy due to the permanent dipole in polar liquid crystal is

$$\Delta \varepsilon_{rp} = \varepsilon_{r\parallel p} - \varepsilon_{r\perp p} = -\frac{N}{\varepsilon_0} \frac{d p_p^2}{2k_B T} (1 - 3 \cos^2 \beta) S \quad (2.61)$$

2.4.2 Permeability

The effect of magnetic fields on liquid crystal molecules are analogous to electric fields. When a magnetic field $\vec{H}$ is applied to the liquid crystal, the molecules will also tend to align with or against the field. However, unlike the local electric field, the local magnetic field on the molecules is approximately the same as the externally applied magnetic field, because the magnetic interaction between molecules is weak.

The magnetization $\vec{M}$ is

$$\vec{M} = N \vec{\kappa}_m \cdot \vec{H} \quad (2.62)$$

where N is the molecular number density,

$$\vec{\kappa}_m = \begin{bmatrix} \kappa_{\perp} & 0 & 0 \\ 0 & \kappa_{\perp} & 0 \\ 0 & 0 & \kappa_{\parallel} \end{bmatrix} \quad (2.63)$$

$\kappa_{\parallel}$ and $\kappa_{\perp}$ are molecular magnetic polarizabilities along and perpendicular to the long molecular axis $\hat{a}$, respectively.

By similar manipulation, we have

$$\vec{M} = N \kappa_{\perp} \vec{H} + N \Delta \kappa (\hat{a} \hat{a}) \cdot \vec{H} \quad (2.64)$$

where $\Delta \kappa = \kappa_{\parallel} - \kappa_{\perp}$.

Likewise, after taking account of the thermal motion of the molecules, the averaged magnetization is

$$\langle \vec{M} \rangle = N \left(\kappa_{\perp} \vec{I} + \Delta \kappa \hat{a} \hat{a} \right) \cdot \vec{H} = \vec{\chi} \cdot \vec{H} \quad (2.65)$$

where $\vec{\chi}$ is the magnetic susceptibility tensor.

Substituting (2.38) into (2.65) leads to

$$\vec{\chi} = \begin{bmatrix} \chi_{\perp} & 0 & 0 \\ 0 & \chi_{\perp} & 0 \\ 0 & 0 & \chi_{\parallel} \end{bmatrix} \quad (2.66)$$

where

$$\chi_{\perp} = N \left(\kappa_{\perp} + \frac{1-S}{3} \Delta \kappa \right) \quad (2.67)$$

$$\chi_{\parallel} = N \left(\kappa_{\perp} + \frac{2S+1}{3} \Delta \kappa \right) \quad (2.68)$$

The magnetic permeability tensor is

$$\vec{\mu}_r = \vec{I} + \vec{\chi} = \begin{bmatrix} \mu_{r\perp} & 0 & 0 \\ 0 & \mu_{r\perp} & 0 \\ 0 & 0 & \mu_{r\parallel} \end{bmatrix} \quad (2.69)$$

where

$$\mu_{r\perp} = 1 + N \left(\kappa_{\perp} + \frac{1-S}{3} \Delta \kappa \right) \quad (2.70)$$

$$\mu_{r\parallel} = 1 + N \left(\kappa_{\perp} + \frac{2S+1}{3} \Delta \kappa \right) \quad (2.71)$$

The corresponding magnetic anisotropy is

$$\Delta \mu_r = \mu_{r\parallel} - \mu_{r\perp} = N \Delta \kappa S \quad (2.72)$$

For most liquid crystals, $\Delta \mu_r$ is usually positive and small.

References

1. Chandrasekhar S (1992) Liquid crystals, 2nd edn. Cambridge University Press, Cambridge University Press
2. Yang DK, Wu ST (2015) Fundamentals of liquid crystal devices, Series: Wiley—SID series in display technology, 2nd edn. John Wiley & Sons, New York
3. Priestley EB, Wojtowicz PJ, Sheng P (eds) (1975) Introduction to liquid crystals. Plenum Press, New York
4. De Gennes PG, Prost J (1993) The physics of liquid crystals, Series: The international series of monographs on physics, vol 83. Oxford University Press, Oxford
5. Virga EG (1994) Variational theories for liquid crystals, Series: Chapman and hall/CRC applied mathematics and mathematical computation, vol 8. Chapman and Hall, London
6. Al-Barwani MS (1999) Computer modeling of liquid crystals. Ph. D. Dissertation, University of Bristol
7. Bagheri-Hamaneh M (2006) Theory, modeling, and simulation of liquid crystals and polymers. Ph. D. Dissertation, Case Western Reserve University
8. Nochetto RH, Walker SW, Zhang W (2015) Numerics for liquid crystals with variable degree of orientation. MRS Online Proc Libr 1753:66–71
9. Nochetto RH, Walker SW, Zhang W (2017) A finite element method for nematic liquid crystals with variable degree of orientation. SIAM J Numer Anal 55(3):1357–1386
10. Morvant A, Seal E, Walker S (2018) A coupled Ericksen/Allen-Cahn model for liquid crystal droplets. Comput Math Appl 75(11):4048–4065
11. Nochetto RH, Walker SW, Zhang W (2018) The Ericksen model of liquid crystals with colloidal and electric effects. J Comput Phys 352:568–601
12. Allen MP (2019) Molecular simulation of liquid crystals. Mol Phys 117(18):2391–2417
13. Diegel A, Walker S (2019) A finite element method for a phase field model of nematic liquid crystal droplets. Commun Comput Phys 25(1):155–188

14. Zhang Y, Xuan C, Jiang Y, Huo Y (2019) Continuum mechanical modeling of liquid crystal elastomers as dissipative ordered solids. *J Mech Phys Solids* 126:285–303
15. Walker S (2020) A finite element method for the generalized Ericksen model of nematic liquid crystals. *ESAIM: Math Modell Num Anal* 54(4):1181–1220
16. Wang W, Zhang L, Zhang P (2021) Modelling and computation of liquid crystals. *Acta Num* 30:765–851
17. Chen J, Cranton W, Fihn M (eds) (2012) Handbook of visual display technology, Series: Springer reference. Springer
18. Chen J, Cranton W, Fihn M (eds) (2016) Handbook of visual display technology, series: Springer reference. Springer
19. Sadoc JF, Mosseri R, Selinger JV (2020) Liquid crystal director fields in three-dimensional non-Euclidean geometries. *New J Phys* 22, art no 093036
20. Lednei M, Pinkevich I, Reshetnyak V, Sluckin T (2000) Rayleigh-Gans theory of light scattering in filled nematics. *Mol Cryst Liq Cryst Sci Technol Sect A. Mol Cryst Liq Cryst* 352(1):389–398
21. Kadanoff LP (1965) Scaling laws for ising models near Tc. *Physics Physique Fizika* 2(6):263
22. Widom B (1965) Equation of state in the neighborhood of the critical point. *J Chem Phys* 43(11):3898–3905
23. Halperin BI, Hohenberg PC (1967) Generalization of scaling laws to dynamical properties of a system near its critical point. *Phys Rev Lett* 19(12):700–703
24. Halperin I, Hohenberg PC (1969) Scaling laws for dynamic critical phenomena. *Phys Rev* 177(2):952–971
25. Ferrell RA (1970) Decoupled-mode dynamical scaling theory of the binary-liquid phase transition. *Phys Rev Lett* 24(21):1169–1172
26. Hilfer R (1991) Thermodynamic scaling derived via analytic continuation from the classification of Ehrenfest. *Phys Scr* 44(4):321
27. Hilfer R (1992) Scaling theory and the classification of phase transitions. *Mod Phys Lett B* 6(13):773–784
28. Amit DJ (1984) Field theory, the renormalization group, and critical phenomena, revised 2nd edn. World Scientific
29. Collins JC (1984) Renormalization: an introduction to renormalization, the renormalization group, and the operator-product expansion, series: Cambridge monographs on mathematical physics. Cambridge University Press, Cambridge
30. Binney JJ, Dowrick NJ, Fisher AJ, Newman MEJ (1992) The theory of critical phenomena: an introduction to the renormalization group. Oxford Science Publications, Oxford University Press, Series
31. Goldenfeld N (1992) Lectures on phase transitions and the renormalization group, series: Frontiers in physics. CRC, Boca Raton
32. Lavis DA, Bell GM (1999) Statistical mechanics of lattice systems volume 2: exact, series and renormalization group methods, series: Texts and monographs in physics. Springer, Berlin
33. Schwabl F (2002) Statistical mechanics, series: Advanced texts in physics. Springer
34. Amit DJ, Martin-Mayor V (2005) Field theory, the renormalization group, and critical phenomena: graphs to computers, 3rd edn. World Scientific
35. Zinn-Justin J (2007) Phase transitions and renormalisation group, series: Oxford graduate texts. Oxford University Press
36. Köbler U, Hoser A (2010) Renormalization group theory: impact on experimental magnetism, series: Springer series in materials science, vol 127. Springer, Berlin
37. Fréedericksz V, Repiewa A (1927) Theoretisches und Experimentelles zur Frage nach der Natur der anisotropen Flüssigkeiten. *Z Phys* 42(7):532–546
38. Oseen CW (1933) The theory of liquid crystals. *Trans Faraday Soc* 29(140):883–899
39. Onsager L (1949) The effects of shape on the interaction of colloidal particles. *Ann N Y Acad Sci* 51(4):627–659
40. Frank FC (1958) I. Liquid crystals. On the theory of liquid crystals. *Disc Faraday Soc* 25:19–28

41. Maier W, Saupe A (1958) Eine einfache molekulare theorie des nematischen kristallinflüssigen zustandes. *Zeitschrift für Naturforschung A: J Phys Sci* 13(7):564–566
42. Maier W, Saupe A (1959) Eine einfache molekular-statistische theorie der nematischen kristallinflüssigen phase.1, *Zeitschrift für Naturforschung A: J Phys Sci* 14(10):882–889
43. Maier W, Saupe A (1960) Eine einfache molekular-statistische theorie der nematischen kristallinflüssigen phase. 2, *Zeitschrift für Naturforschung A: J Phys Sci* 15(4):287–292
44. Maier W, Meier G (1961) Eine einfache Theorie der dielektrischen Eigenschaften homogen orientierter kristallinflüssiger Phasen des nematischen Typs. *Zeitschrift für Naturforschung A: J Phys Sci* 16(3):262–267
45. Ericksen JL (1962) Hydrostatic theory of liquid crystals. *Arch Ration Mech Anal* 9(1):371–378
46. Ericksen JL (1966) Some magnetohydrodynamic effects in liquid crystals. *Arch Ration Mech Anal* 23(4):266–275
47. Ericksen JL (1966) Inequalities in liquid crystal theory. *Phys Fluids* 9(6):1205–1207
48. Brochard F, de Gennes PG (1970) Theory of magnetic suspensions in liquid crystals. *J Phys Paris* 31(7):691–708
49. Chandrasekhar S, Shashidhar R, Tara N (1970) Theory of melting of molecular crystals: the liquid crystalline phase. *Mol Cryst Liq Cryst* 10(4):337–358
50. Chandrasekhar S, Madhusudana NV (1971) Molecular statistical theory of nematic liquid crystals. *Acta Crystallographica A: Found Crystallogr* 27(4):303–313
51. McMillan W (1971) Simple molecular model for the smectic A phase of liquid crystals. *Phys Rev A* 4(3):1238–1246
52. McMillan WL (1973) Simple molecular theory of the smectic C phase. *Phys Rev A* 8(4):1921–1929
53. Turnbull RJ (1973) Theory of electrohydrodynamic behaviour of nematic liquid crystals in a constant field. *J Phys D: Appl Phys* 6(14):1745–1754
54. Berreman DW (1975) Elastic continuum theory cutoffs and order in nematics and solids. *J Chem Phys* 62(3):776–778
55. Humphries RL, Luckhurst GR (1976) A statistical theory of liquid crystalline mixtures: phase separation. *Proc Royal Soc London A* 352(1668):41–56
56. Murakami J (1977) Molecular theory of surface tension for liquid crystal. *J Phys Soc Jpn* 42(1):210–216
57. Leslie FM (1979) Theory of flow phenomena in liquid crystals, series: *Advances in liquid crystals*, vol 4. Elsevier, pp 1–81
58. Faber TE (1981) A continuum theory of disorder in nematic liquid crystals. V. Anisotropy and order-dependence of the Frank constants. *Proc Royal Soc A: Math Phys Eng Sci* 375(1763):579–597
59. Madhusudana NV (1981) Statistical theories of nematic liquid crystals. *Bull Mater Sci* 3(2):119–131
60. Gelbart WM (1982) Molecular theory of nematic liquid crystals. *J Phys Chem* 86(22):4298–4307
61. Ten Bosch A, Maïssa P, Sixou P (1983) A Landau-de Gennes theory of nematic polymers. *Journal de Physique (Paris) Lettres* 44(3):L105–L111
62. Vertogen G (1983) Elastic constants and the continuum theory of liquid crystals. *Physica A* 117(1):227–231
63. Ghosh SK (1984) A model for the orientational order in liquid crystals. *Il Nuovo Cimento D* 4(3):229–244
64. Hornreich RM (1985) Landau theory of the isotropic–nematic critical point. *Phys Lett A* 109(5):232–234
65. Ericksen JL, Kinderlehrer D (eds) (1987) Theory and applications of liquid crystals, series: *The IMA volumes in mathematics and its applications*, vol 5. Springer, New York
66. Lee SD (1987) A numerical investigation of nematic ordering based on a simple hard-rod model. *J Chem Phys* 87(8):4972–4974

67. Longa L, Monselesan D, Trebin HR (1987) An extension of the Landau-Ginzburg-de Gennes theory for liquid crystals. *Liq Cryst* 2(6):769–796
68. Kurik MV, Lavrentovich OD (1988) Defects in liquid crystals: homotopy theory and experimental studies. *Sov Phys Uspekhi* 31(3):196–224
69. Lee SD (1988) The Onsager-type theory for nematic ordering of finite-length hard ellipsoids. *J Chem Phys* 89(11):7036–7037
70. Wu ST, Wu CS (1990) Experimental confirmation of Osipov-Terentjev theory on the viscosity of liquid crystals. *Phys Rev A* 42(4):2219–2227
71. Wu ST, Wu CS (1990) Rotational viscosity of nematic liquid crystals. *Liq Cryst* 8(2):171–182
72. Wu ST (1991) A semiempirical model for liquid-crystal refractive index dispersions. *J Appl Phys* 69(4):2080–2087
73. Cemal Eringen A (1992) Continuum theory of microstretch liquid crystals. *J Math Phys* 33(12):4078–4086
74. Leslie FM (1992) Continuum theory for nematic liquid crystals. *Continuum Mech Thermodyn* 4(3):167–175
75. Teixeira PIC, Sluckin TJ, Sullivan DE (1993) Landau–de Gennes theory of anchoring transitions at a nematic liquid crystal–substrate interface. *Liq Cryst* 14(4):1243–1253
76. Vaupotič N, Kralj S, Čopič M, Sluckin TJ (1996) Landau–de Gennes theory of the chevron structure in a smectic liquid crystal. *Phys Rev E* 54(4):3783–3792
77. P. Biscari (1997) Intrinsically biaxial systems: a variational theory for elastomers. *Mol Cryst Liq Cryst Sci Technol. Sect A. Mol Cryst Liq Cryst* 299(1):235–243
78. Allen MP (1999) Molecular simulation and theory of liquid crystal surface anchoring. *Mol Phys* 96(9):1391–1397
79. Demus D, Goodby J, Gray GW, Spiess HW, Vill V (eds) (1999) *Physical properties of liquid crystals*. Wiley
80. Leslie FM (1999) A theory of flow in smectic liquid crystals, series: Rheology series, vol 8. Elsevier, pp 591–611
81. Allen MP (2000) Molecular simulation and theory of the isotropic-nematic interface. *J Chem Phys* 112(12):5447–5453
82. Andrienko D, Allen MP (2000) Molecular simulation and theory of a liquid crystalline disclination core. *Phys Rev E* 61(1):504–510
83. Barbero G, Evangelista LR (2000) An elementary course on the continuum theory for nematic liquid crystals, series: Series on liquid crystals, vol 3. World Scientific
84. Govind AS, Madhusudana NV (2001) A simple molecular theory of smectic- liquid crystals. *Europhys Lett* 55(4):505–511
85. Lavrentovich OD, Pasini P, Zannoni C, Žumer S (2001) Defects in liquid crystals: computer simulations, theory and experiments, series: NATO science II: mathematics, physics and chemistry, vol 43. Springer, Berlin
86. Stewart W (2004) The static and dynamic continuum theory of liquid crystals, series: Liquid crystals book series. CRC Press, Boca Raton
87. Allender D, Longa L (2008) Landau–de Gennes theory of biaxial nematics reexamined. *Phys Rev E* 78(1), art no 011704
88. Majumdar A (2010) Equilibrium order parameters of nematic liquid crystals in the Landau-De Gennes theory. *Eur J Appl Math* 21(2):181–203
89. Majumdar A, Zarnescu A (2010) Landau–De Gennes theory of nematic liquid crystals: the Oseen-Frank limit and beyond. *Arch Ration Mech Anal* 196(1):227–280
90. Majumdar A (2012) The Landau-de Gennes theory of nematic liquid crystals: uniaxiality versus biaxiality. *Commun Pure Appl Anal* 11(3):1303–1337
91. Seguin B, Fried E (2012) Statistical foundations of liquid-crystal theory. I: discrete systems of rod-like molecules. *Arch Ration Mech Anal* 206(3):1039–1072
92. Buka A, Eber N (eds) (2013) *Flexoelectricity in liquid crystals: theory, experiments and applications*. Imperial College Press
93. Stewart IW (2013) Ericksen-Leslie theory for nematic liquid crystals

94. Hakobyan MR (2014) Onsager theory of nematic liquid crystals doped with ferroelectric nanoparticles. *Proc Proc Yerevan State Univer: Phys Math Sci* 51(2):54–59
95. Luckhurst GR, Sluckin TJ (eds) (2015) *Biaxial nematic liquid crystals: theory, simulation and experiment*. John Wiley & Sons, New York
96. Paicu M (2015) Some results on the nematic liquid crystals theory
97. Kitavtsev G, Robbins JM, Slastikov V, Zarnescu A (2016) Liquid crystal defects in the Landau–de Gennes theory in two dimensions—beyond the one-constant approximation. *Math Mod Meth Appl Sci* 26(14):2769–2808
98. Selinger JV (2016) *Introduction to the theory of soft matter: from ideal gases to liquid crystals, series: Soft and biological matter*. Springer
99. Gârlea IC, Mulder BM (2017) The Landau-de Gennes approach revisited: a minimal self-consistent microscopic theory for spatially inhomogeneous nematic liquid crystals. *J Chem Phys* 147(24), art no 244505
100. Jiang X, Zhou X, Zhang Z (2017) Landau–de Gennes theory for a—1 boojum in a degenerate hybrid-aligned nematic cell. *Liq Cryst* 44(3):490–499
101. Majumdar A, Wang Y (2018) Remarks on uniaxial solutions in the Landau–de Gennes theory. *J Math Anal Appl* 464(1):328–353
102. Canevari G, Taylor JM (2019) Variational theories of liquid crystals: materials science at many length scales
103. Douglas B (2019) Chiral topological defects in nematic liquid crystals and classical field theories. Baccalaureate Thesis, Oregon State University
104. Tang X, Selinger JV (2019) Theory of defect motion in 2D passive and active nematic liquid crystals. *Soft Matter* 15(4):587–601
105. Schimming CD, Viñals J (2020) Computational molecular field theory for nematic liquid crystals
106. Xu J, Chen JZY (2020) General liquid-crystal theory for anisotropically shaped molecules: symmetry, orientational order parameters, and system free energy. *Phys Rev E* 102(6), art no 062701
107. Feng X, Li S (2022) A molecular-based Q-tensor hydrodynamic theory of smectic liquid crystals. *Axioms* 11(10), art no 495
108. van der Schoot P (2022) Molecular theory of nematic (and other) liquid crystals: an introduction, series: Springer Briefs in physics. Springer, Berlin
109. Zöcher H (1933) The effect of a magnetic field on the nematic state. *Trans Faraday Soc* 29(140):945–957
110. Mizel VJ (1990) Variational problems for liquid crystals with variable degree of orientation. In: 1990 workshop on calculus of variations and nonlinear material behavior
111. Ericksen JL (1991) Liquid crystals with variable degree of orientation. *Arch Ration Mech Anal* 113(2):97–120
112. Lisin VB, Potapov AI (1997) Variational principle in the mechanics of liquid crystals. *Int J Non-Linear Mech* 32(1):55–62
113. Berdichevsky V (2009) *Variational principles of continuum mechanics: I. Fundamentals, series: Interaction of mechanics and mathematics*. Springer, Berlin
114. Berdichevsky V (2009) *Variational principles of continuum mechanics: ii. applications, series: Interaction of mechanics and mathematics*. Springer, Berlin
115. Liu C, Sun H (2009) On energetic variational approaches in modeling the nematic liquid crystal flows. *Discrete Contin Dyn Syst* 23(1–2):455–475
116. Ball JB (2017) Mathematics and liquid crystals. *Mol Cryst Liq Cryst* 647(1):1–27
117. Gevorkyan EV (2018) Variational approach in the theory of liquid-crystal state. *J Phys-Conf Series-Int Interdiscipl Conf “Euler Readings MRSU 2017”* 22–24 November 2017, Moscow Region State University (MRSU), Russian Federation 996(1), art no 012020
118. Henao D (2018) Variational analysis of liquid crystals
119. Li Q, Wang C (2022) On a variational problem of nematic liquid crystal droplets. *arXiv*, art no 2211.01218v1

120. Ornstein LS, Kast W (1933) New arguments for the Swarm theory of liquid crystals. *Trans Faraday Soc* 29(140):931–944
121. Saupe A (1968) Recent results in the field of liquid crystals. *Angew Chem* 7(2):97–112
122. Kelker H (1988) Survey of the early history of liquid crystals. *Mol Cryst Liq Cryst Incorporating Nonlinear Opt* 165(1):1–43
123. Brown GH, Shaw WG (1957) The mesomorphic state—liquid crystals. *Chem Rev* 57(6):1049–1157
124. Chatelain P (1951) Étude théorique de la diffusion de la lumière par un fluide présentant un seul axe d'isotropie: application aux cristaux liquides du type nématique. *Acta Crystallographica A: Found Crystallogr* 4(5):453–457
125. Oseen CW (1929) Die anisotropen Flüssigkeiten: Tatsachen und Theorien, Series: Fortschritte der Chemie, Physik und physikalischen Chemie, vol 20. Gebrüder Borntraeger, Berlin
126. Alouges F, Ghidaglia JM (1997) Minimizing Oseen-Frank energy for nematic liquid crystals: algorithms and numerical results. *Annales de l'Institut Henri Poincaré A: Physique théorique* 66(4):411–447
127. Majumdar A (2018) The Oseen-Frank theory for nematic liquid crystals, harmonic maps and defects. Summer school on “frontiers of applied and computational mathematics”
128. Selinger JV (2018) Interpretation of saddle-splay and the Oseen-Frank free energy in liquid crystals. *Liq Cryst Rev* 6(2):129–142
129. Taylor JM (2018) Oseen-Frank-type theories of ordered media as the Γ -limit of a non-local mean-field free energy. *Math Mod Meth Appl Sci* 28(4):615–657
130. Liu L (2019) The Oseen-Frank theory of liquid crystals. Ph. D. Dissertation, University of Oxford
131. Di Fratta G, Robbins JM, Slastikov V, Zarnescu A (2020) Landau-de Gennes corrections to the Oseen-Frank theory of nematic liquid crystals. *Arch Ration Mech Anal* 236(2):1089–1125
132. Zocher H (1925) Über freiwillige Strukturbildung in Solen (Eine neue Art anisotrop flüssiger Medien.). *Zeitschrift für anorganische und allgemeine Chemie* 147(1):91–110
133. Cemal Eringen A (1979) Continuum theory of nematic liquid crystals subject to electromagnetic fields. *J Math Phys* 20(12):2671–2681
134. de Jeu W (1980) Physical properties of liquid crystalline materials, series: Liquid crystal monographs, vol 1. Gordon and Breach
135. Self RH, Please CP, Sluckin TJ (2002) Deformation of nematic liquid crystals in an electric field. *Eur J Appl Math* 13(1):1–23
136. Romeo M (2019) Electromagnetic coupling in nematic liquid crystals modeled as microcontinua. *Continuum Mech Thermodyn* 31(2):587–601
137. Zocher H (1969) Some topics of liquid crystals yet to be discussed. *Mol Cryst* 7(1):165–175
138. Watson MC, Brandt EG, Welch PM, Brown FL (2012) Determining biomembrane bending rigidities from simulations of modest size. *Phys Rev Lett* 109(2), art no 028102
139. Ter Haar D, (ed) (1965) Collected papers of L. D. Landau. Gordon and Breach, New York
140. de Gennes PG (1971) Short range order effects in the isotropic phase of nematics and cholesterics. *Mol Cryst Liq Cryst* 12(3):193–214
141. De Gennes PG, Prost J (1974) The physics of liquid crystals, series: The international series of monographs on physics. Oxford University Press, Oxford
142. Gartland EC, Palfy-Muhoray P, Varga RS (1991) Numerical minimization of the Landau-de Gennes free energy: defects in cylindrical capillaries. *Mol Cryst Liq Cryst* 199(1):429–452
143. Gupta B, Ilg P (2013) Energetic and entropic contributions to the Landau–de Gennes potential for Gay-Berne models of liquid crystals. *Polymers* 5(2):328–343
144. Isić G, Vasić B, Zografopoulos DC, Beccherelli R, Gajić R (2015) Electrically tunable critically coupled terahertz metamaterial absorber based on nematic liquid crystals. *Phys Rev Appl* 3(6), art no 064007
145. Majumdar A (2018) The Landau-de Gennes theory for nematic liquid crystals. In: Summer school on “frontiers of applied and computational mathematics”
146. Zhou Y (2018) Modeling of nematic liquid crystals under the effect of chirality, external fields and surface conditions. Ph. D. Dissertation, The University of Chicago

147. Sussman DM, Beller DA (2019) Fast, scalable, and interactive software for Landau-de Gennes numerical modeling of nematic topological defects. *Front Phys* 7, art no 204
148. Allen SM, Cahn JW (1979) A microscopic theory for antiphase boundary motion and its application to antiphase domain coarsening. *Acta Metall* 27(6):1085–1095
149. Onsager L (1942) Anisotropic solutions of colloids. *Phys Rev* 62(11–12):558–559
150. Zwanzig R (1963) First-order phase transition in a gas of long thin rods. *J Chem Phys* 39(7):1714–1721
151. Sheng P (1974) Hard rod model of the nematic-isotropic phase transition. *RCA Rev* 35(1):132–143
152. Khokhlov AR, Semenov AN (1981) Liquid-crystalline ordering in the solution of long persistent chains. *Physica A* 108(2–3):546–556
153. Khokhlov AR, Semenov AN (1982) Liquid-crystalline ordering in the solution of partially flexible macromolecules. *Physica A* 112(3):605–614
154. Vroege GJ, Lekkerkerker HN (1992) Phase transitions in lyotropic colloidal and polymer liquid crystals. *Rep Prog Phys* 55(8):1241–1309
155. Camp PJ, Mason CP, Allen MP, Khare AA, Kofke DA (1996) The isotropic-nematic transition in uniaxial hard ellipsoid fluids: coexistence data and the approach to the Onsager limit. *J Chem Phys* 105(7):2837–2849
156. Speranza A, Sollich P (2002) Simplified Onsager theory for isotropic–nematic phase equilibria of length polydisperse hard rods. *J Chem Phys* 117(11):5421–5436
157. Malijevsky A, Vargá S (2010) Phase behaviour of parallel hard rods in confinement: an Onsager theory study. *J Phys: Condens Matter* 22(17), art no 175002
158. Zhang WY, Jiang Y, Chen JZY (2012) Solution of the Onsager model for the structure of rigid rods confined on a spherical surface. *Phys Rev E* 85(6), art no 061710
159. Ghazi SM, Behzadi F, Aliabadi R (2020) Second-virial Onsager theory and its limitations in the prediction of the ordering transitions of confined hard rods between two parallel hard walls. *J Phys Soc Jpn* 89(11), art no 114601
160. Curie P (1895) *Lois expérimentales du magnétisme. Propriétés magnétiques des corps à diverses températures/Magnetic properties of materials at various temperatures*. Ph. D. Dissertation
161. Weiss P (1907) L’hypothèse du champ moléculaire et la propriété ferromagnétique. *Journal de Physique Théorique et Appliquée* 6(1):661–690
162. Eugene Stanley H (1971) *Introduction to phase transitions and critical phenomena*. Oxford University Press, New York
163. Humphries RL, James PG, Luckhurst GR (1972) Molecular field treatment of nematic liquid crystals. *J Chem Soc, Faraday Trans 2: Mol Chem Phys* 68:1031–1044
164. Chaikin PM, Lubensky TC (1995) *Principles of condensed matter physics*. Cambridge University Press
165. Tanaka T (1998) A theory of mean field approximation. In: 1998 international conference on neural information processing systems (NIPS), art no , pp 351–357
166. Kadanoff LP (2009) More is the same; phase transitions and mean field theories. *J Stat Phys* 137(5–6):777–797
167. Kolomietz VM, Shlomo S (2020) *Mean field theory*. World Scientific
168. Sakthivadivel DAR (2022) Magnetisation and mean field theory in the ising model. *SciPost Phys Lect Notes*, art no 35
169. Collings PJ, Hird M (1997) *Introduction to liquid crystals: chemistry and physics*, series: Liquid crystals book series. CRC Press, Boca Raton
170. Ciferri A (ed) (1991) *Liquid crystallinity in polymers: principles and fundamental properties*. VCH Publishers, Weinheim
171. Ericksen JL (1961) Conservation laws for liquid crystals. *Trans Soc Rheol* 5(1):23–34
172. Leslie FM (1968) Some constitutive equations for liquid crystals. *Arch Ration Mech Anal* 28(4):265–283
173. Atkin RJ, Sluckin TJ (2003) Frank Matthews Leslie. 8 March 1935—15 June 2000. In: *Biographical memoirs of fellows of the royal society*, vol 49, pp 315–333

174. Duhem P (1893) Le potentiel thermodynamique et la pression hydrostatique. In: *Annales Annales Scientifiques de l'École Normale Supérieure* 3, vol 10, pp 183–230
175. Ericksen JL (1959) Anisotropic fluids. *Arch Ration Mech Anal* 4(1):231–237
176. Anzelius A (1931) Über die Bewegung der anisotropen Flüssigkeiten. Uppsala Universitets Arsskrift
177. Miesowicz M (1946) The three coefficients of viscosity of anisotropic liquids. *Nature* 158(4001):27
178. Saupe A (1960) Die Biegunselastizität der nematischen Phase von Azoxyanisol. *Zeitschrift für Naturforschung A: J Phys Sci* 15(9):815–822
179. Porter RS, Johnson JF (1962) Orientation of nematic mesophases. *J Phys Chem* 66(10):1826–1829
180. Muschik W, Ehrentraut H, Blenk S (1995) Ericksen-Leslie liquid crystal theory revisited from a mesoscopic point of view. *J Non-Equilib Thermodyn* 20(1):92–101
181. Coutand D, Shkoller S (2001) Well-posedness of the full Ericksen-Leslie model of nematic liquid crystals/Sur le caractère bien posé du modèle de cristaux liquides nématiques d'Ericksen-Leslie. *Comptes Rendus hebdomadaires des séances de l'Académie des sciences—Series I—Mathematics* 333(10):919–924
182. Feireisl E, Rocca E, Schimperna G (2011) On a non-isothermal model for nematic liquid crystals. *Nonlinearity* 24(1):243–257
183. Walkington NJ (2011) Numerical approximation of nematic liquid crystal flows governed by the Ericksen-Leslie equations. *ESAIM: Math Model Numer Anal* 45(3):523–540
184. Feireisl E, Frémond M, Rocca E, Schimperna G (2012) A new approach to non-isothermal models for nematic liquid crystals. *Arch Ration Mech Anal* 205(2):651–672
185. Hieber M, Prüss J (2016) Dynamics of the Ericksen-Leslie equations with general Leslie stress I: the incompressible isotropic case. arXiv, art no 1607.06599v1
186. Shibata Y, Suzuki Y (eds) (2016) Mathematical fluid dynamics, present and future: Tokyo, Japan, November 2014, series: Springer proceedings in mathematics and statistics, vol 183. Springer, Berlin, pp 433–459
187. Giga Y, Novotný A (eds) (2018) Handbook of mathematical analysis in mechanics of viscous fluids, series: Springer reference. Springer, pp 1075–1134
188. Cruz PA, Tomé MF, McKeec S, Stewart IW (2019) Numerical solution of the Ericksen-Leslie model for liquid crystalline polymers free surface flows. *J Nonnewton Fluid Mech* 268:30–45
189. Hieber M, Prüss J (2019) Dynamics of the Ericksen-Leslie equations with general Leslie stress II: the compressible isotropic case. *Arch Ration Mech Anal* 233(3):1441–1468
190. Walton J (2019) Ericksen-Leslie and Q-tensor models of spontaneous flow transitions in active nematic liquid crystals
191. Brzezniak Z, Deugoue G, Razafimandimby PA (2020) On the 2D Ericksen-Leslie equations with anisotropic energy and external forces. arXiv, art no 2005.07659v1
192. Cowin SC (1974) The theory of polar fluids. *Adv Appl Mech* 14:279–347
193. Łukaszewicz G (1999) Micropolar fluids: theory and applications, series: Modeling and simulation in science, engineering and technology. Birkhäuser, Boston
194. Rickert W, Vilchevskaya EN, Müller WH (2019) A note on couette flow of micropolar fluids according to Eringen's theory. *Math Mech Comp Syst* 7(1):25–50
195. Gay-Balmaz F, Ratiu TS, Tronci C (2013) Equivalent theories of liquid crystal dynamics. *Arch Ration Mech Anal* 210(3):773–811
196. Cemal Eringen A (1964) Simple microfluids. *Int J Eng Sci* 2(2):205–217
197. Cemal Eringen A (1967) Theory of micropolar fluids. *J Math Mech* 16(1):1–18
198. A. Cemal Eringen (1972) Theory of thermomicrofluids. *J Math Anal Appl* 38(2):480–496
199. Johnson JF, Porter RS (eds) (1974) Liquid crystals and ordered fluids, vol 2, Springer
200. Johnson JF, Porter RS (eds) (1978) Liquid crystals and ordered fluids. Springer
201. Cemal Eringen A (1993) An assessment of director and micropolar theories of liquid crystals. *Int J Eng Sci* 31(4):605–616
202. Eringen AC (1997) A unified continuum theory of liquid crystals. *ARI—Int J Phys Eng Sci* 50(2):73–84

203. Cemal Eringen A (2001) Microcontinuum field theories, II: fluent media. Springer
204. Chen Y, Lee JD, Eskandarian A (2004) Micropolar theory and its applications to mesoscopic and microscopic problems. *CMES—Comput Model Eng Sci* 5(1):35–43
205. Pabst W (2005) Micropolar materials. *Ceramics—Silikáty* 49(3):170–180
206. Chen J, Liang C, Lee JD (2010) Theory and simulation of micropolar fluid dynamics. *Proc Instit Mech Eng Part N: J Nanomater Nanoeng Nanosyst* 224(1–2):31–39
207. Murdoch AL (1987) On the relationship between balance relations for generalised continua and molecular behaviour. *Int J Eng Sci* 25(7):883–914
208. Blenk S, Ehrentraut H, Muschik W (1991) Statistical foundations of macroscopic balances for liquid crystals in alignment tensor formulation. *Physica A* 174(1):119–138
209. Blenk S, Muschijk W (1991) Orientational balances for nematic liquid crystals. *J Non-Equilib Thermodyn* 16(1):67–87
210. Blenk S, Ehrentraut H, Muschik W (1992) Macroscopic constitutive equations for liquid crystals induced by their mesoscopic orientation distribution. *Int J Eng Sci* 30(9):1127–1143
211. Doi M (1980) Rheological properties of rodlike polymers in isotropic and liquid crystalline phases. *Ferroelectrics* 30(1):247–254
212. Kuzuu N, Doi M (1983) Constitutive equation for nematic liquid crystals under weak velocity gradient derived from a molecular kinetic equation. *J Phys Soc Jpn* 52(10):3486–3494
213. Kuzuu N, Doi M (1984) Constitutive equation for nematic liquid crystals under weak velocity gradient derived from a molecular kinetic equation. II. Leslie coefficients for rodlike polymers. *J Phys Soc Jpn* 53(3):1031–1038
214. Doi M, Edwards SF (1986) The theory of polymer dynamics. Oxford University Press, London
215. Doi M, Ohta T (1991) Dynamics and rheology of complex interfaces I. *J Chem Phys* 95(2):1242–1248
216. Larson RG, Doi M (1991) Mesoscopic domain theory for textured liquid-crystalline polymers. *J Rheol* 35(4):539–563
217. Chaubal CV, Leal LG, Fedrickson GH (1995) A comparison of closure approximations for the Doi theory of LCPs. *J Rheol* 39(5):73–103
218. Feng J, Chaubal CV, Leal LG (1998) Closure approximations for the Doi theory: Which to use in simulating complex flows of liquid crystalline polymers? *J Rheol* 42(5):1095–1119
219. Larson RG (1999) The structure and rheology of complex fluids. Oxford University Press, New York
220. Rey AD, Denn MM (2002) Dynamical phenomena in liquid-crystalline materials. *Annu Rev Fluid Mech* 34:233–266
221. Sauerwein RA, de Oliveira MJ (2016) Lattice model for biaxial and uniaxial nematic liquid crystals. *J Chem Phys* 144(19), art no 194904
222. Rabbi AR, Al Faysal J (2020) Preparation, characterization and applications of liquid crystals: a review. *IOSR J Appl Chem* 13(12):43–54
223. Gay JG, Berne BJ (1981) Modification of the overlap potential to mimic a linear site-site potential. *J Chem Phys* 74(6):3316–3319
224. Jones JE (1924) On the determination of molecular fields—I. From the variation of the viscosity of a gas with temperature. *Proc Royal Soc London. Series A* 106(738):441–462
225. Jones JE (1924) On the determination of molecular fields. —II. From the equation of state of a gas. *Proc Royal Soc London Series A* 106(738):463–477
226. Lennard-Jones JE (1931) Cohesion. *Proc Phys Soc* 43(5):461–482
227. Picken SJ, van Gunsteren WF, van Duijnen PT, de Jeu WH (1989) A molecular dynamics study of the nematic phase of 4-n-pentyl-4'-cyanobiphenyl. *Liq Cryst* 6(3):357–371
228. Wilson MR, Allen MP (1991) Computer simulations of mesogenic molecules using realistic atom-atom potentials. *Mol Cryst Liq Cryst* 198(1):465–477
229. Wilson MR, Allen MP (1992) Structure of trans-4-(trans-4-n-pentylcyclohexyl)cyclohexylcarbonitrile (CCH5) in the isotropic and nematic phases: a computer simulation study. *Liq Cryst* 12(1):157–176
230. Paoloni GV, Ciccotti G, Ferrario M (1993) Simulation of site-site soft-core liquid crystal models. *Mol Phys* 80(2):297–312

231. Adams DJ, Luckhurst GR, Phippen RW (1987) Computer simulation studies of anisotropic systems: XVII. The Gay-Berne model nematogen. *Mol Phys* 61(6):1575–1580
232. Luckhurst GR, Stephens RA, Phippen RW (1990) Computer-simulation studies of anisotropic systems: XIX. Mesophases formed by the Gay-Berne model mesogen. *Liq Cryst* 8(4):451–464
233. de Miguel E, Rull LF, Chalam MK, Gubbins KE (1991) Liquid crystal phase diagram of the Gay-Berne fluid. *Mol Phys* 74(2):405–424
234. Berardi R, Emerson APJ, Zannoni C (1993) Monte Carlo investigations of a Gay-Berne liquid crystal. *J Chem Soc, Faraday Trans* 89(22):4069–4078
235. Sarman S, Evans DJ (1993) Statistical mechanics of viscous flow in nematic fluids. *J Chem Phys* 99(11):9021–9478
236. Emerson APJ, Luckhurst GR, Whatling SG (1994) Computer simulation studies of anisotropic systems: XXIII. The Gay-Berne discogen. *Mol Phys* 82(1):113–124
237. Berardi R, Fava C, Zannoni C (1995) A generalized Gay-Berne intermolecular potential for biaxial particles. *Chem Phys Lett* 236(4–5):462–468
238. Persson RAX (2012) Note: modification of the Gay-Berne potential for improved accuracy and speed. *J Chem Phys* 136(22), art no 226101
239. Moussa F, Benattar JJ, Williams C (1983) Positional order and bond orientational order in the liquid crystal smectic F phase. *Mol Cryst Liq Cryst* 99(1):145–154
240. Brock JD, Aharony A, Birgeneau RJ, Evans-Lutterodt KW, Litster JD, Horn PM, Stephenson GB, Tajbakhsh AR (1986) Orientational and positional order in a tilted hexatic liquid-crystal phase. *Phys Rev Lett* 57(1):98–101
241. DiLisi GA (2019) An introduction to liquid crystals, series: IOP concise physics. Morgan & Claypool Publishers
242. Strandburg KJ (ed) (1992) Bond-orientational order in condensed matter systems, series: Partially ordered systems. Springer
243. Tanaka H (2012) Bond orientational order in liquids: towards a unified description of water-like anomalies, liquid-liquid transition, glass transition, and crystallization: bond orientational order in liquids. *Euro Phys J E: Soft Matter Biol Phys* 35(10), art no 113
244. Mickel W, Kapfer SC, Schröder-Turk GE, Mecke K (2013) Shortcomings of the bond orientational order parameters for the analysis of disordered particulate matter. *J Chem Phys* 138(4), art no 044501
245. Zaluzhnyy IA, Kurta RP, Sulyanova EA, Gorobtsov OY, Shabalin AG, Zozulya AV, Menushenkov AP, Sprung M, Krówczynski A, Górecka E, Ostrovskii BI, Vartanyants IA (2017) Structural studies of the bond-orientational order and hexatic–smectic transition in liquid crystals of various compositions. *Soft Matter* 13(17):3240–3252
246. Haeberle J, Sperl M, Born P (2019) Distinguishing noisy crystalline structures using bond orientational order parameters. *Euro Phys J E: Soft Matter Biol Phys* 42(11), art no 149
247. Zeng SY, Hsu CH, Wu TM (2022) Bond orientational order parameters for classifying solid-like clusters in a Lennard-Jones system near liquid–solid transition and at solid states. *J Phys Chem A* 126(12):2018–2030
248. Mermin ND (1968) Crystalline order in two dimensions. *Phys Rev* 176(1):250–254
249. Jaster A (2004) The hexatic phase of the two-dimensional hard disks system. *Phys Lett A: General, Atomic Solid State Phys* 330(1–2):120–125
250. Zanghellini J, Keim P, von Grünberg HH (2005) The softening of two-dimensional colloidal crystals. *J Phys: Condens Matter* 17(45):S3579–4044
251. Keim P, Maret G, von Grünberg HH (2007) Frank’s constant in the hexatic phase. *Phys Rev E* 75(3), art no 031402
252. Gasser U, Eisenmann C, Maret G, Keim P (2010) Melting of crystals in two dimensions—mini review. *ChemPhysChem* 11(5):963–970
253. Kapfer S, Krauth W (2015) Two-dimensional melting: from liquid-hexatic coexistence to continuous transitions. *Phys Rev Lett* 114(3), art no 035702
254. Beekman AJ, Nissinen J, Wu K, Liu K, Slager RJ, Nussinov Z, Cvetkovic V, Zaanen J (2017) Dual gauge field theory of quantum liquid crystals in two dimensions. *Phys Rep* 683:1–110

255. Kosterlitz JM, Thouless DJ (1972) Long range order and metastability in two-dimensional solids and superfluids. *J Phys C: Solid State Phys* 5(11):L124–L126
256. Kosterlitz JM, Thouless DJ (1973) Ordering metastability, and phase transitions in two-dimensional systems. *J Phys C: Solid State Phys* 6(7):1181–1203
257. Kosterlitz JM (1974) The critical properties of the two-dimensional XY model. *J Phys C: Solid State Phys* 7(6):1046–1060
258. Nelson DR, Kosterlitz JM (1977) Universal jump in the superfluid density of two-dimensional superfluids. *Phys Rev Lett* 39(19):1201–1205
259. Halperin BI, Nelson DR (1978) Theory of two-dimensional melting. *Phys Rev Lett* 41(2):121–124
260. Halperin BI, Nelson DR (1978) Theory of two-dimensional melting. *Phys Rev Lett* 41(7):519–124
261. Nelson DR, Halperin BI (1979) Dislocation-mediated melting in two dimensions. *Phys Rev B* 19(5):2457–2484
262. Young AP (1979) Melting and the vector Coulomb gas in two dimensions. *Phys Rev B* 19(4):1855–1866
263. Bruinsma R, Nelson DR (1981) Bond orientational order in smectic liquid crystals. *Phys Rev B* 23(1):402–3065
264. Nelson DR, Toner J (1981) Bond-orientational order, dislocation loops, and melting of solids and smectic-A liquid crystals. *Phys Rev B* 24(1):363–387
265. Steinhardt PJ, Nelson DR, Ronchetti M (1981) Icosahedral bond orientational order in supercooled liquids. *Phys Rev Lett* 47(18):1297–1300
266. Steinhardt PJ, Nelson DR, Ronchetti M (1983) Bond-orientational order in liquids and glasses. *Phys Rev B* 28(2):784–805
267. Kosterlitz M (2016) Commentary on ordering, metastability and phase transitions in two-dimensional systems. *J Phys: Condens Matter* 28(48), art no 481001
268. Birgeneau RJ, Litster JD (1978) Bond orientational order model for smectic B liquid crystals. *Journal de Physique (Paris) Lett* 39(21):L399–L402
269. Leadbetter AJ, Frost JC, Mazid MA (1979) Interlayer correlations in smectic B phases. *Journal de Physique (Paris) Lett* 40(14):L325–L329
270. Pindak R, Moncton DE, Davey SC, Goodby JW (1981) X-ray observation of a stacked hexatic liquid-crystal B phase. *Phys Rev Lett* 46(16):1135–1138
271. Taylor TR, Fergason JL, Arora SL (1970) Biaxial liquid crystals. *Phys Rev Lett* 24(8):359–362
272. Balinskii AA, Volovik GE, Kats EI (1984) Disclination symmetry in uniaxial and biaxial nematic liquid crystals. *Soviet Phys J Exp Theor Phys* 60(4):738–753
273. Ranganath GS (1988) On defects in biaxial nematic liquid crystals. *Curr Sci* 57(1):1–6
274. Allen MP (1990) Computer simulation of a biaxial liquid crystal. *Liq Cryst* 8(4):499–511
275. Luckhurst GR (2001) Biaxial nematic liquid crystals: fact or fiction? *Thin Solid Films* 393(1–2):40–52
276. Priezjev NV, Pelcovits RA (2002) Coarsening dynamics of biaxial nematic liquid crystals. *Phys Rev E* 66(5), art no 051705
277. Madsen LA, Dingemans TJ, Nakata M, Samulski ET (2004) Thermotropic biaxial nematic liquid crystals. *Phys Rev Lett* 92(14), art no 145505
278. M. Bates and G. Luckhurst, Biaxial nematic phases and V-shaped molecules: A Monte Carlo simulation study. *Phys Rev E* 72(5), art no 051702
279. Prasad V, Kang SW, Suresh KA, Joshi L, Wang Q, Kumar S (2005) Thermotropic uniaxial and biaxial nematic and smectic phases in bent-core mesogens. *J Am Chem Soc* 127(49):17224–17227
280. Dingemans TJ, Madsen LA, Zafiropoulos NA, Lin W, Samulski ET (2006) Uniaxial and biaxial nematic liquid crystals. *Philos Trans Royal Soc London A* 364(1847):2681–2696
281. Vanakaras AG, Photinos DJ (2008) Thermotropic biaxial nematic liquid crystals: spontaneous or field stabilized? *J Chem Phys* 128(15), art no 154512
282. Karahaliou PK, Vanakaras AG, Photinos DJ (2009) Symmetries and alignment of biaxial nematic liquid crystals. *J Chem Phys* 131(12), art no 124516

283. van den Pol E, Thies-Weesie DME, Petukhov AV, Byelov DV, Vroege GJ (2010) Uniaxial and biaxial liquid crystal phases in colloidal dispersions of board-like particles. *Liq Cryst* 37(6–7):541–651
284. Sai Preeti G, Chiccoli C, Pasini P, Sastry VSS, Zannoni C (2013) On defects in biaxial nematic films with random planar surface alignment: a Monte Carlo study. *Mol Cryst Liq Cryst* 573(1):10–17
285. Liu Q, Ackerman PJ, Lubensky TC, Smalyukh II (2016) Biaxial ferromagnetic liquid crystal colloids. *Proc Nat Acad Sci United States Am* 113(38):10479–10484
286. Chiccoli C, Evangelista LR, Pasini P, Skačej G, Teixeira de Souza R, Zannoni C (2018) On the defect structure of biaxial nematic droplets. *Sci Rep* 8, art no 2130
287. Kralj M, Kralj M, Kralj S (2021) Topological defects in nematic liquid crystals: laboratory of fundamental physics. *Physica Status Solidi a: Appl Mater Sci* 218(17), art no 2000752
288. Apreutesei D, Mehl GH (2006) Completely miscible disc and rod shaped molecules in the nematic phase. *Chem Commun* 6:609–611
289. Mori H, Gartland EC, Kelly JR, Bos PJ (1999) Multidimensional director modeling using the Q tensor representation in a liquid crystal cell and its application to the π cell with patterned electrodes. *Jpn J Appl Phys Part 1*, 38(1A):135–146
290. Bonito A, Nohetto RH (eds) (2021) Geometric partial differential equations—part II, series: Handbook of numerical analysis, vol 22, Elsevier, pp 313–382
291. Hess S (1975) Irreversible thermodynamics of nonequilibrium alignment phenomena in molecular liquids and in liquid crystals. *Zeitschrift für Naturforschung A: J Phys Sci* 30(6–7):728–738
292. Hess S (1975) Irreversible thermodynamics of nonequilibrium alignment phenomena in molecular liquids and in liquid crystals II Viscous flow and flow alignment in the isotropic (stable and metastable) and nematic phases. *Zeitschrift für Naturforschung A: J Phys Sci* 30(10):1224–1232
293. Sonnet A, Kilian A, Hess S (1995) Alignment tensor versus director—description of defects in nematic liquid-crystals. *Phys Rev E* 52(1):718–722
294. Milson R, Coley A, Pravda V, Pravdová A (2005) Alignment and algebraically special tensors in Lorentzian geometry. *Int J Geometric Meth Mod Phys* 2(1):41–61
295. Ilg P, Hess S (2006) Two-alignment tensor theory for the dynamics of side chain liquid-crystalline polymers in planar shear flow. *J Non-Newtonian Fluid Mech* 134(1–3):2–7
296. Latham MP, Hanson P, Brown DJ, Pardi A (2008) Comparison of alignment tensors generated for native tRNAval using magnetic fields and liquid crystalline media. *J Biomol NMR* 40(2):83–94
297. Sonnet AM, Virga EG (2012) Dissipative ordered fluids: theories for liquid crystals. Springer
298. Zhu G (ed) (2012) NMR of proteins and small biomolecules, series: Topics in current chemistry, vol 326. Springer, Berlin
299. Mottram NJ, Newton CJP (2014) Introduction to Q-tensor theory. arXiv, art no 1409.3542v2
300. Tzvetkova P, Sternberg U, Gloge T, Navarro-Vázquez A, Luy B (2019) Configuration determination by residual dipolar couplings: accessing the full conformational space by molecular dynamics with tensorial constraints. *Chem Sci* 10:8774–8791
301. Gray GW (1962) Molecular structure and the properties of liquid crystals. Academic Press
302. Pasechnik SV, Chigrinov VG, Shmeliova DV (2009) Liquid crystals: viscous and elastic properties. Wiley
303. Solymar L, Walsh D, Syms RRA (2014) Electrical properties of materials, 9th edn. Oxford University Press
304. Lehmann O (1889) Über fließende Krystalle. *Z Phys Chem* 4U(1):462–472
305. Brown GH (1973) Structure, properties, and some applications of liquid crystals. *J Opt Soc Am* 63(12):1505–1514
306. Dąbrowski R, Kula P, Herman J (2013) High birefringence liquid crystals. *Crystals* 3(3):443–482
307. Tani J, Takagi T, Nakaniwa H, Ohtomo K, Kosugo K (1996) Vibration suppression effect of liquid crystal under electromagnetic field. *J Intell Mater Syst Struct* 7(3):272–277

308. Wang M, He L, Zorba S, Yin Y (2014) Magnetically actuated liquid crystals. *Nano Lett* 14(7):3966–3971
309. Christou MA, Polycarpou AC, Papanicolaou NC (2015) Modeling of nematic liquid crystal cells subject to an externally applied field. *Optik* 126(24):5269–5275
310. Guillamat P, Ignés-Mullol J, Sagués F (2016) Control of active liquid crystals with a magnetic field. *Proc Nat Acad Sci United States Am* 113(20):5498–5502
311. Shuai M, Klitnick A, Shen Y, Smith GP, Tuchband MR, Zhu C, Petschek RG, Mertelj A, Lisjak D, Čopič M, MacLennan JE, Glaser MA, Clark NA (2016) Spontaneous liquid crystal and ferromagnetic ordering of colloidal magnetic nanoplates. *Nat Commun* 7, art no 10394
312. Dorohoi DO, Barzic AI, Aflori M (eds) (2017) Electromagnetic radiation in analysis and design of organic materials: electronic and biotechnology applications. CRC, Boca Raton
313. Kazem-Rostami M (2017) Photoswitchable liquid crystal design. *Synthesis* 49(6):1214–1222
314. Blinov LM, Chigrinov VG (1994) Electrooptic effects in liquid crystal materials, series: Partially ordered systems. Springer
315. Fréedericksz V, Zolina V (1933) Forces causing the orientation of an anisotropic liquid. *Trans Faraday Soc* 29(140):919–930
316. Kopcansky P, Koneracka M, Zavisova V, Jadzyn J, Czechowski G, Zywuicki B (1997) Study of magnetic Fredericksz transition in ferronematics liquid crystals doped with fine magnetic particles. *Journal de Physique IV France* 7(C1):C1-565–C1-566
317. Barboza R, Bortolozzo U, Assanto G, Vidal-Henriquez E, Clerc MG, Residori S (2012) Vortex induction via anisotropy stabilized light-matter interaction. *Phys Rev Lett* 109(14), art no 143901
318. Takezoe H (2014) Historical overview of polar liquid crystals. *Ferroelectrics* 468(1):1–17

Chapter 3

Microwave, Millimeter Wave and Terahertz Applications of Liquid Crystal



Although liquid crystal display has been extensively applied, the narrow niche of optical applications is out of the scope of this chapter. Instead, attention here is focused on non-display applications of liquid crystal in microwave, millimeter wave and terahertz wave bands. In accordance, this chapter begins with a brief introduction of the electromagnetic spectrum with intensified interest in microwave, millimeter wave and terahertz wave bands. An overview about applications of liquid crystal at microwave, millimeter wave and terahertz wave frequencies is next presented. The overview and the following topical reviews are based on a literature survey and the collected literatures. Finally, brief reviews on more specific topics are given.

3.1 Electromagnetic Spectrum

In electromagnetics, frequency f and wavelength λ are often used interchangeably because of the following simple relationship

$$f\lambda = c \quad (3.1)$$

where c is the speed of light in free space.

There is no known limit of frequency or wavelength for electromagnetic spectrum. The bands shown in Fig. 3.1 cover electromagnetic waves with frequencies ranging from below 1 Hz to above 10^{25} Hz, corresponding to wavelengths from thousands of kilometers down to a fraction of the size of an atomic nucleus. The band boundaries are fairly arbitrary and are used variously between different fields of study. The electromagnetic waves in each of these bands have different characteristics.

The International Telecommunication Union (ITU) divides the radio spectrum into 12 bands with traditional names and short notations as shown in Fig. 3.2. Each radio band begins at a wavelength which is a power of ten (10^n) meters, with corresponding

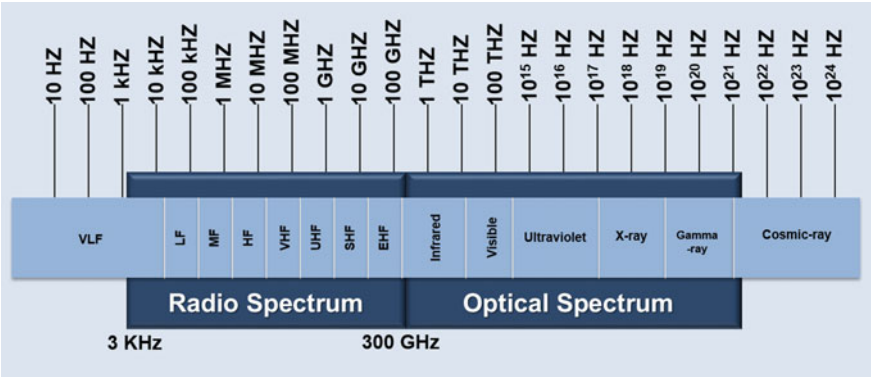


Fig. 3.1 Electromagnetic spectrum

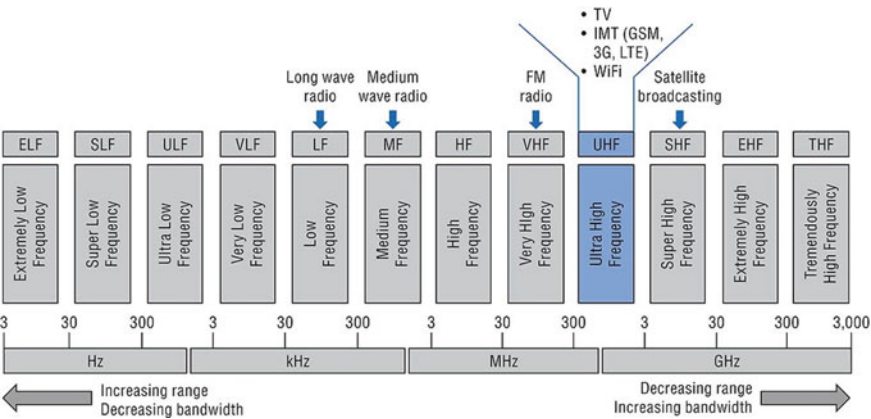


Fig. 3.2 Radio spectrum

frequency of $3 \times 10^{8-n}$ Hz, and covers a decade of frequency or wavelength. In particular, as can be seen from Fig. 3.3, microwave, millimeter wave, and terahertz wave sit at the higher end in the radio spectrum.

3.1.1 Microwave

Microwave or μ -wave has been widely used in modern technology. Although different sources define microwave incompatibly, the range between 1 and 100 GHz is usually defined as the frequencies of microwave in radio frequency engineering. An alternative range from 300 MHz to 300 GHz is also commonly accepted. This later definition is adopted in this chapter, and in general, in this book.

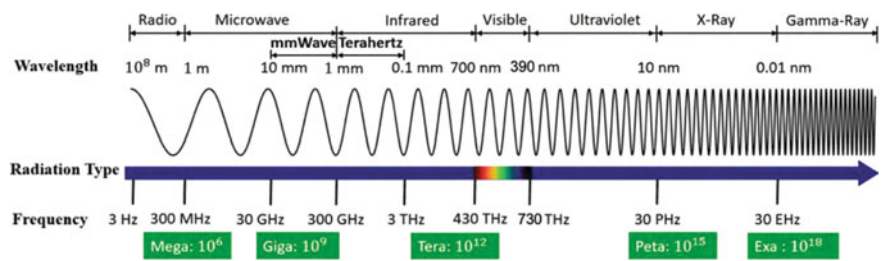


Fig. 3.3 Microwave, millimeter wave and terahertz wave in electromagnetic spectrum

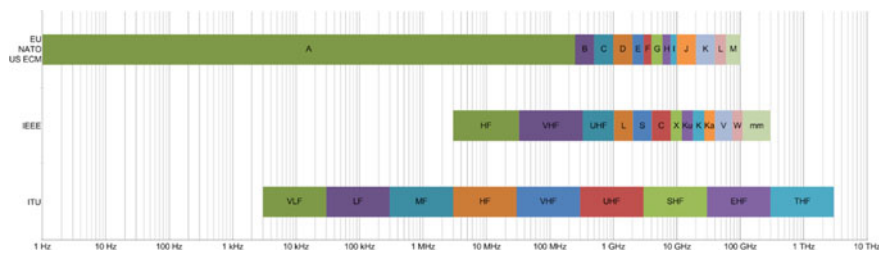


Fig. 3.4 Radar band designations by ITU, IEEE, EU, NATO, and US ECM

Microwave bands are designated by letters which had its origin in World War II. Similarly, different organizations such as ITU, the Institute of Electrical and Electronics Engineers (IEEE), the European Union (EU), the North Atlantic Treaty Organization (NATO), and the US electronic countermeasures (ECM) industry have similar but somewhat incompatible designations as shown in Fig. 3.4.

3.1.2 Millimeter Wave

Millimeter wave, sometimes abbreviated as MMW or mm-wave, ranges from 30 to 300 GHz. It is so named because of the millimeter order of its wavelength. Its official ITU designation is the Extremely high frequency (EHF).

Since the pioneering investigation by Indian physicist Jagadish Chandra Bose [1–6], millimeter wave has been used for military fire-control radar, airport security scanners, short range wireless networks, scientific research and many other applications. In recent years, limitation in high-speed and huge capacity wireless communications at microwave band has drawn intense concern from general public. The ever-increasing demand in wireless data transmission capacity from the emerging 5G communications and the forthcoming 6G communications has exposed millimeter wave as the promising candidate of choice because of the availability of large bandwidths at millimeter wave frequencies. The need for compact, versatile, and

lightweight millimeter wave circuits, devices and subsystems presents serious new challenges to the community.

3.1.3 Terahertz Wave

The official ITU designation for terahertz wave is tremendously high frequency (THF) for frequencies from 0.3 THz to 3 THz. Meanwhile, it also bears many aliases: submillimeter wave, T-rays, T-waves, T-light, T-lux or simply THz. Lower boundary of 0.1 THz and upper boundary of 10 THz or even 30 THz are also observed in some other definitions.

Terahertz wave occupies a transition zone known as the terahertz gap where the ranges of microwave and far infrared light wave overlap. The terahertz gap also implies superficial understanding of its physical nature, nascent technology for its generation and manipulation, and embryonic applications. It had been very difficult to generate terahertz wave until quite recently.

One of the distinctive advantages of terahertz wave against X-ray is its high transparency to non-conducting materials due to the relatively low energy of each photon. In other words, THz is capable of penetrating a specimen under test without damaging it, especially when it is opaque at visible frequencies. This non-ionizing high penetrating power has become increasingly important for many in vivo biological applications and testing, for example, cancer diagnosis and full-body security scanning.

Another unique property that makes terahertz wave uniquely useful in organic molecular crystals is the sensitivity to crystal lattice vibration, magnetic spins, hydrogen bonds, inter-molecular interaction, and water. Even though it is possible to excite molecules using a variety of energies, it is only through the careful selection of the low energy in the terahertz range that it is possible to selectively excite crystal lattice vibrations and study in a unique way the presence and nature of interactions between molecules.

Apparently, terahertz wave can provide much larger bandwidths for high-speed and huge capacity wireless communication. Besides, terahertz wave has excellent potential to help understand fundamental and exciting new challenges at the interface between physics, materials chemistry and life sciences. Following the new breakthroughs in semiconductor physics and femtosecond laser technology in the 1990s, terahertz wave has exhibited its promising potential for nondestructive evaluation and testing, biomedical engineering, security, scientific research, manufacturing, and communications. Within the last decades, exciting applications of terahertz wave in a diverse range have greatly increased. In connection with these already existing and with potential applications especially the envisioned ultra-fast ubiquitous 6G communication, it is imperative to improve devices for emission, modulation and detection of terahertz wave.

3.2 An Overview

Liquid crystal materials play a paramount role in countless nondisplay applications [7–10] as briefed in Chap. 1 of this book. On the other hand, microwave, millimeter wave, and terahertz liquid crystal is relatively new but developing with increasing practical significance. Nevertheless, liquid crystal has drawn considerable attention from microwave, millimeter wave and terahertz community. To certain extent, liquid crystal is a game changer.

Researchers and engineers have been endeavoring on the use of liquid crystal in numerous electromagnetic systems to realize devices of favorable traits including miniaturization, large capacity, lightweight, high broadband tunability, dynamic frequency selection, ultra-low power consumption, and broad tuning range. Extensive and intensive researches have significantly advanced liquid crystal into one of the hot research frontiers for cutting-edge microwave, millimeter wave, and terahertz technologies. More roles and functions remain to be discovered.

Although a number of featured reviews [9, 11–39] are available, the full picture of the state of the art is yet not drawn. In this regard, the authors try to make an as comprehensive as possible review on the up-to-date applications of liquid crystal at microwave, millimeter wave, and terahertz wave frequencies.

3.2.1 A Literature Survey

Following a long time personal practice to look for and archive interesting literatures, a preliminary literature survey on liquid crystal has been being conducted. It is of course not exhaustive and will never be so claimed, especially from the point of view of language because the authors can freely read only Chinese and English.

The survey is generally based on the keyword liquid crystal and its Chinese translation 液晶. Specific mesophases are generally not considered due to enormous diversity and limited time. The reference-in-reference technique is also applied whenever necessary and feasible. Found literatures including books, articles, standards, patents, degree theses, technical reports are chronologically documented and downloaded if possible. A yearly counting spanning 1840 and 2023 is given in Fig. 3.5 in solid black line.

A fine survey on electromagnetic applications of liquid crystal is further carried out among the above literature survey result. More keywords including electromagnetic, microwave, millimeter wave, terahertz wave, mmW, THz and the corresponding Chinese terms are imposed. Microwave, millimeter wave, and terahertz wave applications of liquid crystal are then identified by checking the collected publications one by one. As of March 20, 2023, 825 publications have been collected. The result is also shown in Fig. 3.5 in blue dashed line.

It is exciting to notice that microwave, millimeter wave, and terahertz liquid crystal is a very promising topic for master and PhD candidates. As of March 20,

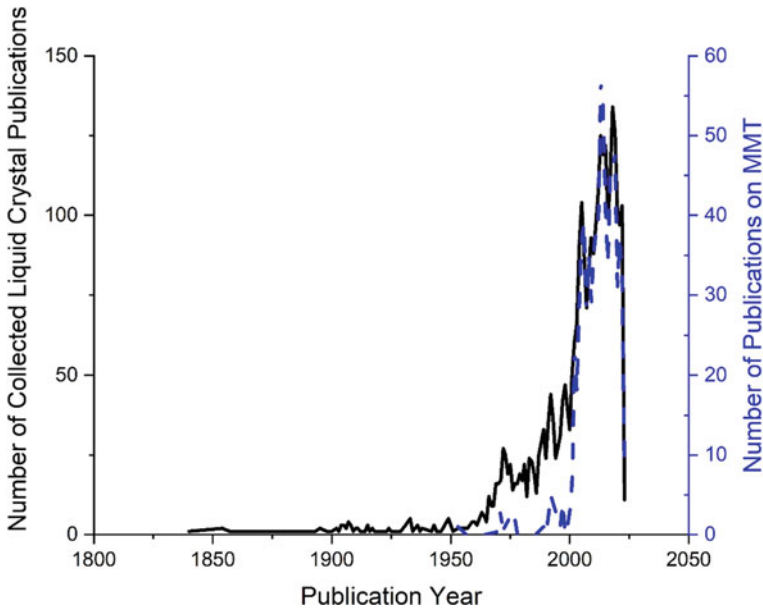


Fig. 3.5 Personally collected literatures on liquid crystals

2023, the chronological bibliography includes 5 master theses [16, 40–44] and 28 PhD dissertations [45–71] which are focused on microwave, millimeter wave, and terahertz liquid crystal.

3.2.2 Classification

Numerous applications of liquid crystal at microwave, millimeter wave and terahertz frequencies have been presented among the thousands of publications collected through the above literature survey. These applications can be classified into tens or even hundreds of categories according to different criteria. In this book, we will only apply the basic criteria to classify these noticed applications. For accuracy, collected unpublished manuscripts are not included in the classification even if the manuscripts have been accepted for publication. The authors sincerely apologize for such intentional negligence. It also has to be pointed out that some similar or even interchangeable terminologies, e.g., composite materials, artificial dielectric, frequency selective surfaces, metamaterials, metasurfaces, reconfigurable intelligent surfaces, are not distinguished.

It is perhaps instinct to trace the progress of any scientific and technological discovery. Thus, time is the first applied classification criterion. Special attention is

given to the pioneering attempts in the twentieth century which will be separately presented in Sect. 3.3 of this chapter.

Liquid crystal is in nature a tunable anisotropic dielectric material of low loss. Under the influence of external stimulus such as electric field, magnetic field, light, or temperature, liquid crystal molecules can be reoriented, leading to continuously tunable electromagnetic properties. A considerable number of tunable circuits, devices and systems such as antennas and antenna arrays, phase shifters, filters, and resonators have been developed or even commercialized. They will be briefed in alphabetical order in Sect. 3.4 of this chapter.

Due to multi-level characteristics of microwave, millimeter wave and terahertz systems, a component may be accommodated into different functional systems. In this regard, care is given to the lowest level functional component in which liquid crystal is applied. Very often, originators' classification is followed. Generally, extended application of the fundamental functional component in which liquid crystal is applied will not be further scrutinized as an independent application of liquid crystal in this book due to their vast diversity.

Besides dielectric anisotropy, liquid crystal materials also bear numerous other materials properties. Some of these properties, e.g., hermeticity, thermal stability, and flexibility, are also very important for microwave, millimeter wave, and terahertz circuits, devices, and systems. Hence, liquid crystal applications at microwave, millimeter wave, and terahertz frequencies can also be classified by the critical property of liquid crystal. In particular, applications involving liquid crystal polymer will be separately discussed in Sects. 3.5 and 3.6 of this chapter. Applications in Sect. 3.5 make use of liquid crystal as a dielectric substrate while Sect. 3.6 is focused on packaging.

3.3 Pioneering Applications in the Twentieth Century

Significance of groundbreaking contributions in science and technology can never be exaggerated. More importantly, the pioneering innovations and the way they were made might further inspire wider and deeper interests. There is no exception for liquid crystal. As such, we follow this common practice to retrospect pioneering applications of liquid crystal at microwave, millimeter wave and terahertz frequencies.

3.3.1 *Polarizer*

Liquid crystal is well known for its long well-established history of applications in visible light, primarily in the display industry. Surprisingly, there might be an earlier track record of its microwave application. To the best knowledge of the authors, microwave and liquid crystal was first simultaneously mentioned in Mann's master

thesis in 1953 [40] while studying the Cotton-Mouton effect [72, 73] in liquid crystal at microwave frequency (9375 MHz). It might be the first ever application of liquid crystal in the concerned frequency bands in this book, a microwave polarizer. The same principle of polarization switch was behind the spatial light modulator (SLM) for phased array antennas [74–82].

3.3.2 Power Meter

Liquid crystal of certain temperature selectively reflects visible light and presents a colored picture in the reflected beams when it is illuminated by white light. This principle was exploited to develop meter of radiation power density [83–94]. Interestingly, interest in liquid crystal power meter has sustained until very recently [95, 96].

3.3.3 Phase Modulation

In early 1990s, the phase modulation effect of liquid crystal on microwaves was discovered [97–100]. By changing the external electric field or magnetic field, the phase of microwave can be well tuned. This can be used in a guided structure to modify the propagation velocity and to control the corresponding phase delay continuously with ease by a low-frequency field of only up to 10 V. This discovery has inspired enormous follow up studies on phase shifter [101–105], retarder, delay line [106–108], phased antenna array [103], and slot antenna array [105].

3.3.4 Photonic Band Gap

In 1999, by infiltrating an optically birefringent nematic liquid crystal into the void regions of an inverse opal, a completely tunable photonic band gap (PBG) [109] is developed.

3.4 Reconfigurable Circuits, Devices, and Systems

Tunable devices and materials have always been extremely important for a variety of applications at microwave, millimeter wave, and terahertz frequencies. Ever since the advent of microwave technology, tunable devices, such as phase shifters, resonators, and antennas, have been indispensable in applications requiring radiofrequency signal filtering, beam shaping, or steering. This necessity becomes even more relevant

in view of a new era in high-bandwidth wireless communications in 5G networks, satellite links, and advanced radars for sensing and safety. The demand for higher-data-rate, energy efficient, tunable, and flexible devices operational under different communication standards and environmental conditions continues to grow exponentially as more and more devices are connected together in the context of internet of things. Also, for security reasons, lightweight field radios and radar systems are required to reconfigure and operate over different frequency bands in a short time span. Unfortunately, as the operating frequency is pushed toward the millimeter wave range or beyond, the performance of traditional microwave tunable elements degrades while their fabrication complexity and cost increases.

Liquid crystal materials are inherently an attractive proposition for its continuously tunable electromagnetic anisotropy, low dielectric constants, moderate losses, low dispersion, and potentially low cost. Numerous liquid crystal materials have been evaluated to feature a relatively high dielectric anisotropy along a preferential direction at microwave, millimeter wave, and terahertz frequencies, usually purposely aligned through rubbing [110]. In particular, by means of an electric or magnetic control field transverse to the direction of electromagnetic wave propagation which superimposes the electromagnetic field, the dielectric permittivity effective for the electromagnetic field can be changed.

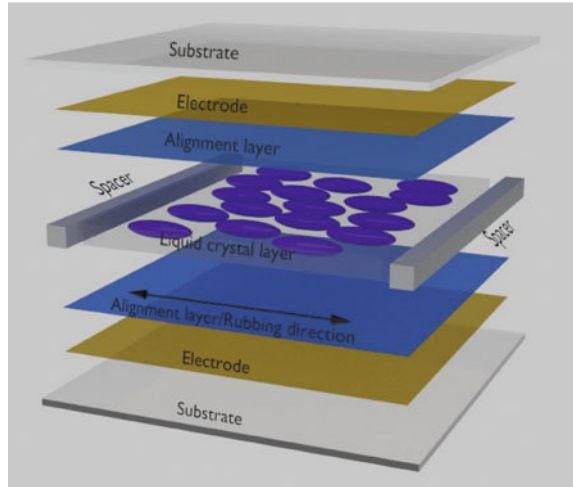
Incorporating liquid crystal can bring about many advantages over ferrite, piezoelectrics, micro-electro-mechanical systems (MEMS), solid-state positive-intrinsic-negative (PIN) diodes, ferroelectric barium strontium titanate (BST) and ferromagnetic yttrium iron garnet (YIG). It offers a low-cost electromagnetic solution to the problem of achieving tunable, adaptive or reconfigurable systems. In this respect, liquid crystals could play an important role in these cutting-edge microwave, millimeter wave and terahertz applications. Research is ongoing on the use of liquid crystals at microwave, millimeter wave and terahertz frequencies, with a significant potential.

3.4.1 Absorber

Both resonant and broadband electromagnetic absorbers ([111–119], chapter 8) have been extensively applied especially in military stealth technology and civil electromagnetic compatibility. A perfect absorber can inhibit the reflection or transmission of electromagnetic waves of any unknown polarization from any unknown direction over a broader bandwidth. A practical electromagnetic absorber is capable to suppress the reflection and transmission from unknown electromagnetic radiators efficiently to the lowest possible level over a wide range of frequencies within a specified band of electromagnetic spectrum.

Along with recent trends toward complicated electromagnetic environments and development of higher-frequency communication equipment, competent absorbers

Fig. 3.6 Plain liquid crystal attenuator



are expected to have many new features such as low cost, light-weight, and flexible. Liquid crystal emerges as one of the appealing solutions to withstand all these challenges and has made pronounced progress.

3.4.1.1 Plain Absorber

A plain liquid crystal attenuator using E7 [120] is demonstrated to be able to modulate the power output of a 3.4-THz quantum-cascade laser. Unlike the liquid crystal metamaterial absorbers which will be discussed shortly, there is no patterned metal layer as can be seen from Fig. 3.6. Instead, both electrodes are conductive polymer biased by a 5 kHz sinusoidal voltage.

A similar plain liquid crystal attenuator as a mask for millimeter-wave single-pixel imaging [121, 122] using 5CB was recently proposed.

3.4.1.2 Metamaterial Absorber

Liquid crystal metamaterial absorbers have been very popular. Very often, a patterned metal layer acts as one of the electrodes to drive liquid crystal as shown in Fig. 3.7.

A microwave liquid crystal (K15) absorber [123] is simulated by using HFSS and measured between 9.8 and 10.3 GHz. The liquid crystal is sandwiched by two rectangular patches and the ground. A similar absorber with BL037 liquid crystal [124] is simulated by using CST and measured from 8.6 to 10.4 GHz.

A terahertz liquid crystal metamaterial absorber [24, 125, 126] is simulated and measured. Liquid crystal 5CB is sandwiched by a rectangular array of electric ring

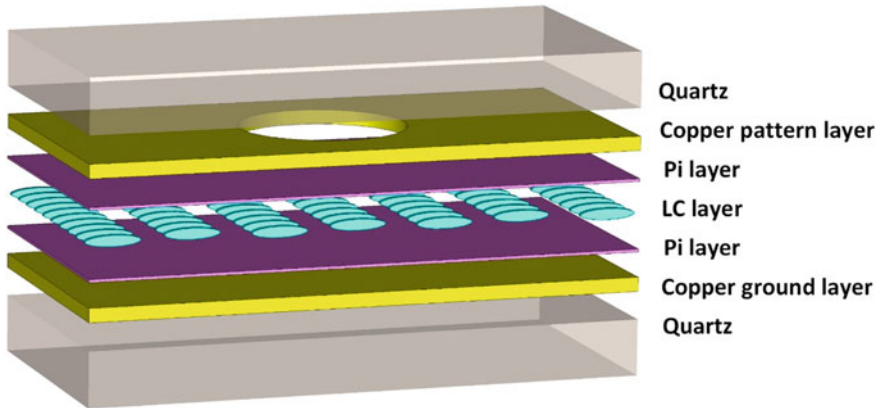


Fig. 3.7 General configuration of liquid crystal metamaterial absorber

resonators and the ground plane. A 6×6 spatial light modulator with LCMS-1107 [127] is subsequently fabricated and measured from 2 to 6 THz.

A terahertz nematic liquid crystal metamaterial absorber based on critical coupling [128] is simulated by a rigorous tensorial formulation of the Landau–de Gennes theory from 0.6 to 1.4 THz. Liquid crystal 1825 is sandwiched by a triangular lattice of circular patches connected by thin wires and the ground plane.

A terahertz nematic liquid crystal metamaterial absorber [129, 130] is simulated by using COMSOL and measured from 0.78 to 0.88 THz. Liquid crystal NJU-LDn-4 is sandwiched by a square array of circular patches and the ground plane.

An F-band liquid crystal metamaterial absorber [131, 132] is simulated and measured from 95 to 125 GHz. Liquid crystal (E7 and S200) is sandwiched by a 25×25 array of circular metal holes and the ground plane.

A terahertz liquid crystal metamaterial absorber [133] is simulated and measured from 0.5 to 0.65 THz. Liquid crystal E7 is sandwiched by an array of complementary split ring resonator and the ground plane.

A terahertz liquid crystal metamaterial absorber [134] is simulated by using CST and measured. Liquid crystal NJU-LDn-4 is sandwiched by a combined electrode and the ground. The combined electrode includes graphene and an array of asymmetric crosses.

A terahertz liquid crystal (S200) metamaterial absorber [135] is simulated by finite element frequency domain and measured from 220 to 325 GHz. The belt-like top electrode makes it polarization sensitive.

A terahertz liquid crystal metamaterial absorber [136] is simulated by using finite difference time domain from 150 to 230 GHz. The symmetric unit cell of split ring resonator makes the absorber polarization insensitive.

A terahertz liquid crystal dual-band metamaterial absorber [137] is simulated by using finite difference time domain (FDTD). Liquid S200 is sandwiched by the ground plane and a square array of electrodes. Each unit cell electrode is a patch

surrounded by a split ring resonator. A 40×40 prototype is also measured from 220 to 325 GHz.

A terahertz metamaterial absorber [138] is measured from 350 to 450 GHz. Polymer network liquid crystal (95% S200 + 5% RM257) instead of nematic liquid crystal is sandwiched by the ground plane and a 60×50 array of circular patches.

A terahertz (140 GHz) liquid crystal (5CB) high impedance surface absorber [139] is proposed. A frequency selective surface of subwavelength slots and the ground sandwich the liquid crystal.

A terahertz liquid crystal (HFUT-HB01) metamaterial absorber [140] is simulated by using finite element method and measured from 90 to 140 GHz. Each unit cell has a circular ring and a T-shaped strip.

A microwave liquid crystal (BaYi-Space LT-5720) metamaterial absorber [141] is simulated by using CST and measured from 8.5 to 13 GHz. Each unit cell includes a cut wire and two square loops with short strips.

A terahertz metamaterial absorber [142] is simulated and measured from 90 to 140 GHz. Polymer network liquid crystal (95% liquid crystal + 5% RM257) is sandwiched by the ground plane and a 50×50 array. Each array elements includes a split ring resonator in a square loop.

A temperature-dependent terahertz liquid crystal absorber [143] taking advantage of the metal–insulator phase change of Vanadium(IV) oxideoxide (VO_2) was simulated by using finite difference time domain (FDTD) from 0.2 THz to 1.4 THz. Four proportional VO_2 crosses and the ground sandwich the liquid crystal (5CB). recent variant to form array elements for broadband terahertz absorption.

3.4.1.3 Silicon Pillary Array

A terahertz liquid crystal metamaterial absorber [144] as reproduced in Fig. 3.8 is simulated by using Lumerical FDTD Solutions. A three-dimensional silicon pillar array is embedded in a liquid crystal (NJU-LDn-4) layer biased by two graphene electrodes.

3.4.2 Antenna

Antenna is perhaps one of the most essential devices in almost all electromagnetic systems. It directs incoming and outgoing electromagnetic waves. Over the years, a wide variety of antennas have been developed for different purposes. Without exception, liquid crystal has been intensively applied to construct antennas and antenna arrays.

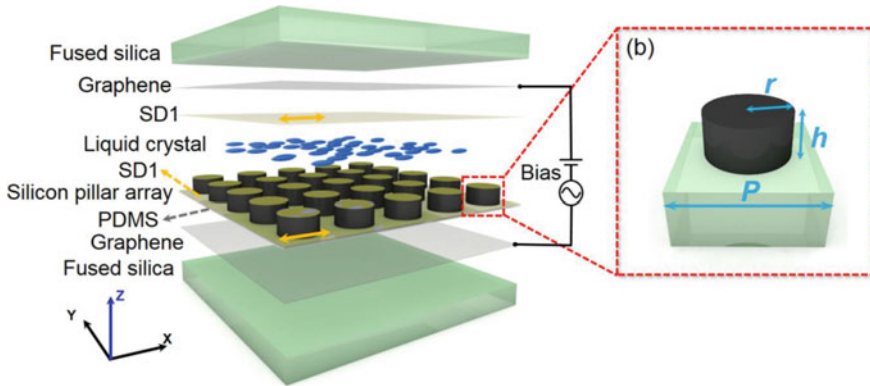


Fig. 3.8 A liquid crystal metamaterial absorber with dielectric pillar array

3.4.2.1 Bowtie

A bow-tie microstrip antenna on liquid crystal substrate for wireless communication such as Bluetooth/WLAN-2.4/WiBree/ZigBee [145] is simulated and measured.

3.4.2.2 Leaky Wave Antenna

A 7.6 GHz composite right/left-handed rectangular waveguide leaky wave antenna [146] is presented. The antenna features beam steering capabilities by inclusion of liquid crystal tuned by static external electric or magnetic fields.

Ka-band leaky wave antenna [56, 147–152] is simulated and measured. Liquid crystal (TUD-649) composite right/left-handed transmission line enables necessary electrical or magnetic tunability.

A liquid crystal (LC CDZSL-016) composite right/left-handed leaky wave antenna [153, 154] is simulated by using CST and measured from 11 to 14 GHz. The center section of the bottom microstrip patch is narrowed down to accommodate a pair of shorted stubs and several other pairs of open-ended stubs.

A liquid crystal leaky wave antenna with a grooved rectangular waveguide and an inverted PCB microstrip structure with eight short slots [155] is simulated by using CST from 10 to 15 GHz.

Liquid crystal substrate integrated waveguide leaky wave antennas with quasi-periodic slots [156–158] are simulated by using HFSS.

3.4.2.3 Lens Antenna

A millimeter-wave liquid crystal lens antenna [159] is simulated by using CST and measured from 50 to 75 GHz. Liquid crystal filling a semicircular shaped parallel-plate waveguide makes the aperture reconfigurable and accordingly beam steerable.

3.4.2.4 Metamaterial Surface Antenna

A metamaterial surface antenna based on diffractive metamaterials [160–162] is commercialized.

3.4.2.5 Patch Antenna

Liquid crystal (Merck K15 or BL037) is used to tune the resonant frequency of a patch antenna [163–166]. Resonance frequency varies between 4.74 and 4.6 GHz (K15) or 4.57 and 4.33 GHz (BL037). A circular polarized tunable patch antenna [167] is similarly tuned by using Dainippon Ink and Chemicals Co. LTD. RDP-85475.

A square patch antenna [168] tuned by liquid crystal (K15 and BL037) is studied. Slots are introduced to reduce its size.

A square patch antenna on liquid crystal substrate [169] is invented.

The operating frequency of a $20 \times 15 \text{ mm}^2$ microstrip patch antenna [166, 170–173] is electrically tuned in the 5 GHz range by liquid crystal (E7). Other liquid crystal materials (MDA-00-3506 and GT3-23001) are also investigated [156].

A 5 GHz patch antenna on liquid crystal (K15) substrate [174] is simulated and measured. It is further miniaturized through slot insertion.

A microstrip patch antenna on liquid crystal substrate [175] is designed. The resonant frequency can be tuned from 34.1 to 37.7 GHz.

A compact circularly polarized low-profile GPS (1.5–1.65 GHz) antenna [176] is designed and measured. The frequency agile nearly square microstrip patch with two orthogonal pairs of irregular and unsymmetrical slits on liquid crystal exhibits higher peak gain and low insertion loss.

Liquid crystal is introduced to compensate the narrow bandwidth of a circularly polarized patch antenna [177]. The resonant frequency can be tuned from 9.5 to 10.25 GHz.

A microstrip patch antenna on biased nematic liquid crystal substrate [178] is accurately modelled by coupled Poisson's equation which is then numerically solved using an iterative finite difference scheme.

An 60 GHz aperture-coupled patch antenna on polymer liquid crystal substrate [179] is designed for integrated transmitters and receivers.

Compact liquid crystal rectangular microstrip patch antenna [180] is simulated by using HFSS and measured from 1.5 to 3 GHz. A bandwidth of 60 MHz for operating frequency of 2.53 GHz and the continuous resonance frequency agility of 530 MHz are observed.

A liquid crystal holographic antenna cylindrically fed through a slot array [181–183] is invented.

Parametric study to optimize liquid crystal patch antenna [184] is conducted by using HFSS.

3.4.2.6 Slot Antenna

The radiation pattern, return loss, power dissipation and quality factor of a microstrip T-slot antenna on liquid crystal substrate for X-band radar [185] is simulated using CONCERTO. The compact rectangular patch is $23.65 \times 2.7 \text{ mm}^2$.

3.4.2.7 Spiral Antenna

A two-arm Archimedean spiral antenna on a liquid crystal Jerusalem high impedance surface ground for monopulse radar application [186] is simulated by using CST.

3.4.3 Antenna Arrays

3.4.3.1 Dipole Antenna

Offset fed printed dipole antenna 2-element, 4-element, and 8-element arrays on liquid crystal polymer material [187] are simulated by using HFSS. The measured impedance bandwidth ($S_{11} < -10 \text{ dB}$) of an 8-element prototype is 15.7 GHz from 24.7 to 40.4 GHz.

A two-element array of collinear printed dipoles with T-shaped defected ground structure for automotive communications [188] is simulated and measured from 20 to 55 GHz. The MIMO antenna operates in two millimeter wave bands, 24.6–42.1 and 50.1–52.5 GHz.

3.4.3.2 Horn Antenna Array

A demonstrative 4×4 horn antenna array with liquid crystal phase shifters for inter-satellite link using a geostationary satellite is simulated [189] and experimentally characterized [66].

3.4.3.3 Patch Antennas

A 2×2 square patch antenna array on liquid crystal substrate [169] is invented to steer beam.

A 2×1 microstrip patch array with liquid crystal loaded coplanar waveguide phase shifter with floating electrode [190] is developed and measured.

A 24 GHz 2×2 microstrip square patch array on liquid crystal (K15) substrate [191] is simulated.

A 4×4 liquid crystal patch array [192] is simulated by using CST. The resonant frequency can be tuned between 9 and 9.38 GHz.

A bandpass filter or frequency selective surface consisting of periodically patterned capacitive and inductive layers in liquid crystal polymer [193, 194] is simulated by using HFSS and measured between 50 and 70 GHz.

A 2×1 mm wave microstrip patch antenna array with sandwich liquid crystal phase shifter [195] is investigated.

A compact liquid crystal planar patch antenna array with meander phase shifters [196] is designed and measured from 11.5 to 13.5 GHz.

A Ka-band liquid crystal (GT3-23001) 10×1 linear array operating from 25.3 to 33.8 GHz [197] is simulated by using CST. Each array element consists of two stacked patches and aperture coupled feeding.

3.4.3.4 Phased Array

Ku and Ka 4×4 liquid crystal reconfigurable phased patch arrays [198] are presented. Meander inverted microstrip line phase shifters, ring resonator phase shifters, and coplanar waveguide phase shifters are compared.

A one dimensional 4×4 phased patch antenna array with four integrated LC phase shifters [199] is built.

A 4×1 slotted patch phased antenna array with reflection-type phase shifter [200–202] is simulated from 50 to 70 GHz. It is capable of scanning up to 27° .

A 1×4 phased microstrip patch array with inverted microstrip line phase shifter on liquid crystal [203–205] is simulated by using CST and measured.

A 39 GHz 4×4 phased array of multilayered metamaterial lens [206] is simulated by using HFSS from 30 to 47 GHz. Each lens consists of a 12×12 array of liquid crystal-loaded time delay unit.

Liquid crystal (GT3-23001) covered infinite waveguide-fed phased-array [207] is analyzed by both modal analysis and commercial softwares (CST and HFSS).

Liquid crystal phased arrays [208] for 5G by ALCAN are reviewed.

A one-dimensional liquid crystal holographic coding phased array [209] is simulated and measured between 11.5 and 13.5 GHz.

3.4.3.5 Reflectarrays

Liquid crystal is used to obtain the necessary phase shift at each reflectarray unit cell so that the beam of the X-band reflectarray [48, 52, 210–214] can be electrically steered. The idea is also demonstrated feasible at 35 [50, 198, 215–223] and 77 GHz [50, 224–226]. Liquid crystal (Merck BL006) is used to electronically switch the

patterns of a 12×12 printed monopulse reflectarray antenna from a sum radiation pattern to a difference one at X-band [171, 227]. CST simulation and measurement [228, 229] of reconfigurable millimeter wave reflectarrays with nematic liquid crystal at center frequencies of 102 and 130 GHz have been carried out.

A Ka band liquid crystal reflectarray with rectangular microstrip patch elements [230] has been developed after a comparative investigation on the tunable phase ranges and loss of square and rectangular elements.

A 16×16 reconfigurable liquid crystal (LC-C1) reflectarray with inverted microstrip three-finger patch element extended tunable phase range [231, 232] is investigated around 77 GHz.

A beam reconfigurable millimeter wave and terahertz reflectarray antenna [233] is invented. Its phase shifter cells consist of several stacked layers of conductive elements on a dielectric substrate alternated with layers of liquid crystal and a conductive plane.

A 77 GHz folded reflectarray [234] is proposed. A phase shifting polarization grid with liquid crystal unit cells offers beam reconfigurability.

Effect of inhomogeneity and anisotropy of liquid crystal on reconfigurable rectangular patch reflectarray [235] is analyzed from 90 to 110 GHz.

A liquid crystal multi-resonant unit cell of three dipoles for reconfigurable reflectarrays [236] is proposed and compared with a single-resonant one. Bandwidth, range of phase and losses are significantly improved from 30 to 40 GHz. Similar F-band reconfigurable reflectarrays are proposed [237–239]. However, uneven orientation, edge effect and increased saturation voltage arise due to insufficient coverage of liquid crystal. As such, a phase shifter with three slots [240] is simulated from 340 to 420 GHz. The corresponding reflectarray is simulated at 380 GHz. Furthermore, a grating electrode is introduced to have better reflection performance and more flexible control of biased voltage [241, 242]. More recently, dual frequency liquid crystal mixtures [243] are applied to improve temporal response of millimeter wave (75–105 GHz) reflectarray.

Dynamic phase range and frequency tunability of liquid crystal X-band patch reflectarray and slot-embedded patch reflectarray [244] are analyzed.

Liquid crystal rectangular patch with embedded circular slot has been identified superior element for tunable X-band reflectarray over regular rectangular patch and rectangular patch with rectangular slot [245].

A liquid crystal folded reflectarray [246] is proposed for reconfigurable, high-gain, low-profile, and low-cost antennas.

An electronically scanned reflectarray antenna at 100 GHz using multiresonant cells based on liquid crystals [247] is designed and measured.

Slot embedded two-patch element for X-band liquid crystal (K15) reflectarray [248] is simulated by using HFSS and measured from 9 and 11 GHz.

Reflectarrays with double dipole phase shifters [43, 69, 249–254] are simulated by using CST and measured. Likewise, a grating electrode is introduced [255].

A 20×20 liquid crystal patch reflectarray with a center operational frequency 108 GHz [256–258] is simulated by using CST from 100 to 120 GHz. The binary phase distribution is optimized by using genetic algorithm.

Liquid crystal reflectarray with slot embedded patch element is comparatively studied again PIN one [259] at X-band through CST and HFSS simulations and measurement.

A 26-row [260] reflectarray with parallel H-shaped metal and liquid crystal in between is simulated and measured from 18 to 24 GHz.

A 10×10 liquid crystal dual-polarized reflectarray capable of 2D beam scanning [261] is simulated by using CST and measured from 26 to 30 GHz. The thin layer of liquid crystal is sandwiched by patterned ground and electrode. The unit cell of the ground pattern is a square patch with two pairs of rectangular slots while the unit cell of the electrode includes a cross, a radial stub, thin bias line and dummy bias lines.

3.4.3.6 Slot Antenna

A 30 GHz 4×4 phased slot array [262] is designed and measured. The slots also act as containers of liquid crystal.

A radiation pattern reconfigurable 18-element liquid crystal waveguide slot array antenna with complementary electric-field-coupled resonators [263] is simulated by CST and measured.

3.4.3.7 Vivaldi Antenna Array

A Ka-band 4×4 Vivaldi antenna array [264] is proposed and simulated by using CST. Anisotropic liquid crystal makes it electronically steerable.

Integrating liquid crystal (K15) finline phase shifter into an antipodal Vivaldi antenna array for W-Band applications makes it reconfigurable [265, 266]. High performance liquid crystal (GT3-23001) offers higher differential phase shift [267].

3.4.3.8 Spiral Antenna

A wearable antenna of a single-armed Archimedean spiral coil on liquid crystal substrate with grid electrodes [268] is simulated by using HFSS. The antenna operates from 3.3 to 3.8 GHz.

3.4.4 Capacitor

A liquid crystal tunable capacitor [269] on glass substrates with gold fractal conductive structures and liquid crystal (E7) in the gaps between fractal fingers was designed and characterized. Bias-dependent $C-V$ and $Q-V$ characteristics in a wide frequency range are experimentally confirmed.

A set of fast switching parallel plate liquid crystal varactors [270, 271] has been designed, fabricated and characterized. The tunability of a liquid crystal parallel plate capacitor [52] on alumina substrate was tested. The liquid crystal parallel plate capacitor is also implemented to characterize liquid crystal [272] or develop a phase shifter [54].

A liquid crystal varactor is formed by overlapping fingers [273–275]. It is then applied to developed tunable coupled lines and ultimately implemented in reconfigurable antenna systems.

A voltage tunable interdigital capacitor loaded with liquid crystal (TUD-649) for a Ka-band composite right/left-handed leaky-wave antenna [152] is proposed and measured.

3.4.5 Filter

3.4.5.1 Bandpass Filter

A tunable stub filter and an improved one based on dual-behavior resonator topology [165, 276] are studied.

A THz Lyot filter of continuously tunable central passband frequency from 0.388 to 0.564 THz [45, 277–279] was developed. The filter has two groups of phase shifters separated by a linear polarizer. In each group, one phase shifter is fixed and the other one is tunable.

An effective narrow-band filter at terahertz frequencies [280] has been constructed. The filter is a Fabry–Perot etalon filled with liquid crystal (Merck E7 or ZLI 2293).

A fully electrically tunable THz filter of Fabry–Pérot cavity filled with dual-frequency switching liquid crystal [281] is constructed. The dual-frequency switching liquid crystal is embedded between the top and bottom fused silica substrates with two metallic comb patterns.

A glass-liquid crystal-glass sandwich bandpass filter having a center frequency of 20 GHz [282] is designed. The center frequency can be tuned by ~ 2 GHz.

A millimeter wave (33 GHz) parallel-coupled microstrip lines bandpass filter on liquid crystal (E7) substrate [283] is presented. The bandwidth is 3.3 GHz and the tunable range is 2 GHz.

A liquid crystal rectangular waveguide bandpass filter for space applications [284] has been demonstrated.

A microstrip square patch dual-mode bandpass filter [57, 285] is proposed. The central frequency can be tuned from 4.54 to 5.19 GHz. Pass-band return loss is improved through patch reshaping [286].

A K-band high quality factor bandpass filter [287] is demonstrated. A rectangular copper waveguide encloses a Rexolite 1422 cavity containing liquid crystal.

High-quality factor liquid crystal substrate integrated waveguide bandpass three-pole Chebyshev filters [288, 289] are proposed.

An inverted microstrip meander loop resonator with two open-circuited stubs is implemented to design a compact liquid crystal dual-mode bandpass filter [290]. The proposed filter operates at 4.7 GHz with about 41% fractional bandwidth (1.94 GHz).

Nematic liquid crystal bandpass filters [291, 292] with different inverted microstrip line resonators are simulated by using HFSS and measured.

A miniaturized nematic liquid crystal (SL-9023) inverted microstrip dual-mode bandpass microwave (2–6 GHz) filter [293] has been designed, manufactured and characterized.

A compact liquid crystal filter with ultrawide and sharp stopbands based on wave interference technique [294] is designed and experimentally validated. The centre rejection frequency can be tuned between 4.434 and 4.814 GHz.

Nematic liquid crystal (LC1917) half-wavelength inverted microstrip open-stub bandpass filters with passband central frequencies of 30, 50, and 85 GHz [295] are simulated by using CST and measured.

A compact microwave liquid crystal band-pass filter with a cross dual-mode resonator and two folded matching transmission lines [296] is simulated by using HFSS and measured from 2.5 and 7 GHz. The tunable range of the center frequency is 770 MHz offset.

A liquid crystal nonradiative dielectric waveguide bandpass filter [297] is simulated by using CST and measured from 57 to 63 GHz. A parasitic mode suppressing electrode network is designed to electrically bias the liquid crystal.

Periodic filters with periodic microstrip stubs on liquid crystal substrate [298] are simulated by using ADS. One of the filters performs at 60 GHz with 3.5 GHz bandwidth.

3.4.5.2 Filtenna

A liquid crystal filtenna [299], namely, a device integrating a substrate integrated waveguide bandpass filter and a microstrip patch antenna, is simulated by HFSS and measure from 1.5 to 2.5 GHz.

3.4.5.3 Band Stop

A Bragg structure filled with liquid crystal (7CB) based electrically for THz waves [300] works as tunable stop-band filter as well as mirror around 300 GHz.

Inverted microstrip line liquid crystal (Military University of Technology in Warsaw 1825) band stop filters [301] are designed and measured from 1 to 4 GHz.

Liquid crystal (Military University of Technology) inverted spurline notch filters [57, 302, 303] are designed and characterized. The rejection frequency can be tuned from 3.40 to 3.75 GHz by using 1631E or from 4.45 to 4.85 GHz by using 1631F.

A compact liquid crystal double-stub bending structure bandstop filter [304] is designed. It exhibits high tunability, wide stopband bandwidth but requires low driving voltage.

A C-band liquid crystal inverted microstrip filter with dual-mode resonator [305] has been simulated by using HFSS and measured from 4 to 8 GHz.

Nematic liquid crystal filters with double-spurline embedded into an inverted microstrip [306] are simulated by using finite difference time domain solver in CST. The 50 GHz central notch frequency filter is measured from 30 to 70 GHz while the 85 GHz one is measured between 60 and 110 GHz.

3.4.6 *Lens*

The focusing properties at 94 GHz of a stacked-layered liquid crystal lens [307, 308] is numerically and experimentally studied.

A thin and low loss 70 GHz liquid crystal Fresnel lens with rolling up electrodes [309] is investigated.

A millimeter wave Fresnel lens based on polymer-dispersed liquid crystal [195, 310, 311] is constructed and measured.

An active terahertz liquid crystal spin-selected lens [312] is simulated by using Lumerical FDTD Solutions and measured from 0.8 to 1.2 THz.

3.4.7 *Metamaterials*

A number of focused or related reviews on metamaterials [313–320] have been published.

Liquid crystal metamaterials typically implement metal-liquid crystal-metal configuration. One or both metal electrodes are geometrically patterned.

3.4.7.1 *Composite Material*

A terahertz metamaterial [321] is devised by randomly dispersing coated core-shell nanospheres in a nematic liquid crystal. By appropriately choosing liquid crystal host and materials for the core and shell, the effective refractive index can vary from negative to positive values in the optical as well as terahertz and microwave ranges.

A two-dimensional array of cubic dielectric resonator in liquid crystal (5CB) [322] is simulated by using FETD in CST from 1 to 100 THz. High refractive index Tellurium is comparatively studied with Ge and Si.

3.4.7.2 Electric Ring Resonator Array

A liquid crystal metamaterial with complimentary electric-LC resonator array [323] is implemented to enable reconfigurability for a passive antenna array.

A tunable frequency selective surface based on electric-LC resonator [324] is synthesized by using equivalent circuit model and simulated by using CST. The gap of the interdigital capacitor is filled with liquid crystal for tunability between 4.60 and 4.97 GHz.

3.4.7.3 Fishnet Array

A negative refractive index fishnet metamaterial [325] is measured from 0.4 to 1 THz. Two arrays of gold fishnet sandwich the polymer dispersed liquid crystal.

Ka-band (25–28 GHz) and millimeter wave (300–330 GHz) liquid crystal metamaterials with gradient-index fishnet array [326, 327] have been simulated by using CST. A Ka-band prototype with two 8×8 fishnet arrays sandwich liquid crystal is also measured from at 27.5 GHz.

Metamaterials with two fishnet arrays and nematic liquid crystal in between is simulated by using COMSOL from 0.7 THz to 1.3 THz [328] or from 70 to 130 GHz [329].

3.4.7.4 Grating

A pair of grating-patterned electrodes is proposed to enhance the propagation of millimeter wave through liquid crystal which is embedded in the electrodes [330]. Measurement is conducted at 50 GHz.

A magnetically tunable phase grating [331, 332] is designed to manipulate terahertz wave from 0.2 to 0.8 THz. The binary grating made of alternating fused silica and nematic liquid crystal (Merck E7) has been experimentally investigated feasible as a polarizing beam splitter. Additional metal hole array may further filter the broadband terahertz signal. Terahertz electrically tunable binary phase gratings of alternating fused silica and nematic liquid crystal (MDA-00-3461) ([333], chapter 10) are also simulated by using finite difference time domain (FDTD) and experimentally studied.

A nematic liquid crystal (Merck E7) is filled in the gaps of a grating comprised of thick aluminum slats to form a microwave liquid crystal wavelength selector [334, 335]. A set of resonant transmission frequencies is recorded for microwaves incident on this structure with their electric field perpendicular to the slats. The resonant frequencies can be sensitively controlled by a voltage applied between adjacent pairs of slats causes the liquid crystal. A more complicated control strategy [336, 337] enables flexible adjustment of the zero-order transmission intensity for any chosen wavelength from a maximum to zero. Interestingly, similar resonant transmission

spectra can be obtained by using a single metallic slit filled with nematic liquid crystal (Merck E7) [337–339].

Coincidentally, the same configuration was numerically and experimentally studied by Tanaka and Sato slightly earlier [340]. The metal (brass), liquid crystal (E44) and frequency bands (47–53 and 86–94 GHz) are different but the observations and conclusions are not significantly different. Furthermore, similar configuration was found functional as beam former and lens [341–344].

A liquid crystal terahertz switch [345] is proposed. Two metallic gratings sandwich the liquid crystal layer which offers electrical tunability.

A terahertz Fabry–Perot-like metamaterial for multi-band linear polarization conversion [346] is simulated by using CST and measured from 0.2 to 1.6 THz. Two orthogonally arranged sub-wavelength metal gratings on silica substrate sandwich liquid crystal (5CB).

3.4.7.5 Metal Hole Array

Filling nematic liquid crystal (5CB) in metallic hole arrays can lower terahertz transmission frequency [278, 347]. The lowered peak transmission frequency can be further tuned magnetically.

A liquid crystal modulator [348] is simulated by using finite difference time domain (FDTD). Two metal hole arrays on quartz substrate sandwich liquid crystal (GT3-23001). A frequency selective surface of a single metal hole array [349, 350] is also simulated by using finite difference time domain (FDTD) and measured from 90 to 140 GHz. Liquid crystal (S200-2 and E7-2) is sandwiched between the metal hole array and the ground plane.

A metasurface with a star metal hole pattern, an interdigital electrode and liquid crystal (HFUT-HB01) in between [351] is simulated and measured from 90 to 140 GHz.

3.4.7.6 Patch Array

A reconfigurable intelligent surface with liquid crystal (Merck GT3-23001) sandwiched by two patch arrays together with a wire grid electrode [352, 353] is simulated by using HFSS from 35 to 45 GHz.

A millimeter-wave nematic liquid crystal 4-bit digital metasurface [354] with square patch array is simulated from 26 to 40 GHz and measured at 32.5 GHz.

A polarization selective liquid crystal metasurface [355] is simulated by using CST and measured from 7 to 14 GHz. The liquid crystal (LT-8750) is sandwiched by two misaligned opposite metal arrays. Each unit cell of the arrays includes two identical rectangular patches. Each patch is connected with a meandered strip.

A direction-variable liquid crystal meta-surface reflector [356, 357] is simulated by using finite difference time domain (FDTD) and measured in anechoic chamber

at 28 GHz. Liquid crystal is sandwiched by an array of patch electrodes and the ground.

3.4.7.7 Slot Array

A V-band frequency selective surface [358] consisting of two slot arrays separated by liquid crystal is presented. The tunable FSS can be switched between transmitting and reflecting structures.

3.4.7.8 Jerusalem Cross Array

A number of tunable micron-scale metallodielectric and all-dielectric frequency selective surfaces based on nematic liquid crystals [359] have been proposed for terahertz application. Nematic liquid crystal serves as superstrate of arrays of Jerusalem cross, Minkowski fractal element, pixelized element synthesized using a genetic algorithm, and square a-Si blocks.

A terahertz liquid crystal programmable metasurface [360] is proposed and measured from 600 to 750 GHz. Each element of the 50×24 metasurface has two identical unit cells. The metal-liquid crystal-metal configuration is implemented in each unit cell. Both the top and bottom metals are Jerusalem cross.

3.4.7.9 Split Ring Resonator Array

Nematic liquid crystal is used to electrically tune negative permeability metamaterial of split ring resonator arrays [359, 361]. Liquid crystal infiltration lowers the resonant frequency and accordingly the negative permeability zone. Furthermore, the resonant frequency monotonically decreases as the bias DC electric field increases.

A magnetically tunable negative permeability metamaterial consisting of two split ring resonator arrays of C-type metal strips printed on teflon fiberglass slabs [362, 363] is designed for X-band operation. The back to back arrays are separated by a nematic liquid crystal.

A liquid crystal metamaterial material with an array of back-to-back Ω -shaped strips [364] is simulated by using QuickWave. Nematic liquid crystal between two Teflon fiberglass slabs serves as substrate for the metal patterns.

Liquid crystal metamaterials with a split ring resonator array [365] are designed and measured from 0.3 to 0.9 THz. The resonant transmittance decreases with increasing voltages while its resonant frequency remains at the same value.

A liquid crystal metamaterial with an array of split ring resonators having suspended conducting cantilevers in the gap region [366] is simulated by using CST and measured from 0.8 to 1.8 THz.

A metal-dielectric-metal structure [367, 368] is simulated by using finite difference time domain (FDTD) and measured from 220 to 330 GHz. Both metal plates

on quartz are patterned 33×33 array of split circular air loops while the sandwiched dielectric is nematic liquid crystal. Another 46×46 array [369] is simulated by using CST and measured from 330 to 500 GHz.

A spatial phase modulator with liquid crystal sandwiched by two orthogonal identical arrays of meandering wires [370] is simulated by using COMSOL and measured from 0.6 to 1.2 THz.

A metal-liquid crystal-metal metamaterial [371] is simulated by using finite difference time domain from 220 to 330 GHz. Each split ring resonator-like metal element has four trapezoidal designed slots.

An optically tunable terahertz metamaterial with liquid crystal sandwiched by two polyethylene terephthalate (PET) substrates [372] is simulated by using finite difference time domain (FDTD) and measured from 0.3 to 1 THz. The bottom PET substrate is patterned an array of split ring resonators.

A terahertz metallic back plate-liquid crystal-complementary split ring resonator programmable metasurface [373] is simulated by using CST and experimentally demonstrated from 0.4 to 0.8 THz.

The anomalous frequency tunability in terahertz liquid crystal metamaterials of D-shaped metamolecule and that of Babinet complementary pattern [374] is investigated.

A C-shape-split-ring-based phase discontinuity metasurface on liquid crystal elastomer substrate [375] is simulated by using CST and measured from 0.4 to 1.4 THz. Interesting, it is tuned through mechanical deformation induced by line-focused infrared light or heating.

3.4.7.10 Wire Array

A tunable microwave metamaterial with negative permeability [376] has been demonstrated. The unit cell contains a pair of short wires printed on Teflon fiberglass slabs and separated by liquid crystal (TEB30A).

3.4.8 Modulator

3.4.8.1 Amplitude Modulator

A low temperature co-fired ceramic amplitude tuner with a liquid crystal stripline phase shifter [289] is simulated by using CST and measured from 20 to 40 GHz. Attenuation is tunable between 11 and 30 dB at 30 GHz.

Liquid crystal terahertz metadevices with arrays of dual-ring resonators [377] or two-gap asymmetric split rings [378] are simulated by using Lumerical FDTD Solutions and measured. The terahertz metadevices exhibit distinguishing functions for transmitted and reflected waves.

3.4.8.2 Amplitude and Phase Modulator

Polymer dispersed liquid crystal is used to modulate the amplitude of optically generated RF-signals [379]. A continuously adjustable polarization independent 360° phase shifter is then formed by weighted superposition of the modulated RF signals with fixed phase relation. Amplitude and phase can be independently adjusted. The same idea was applied to steer a 1×2 microstrip phased array patch antenna [380].

3×3 and 5×5 terahertz liquid crystal spatial light modulators with indium tin oxide or gold finger type patterns for imaging application [381] are designed and measured by THz time domain spectroscopy system. The phase shift and amplitude modulation achieved are $> 90^\circ$ and 30% from 0.08 to 0.3 THz.

3.4.9 Phase Shifters

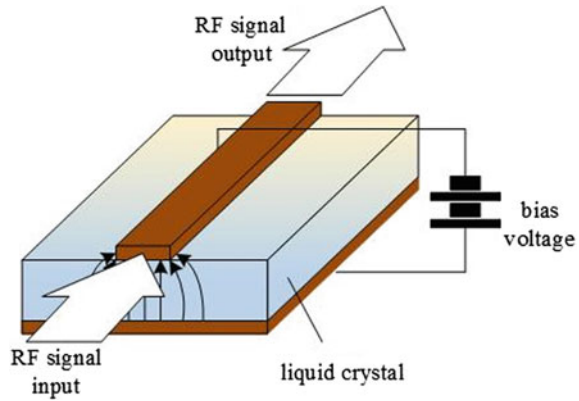
Phase shifters [60, 382] are the hard core for phased antenna arrays to direct electromagnetic beams without mechanical movement. Ideal phase shifters provide low insertion loss, high power handling, instantaneous phase change response, and approximately equal loss in all phase states.

Along with cutting-edge microwave, millimeter wave and terahertz applications such as high-data-rate wireless communications, high-precision automotive radars and hand-gesture sensing, it has become harder and harder for conventional technology of variable phase shifters to meet more and more stringent requirements in wavefront phase control and device performance. Ferrite phase shifters are lumpish and slow to respond to control signals that they cannot be used in applications where rapid beam scanning is required. MMIC phase shifters can be quite expensive and the power handling is limited to 10 milliwatts or so. The binary nature of MEMS (micro-electro-mechanical systems) and solid-state PIN diodes limit their resolution and thereby degrades the beam-scanning performance. In addition, MEMS phase shifters have high losses at microwave and higher frequencies and limited power-handling capability and may need expensive packaging to protect the movable MEMS bridges against the environment. The increased dielectric loss beyond 10 GHz of ferroelectric barium strontium titanate (BST) and ferromagnetic yttrium iron garnet (YIG) thin film phase shifters impedes their implementation for higher frequency applications. Other undesirable phase shifters include the quantum well based terahertz phase shifters. High performance low cost phase shifters are desiderated.

Liquid crystal phase shifters ([383–385], chapter 3) are anticipated to be the white hope to overcome all the aforementioned limitations. Our incomplete preliminary literature survey reveals that liquid crystal phase shifters are probably the most studied application at microwave, millimeter wave and terahertz frequencies. About 200 publications deal with liquid crystal phase shifters.

Generally, as shown in Fig. 3.9, liquid crystal phase shifters at microwave, millimeter wave and terahertz frequencies make use of liquid crystal birefringence and take advantage of its phase modulation effect [97–100]. Liquid crystal either

Fig. 3.9 Generic liquid crystal phase shifter



serves as substrate for the entire phase shifter or resides beneath the patterned conductors. The conducting pattern and the entire device may present different topologies. Adjusting the external stimulus alters the phase velocity of the propagating wave, varying the electrical length and the characteristic impedance of the wave guiding structure, and therefore the phase shift.

3.4.9.1 Coplanar Waveguide

Electrically tunable top grounded coplanar waveguide (or enclosed coplanar waveguide) phase shifters [386–390] are presented. A large-birefringence nematic liquid crystal improves the phase shifter [391].

A demonstrative millimeter wave coplanar waveguide phase shifter [392, 393] is presented. Effect of liquid crystals (K15, E44, and ZLI 4792) on phase shift is compared. A numerical study on the operation principle [394] is further conducted.

Two ferroelectric liquid crystal coplanar waveguide phase shifters [395, 396] with different configurations of electrodes are compared. The measured phase shift is larger when dc voltage is applied to two electrodes on the bottom sides of the upper and lower PTFE substrates.

Fast phase shifters are developed by using coplanar waveguide with electrode floating on standard nematic liquid crystal (BL006) [190, 397–399] or ferroelectric liquid crystal (AZ Electronic Materials FELIX-015/000) [400, 401].

A triangular upper electrode is proposed to improve the phase-shifting performance of a coplanar waveguide millimeter wave liquid crystal (5CB) phase shifter [402].

A tunable microwave liquid crystal phase shifter based on periodically loaded coplanar waveguide [403] is presented.

Coplanar waveguide phase shifters have been tested for feasibility in Ku and Ka 4×4 liquid crystal reconfigurable phased patch arrays [198].

A W-band loaded line phase shifter [404, 405] is developed based on liquid crystals and MEMS technology. The coplanar waveguide is loaded by varactors with liquid crystal as a tunable dielectric layer underneath gold bridges.

A coplanar waveguide liquid crystal phase shifter [389] is simulated at 5, 11, and 18 GHz.

A simple coplanar liquid crystal (5CB) reconfigurable phase-shifter [406] is characterized from 5 to 40 GHz.

A top grounded coplanar waveguide phase shifter on liquid crystal (E7 and MDA-00-3506) substrate [407] is investigated from 30 to 60 GHz. The measurements show advantage of MDA-00-3506 against E7.

A millimeter wave (up to 45 GHz) liquid crystal slow-wave coplanar waveguide phase shifter [408] is proposed.

Polymer stabilization by UV light irradiation is proposed to improve the decay time of nematic liquid crystals (BL006) coplanar waveguide microwave (up to 30 GHz) phase shifters [409].

Effect of bias voltage and position on a liquid crystal coplanar waveguide phase shifter is simulated by using HFSS from 10 to 50 GHz [410].

3.4.9.2 Dielectric Waveguide

A liquid crystal dielectric waveguide phase shifter [411] is simulated by using CST and measured from 75 to 110 GHz.

A V-band liquid crystal parallel-plate dielectric waveguide phase shifter [412] is simulated by using CST and measured from 50 to 75 GHz.

Terahertz nematic liquid crystal non-radiative dielectric (NRD) waveguide phase shifter [413, 414] is measured at 350 GHz. Effect of liquid crystal thickness and polyethylene terephthalate film on phase shift and decay time is studied.

A liquid crystal non-radiative dielectric (NRD) waveguide phase shifter [415] is simulated by using HFSS from 80 to 150 GHz.

3.4.9.3 Fiber

A liquid crystal fiber phase shifter for a 100 GHz radiometer single-pole double-throw RF switch [416] is simulated by using CST and measured from 90 to 110 GHz.

3.4.9.4 Finline

The phase shifting performance of K15 and MDA-03-2838 at 40 GHz is experimentally compared by using a finline based phase shifter [265, 417]. MDA-03-2838 outperforms K15 in terms of phase shift and insertion loss but responds more slowly.

A W-band liquid crystal (K15) antipodal finline phase shifter [418] is developed for reconfigurable broadband Vivaldi antenna array.

3.4.9.5 Grating

A terahertz phase shifter with high birefringence liquid crystal (E7) sandwiched by two parallel fused silica slides covered by sub-wavelength Au gratings [419] is developed. A variant [420, 421] is further developed by replacing one of the gratings by graphene.

A terahertz phase shifter based on sub-wavelength dielectric gradient grating filled with polymer dispersed liquid crystal [422] is simulated by using CST and measured from 0.2 to 1.1 THz.

3.4.9.6 Grid

A U-band liquid crystal grid phase shifter [423] is proposed. Liquid crystal (K15 or BL006) is sandwiched by an inductive grid and a complementary capacitive grid.

3.4.9.7 Groove Gap Waveguide

A millimeter wave liquid crystal phase shifter based on groove gap waveguide [424] is proposed for a monopulse antenna.

3.4.9.8 Inverted Microstrip

Tunable inverted microstrip phase shifters using nematic liquid crystal K15 [156, 226, 387, 389, 425–428] are designed. The phase shift performance can be improved by either modified topologies of periodic lines [54, 168, 389, 429, 430], periodic slot lines [431], periodic polygonal bridges [432], and continuously varying transmission line [168], or novel mixtures [165, 221, 432–435].

Meander inverted microstrip line phase shifters have been tested for feasibility in Ku and Ka 4×4 liquid crystal reconfigurable phased patch arrays [198].

The third order intercept point IP3 at microwave frequencies of an inverted microstrip line phase shifter with 5 CB or MDA-03-2844 [221, 436] is measured. The phase shifter is highly linear.

Ferroelectric liquid crystal and standard liquid crystal 5CB are compared according to the measured phase shifting performance of inverted microstrip phase shifters [437]. Ferroelectric liquid crystal responds more quickly but is weaker in tenability.

An inverted Meander line millimetre-wave liquid crystal phase shifter [438] is presented. Two liquid crystal materials (E7 and MDA-00-3506) are tested.

An inverted microstrip line phase shifter with through hole [439] is analyzed by using finite difference time domain method.

A millimeter wave inverted microstrip liquid crystal phase shifter [440] is demonstrated to have a tunable 300° cm phase shift at 110 GHz.

A microwave inverted microstrip liquid crystal phase shifter [441] is simulated by using FDTD up to 30 GHz. The high-frequency performance is further improved by employing a novel large birefringence liquid crystal and an optimized design [442–444].

A 75 mm long liquid crystal meander delay line is measured as an alternate of a spiral delay line [445–447] from 10 to 20 GHz. The spiral delay line is then implemented to develop a 2-D electronically steered phased microstrip patch antenna array.

Liquid crystal inverted microstrip meander delay lines [448] are implemented to develop a 2×2 dual-fed polarization agile microstrip patch antenna array. The antenna prototype is designed at 13.75 GHz and measured from 12 to 16 GHz.

A folded inverted microstrip line phase shifter on highly anisotropic liquid crystal substrate [449] has been designed and measured up to 6 GHz.

Liquid crystal meander inverted microstrip line phase shifters [450, 451] are implemented to construct a 1×4 phased dielectric resonator antenna array. Comparison with a 1×4 microstrip patch antenna array is done at 10 GHz.

Negative dielectric anisotropic liquid crystal is introduced to develop a millimeter wave inverted microstrip line phase shifter [452].

An liquid crystal inverted microstrip meander line phase shifter [453] is simulated by using HFF up to 10 GHz.

A compact high figure-of-merit liquid crystal meander inverted microstrip line phase shifter [454] is proposed.

3.4.9.9 Opposed Coplanar Waveguide

Liquid crystal phase shifter based on opposed coplanar waveguide (OCPW) [455] is simulated by using HFSS and measured from 9 to 16 GHz.

3.4.9.10 Photonic Bandgap Fiber

Microwave true-time delay through a compact liquid–crystal photonic-band-gap-fiber is demonstrated [456, 457].

3.4.9.11 Rectangular Waveguide

Rectangular copper waveguide phase shifters with Rexolite 1422 cavity containing liquid crystal [66, 287, 447, 458–462] are implemented in a proof-of-concept 4×4 electronic steerable Ka-band horn antenna array and a 16×16 phased horn antenna array with two distribution networks. A similar 250 GHz liquid crystal phase shifter [463] is also simulated.

A liquid crystal rectangular waveguide phase shifter [199] is fabricated in LTCC technology.

Four rectangular waveguide liquid crystal phase shifters are integrated into a LTCC antenna array for satellite communication at 30 GHz [464].

Low-loss W-band (80–110 GHz) rectangular waveguide phase shifters enclosing a PTFE cavity containing liquid crystal (TUD-126) are proposed. The permanent magnet-biased phase shifter [465] exhibits a differential phase shift of 307° – 318° and an insertion loss of 2.1–2.7 dB between 99 and 105 GHz while the differential phase shift and the insertion loss of the electrically biased one from 96 to 104 GHz [466] are 364° – 384° and < 3.3 dB.

3.4.9.12 Ridged Waveguide

A W-Band ridged waveguide phase shifter [467] is presented. Liquid crystal (K15, MDA-03-2844, or MDA-05-1132) between the lower waveguide wall and the ridge makes it tunable.

An optical true time delay device for millimeter wave antenna array [67, 468–470] is designed by incorporating an anisotropic liquid crystal cladding layer into the ridge waveguide to control group delay in three coupled periodic silicon ridge waveguides.

A liquid crystal ridge gap waveguide phase shifter [471] is simulated by using CST and measured from 20 to 30 GHz.

3.4.9.13 Ring Resonator

Dual-mode ring resonator phase shifters have been tested for feasibility in Ku and Ka 4×4 liquid crystal reconfigurable phased patch arrays [198, 472, 473].

3.4.9.14 Sandwich

A room temperature terahertz phase shifter [278, 279, 474, 475] with nematic liquid crystal (Merck 5CB) sandwiched between fused silica plates magnetically controlled by a rotary magnet demonstrated a maximum phase shift of 141° at 1.025 THz. Larger tunable phase can be achieved by different liquid crystal (E7) [278, 476], thicker liquid crystal [477], or electrical control [478]. A pair of permanent magnets can also be used to sandwich the liquid crystal to develop phase shifters [279, 479].

Room temperature phase shifters/retarders of phase shift over 2π at 1 THz using magnetically controlled 5CB and E7 [45] have been developed. Phase shift exceeding $\pi/2$ at 1 THz can be achieved by electrically tuning E7 sandwiched between fused silica plates [480].

A terahertz (500 GHz and 1 THz) liquid crystal (BL111) phase shifter with a grid electrode [481] makes it fully electrically controllable and reduces its mechanical complexity.

An electrically controlled terahertz phase shifter [482] with nematic liquid crystal (Merck E7) sandwiched between fused silica plates is developed. It is implemented to devise a liquid crystal Solc filter whose central pass band frequency can be tuned from 0.717 to 1.142 THz.

A terahertz (up to 2.5 THz) phase shifter with polymer stabilized liquid crystal sandwiched between two fused silica plates [483] is proposed.

Calculation by calculus of variations method shows that microwave (60 GHz) phase-shift per unit-length can be increased substantially by introducing a twisted configuration into nematic liquid crystal (E7, K15, and E44) [484, 485]. The effect of anchoring on twisted and supertwisted nematic liquid crystal is further studied [486].

Terahertz liquid crystal phase shifters with graphene electrode [487–490] are proposed. Similarly, indium-tin-oxide nanostructures [489, 491–493] and indium-tin-oxide (ITO) finger-type pattern (FTP) [485] are proposed for biasing and alignment.

Terahertz liquid crystal phase shifter with terahertz in plane and terahertz out of plane (TIP-TOP) electrodes [494–497] is invented.

DMSO-doped PEDOT:PSS thin films is proposed as transparent polymer electrodes for a liquid crystal (E7) terahertz phase shifter [498, 499].

A hydrogen-bonded liquid crystal phase shifter [500] is simulated by using the Jones matrix method and measured at 2.5 THz.

A phase shift device [501], either a phase shifter or a variable delay line, is invented. The device is formed by sandwiching liquid crystal with periodic partially overlapping signal and ground electrodes.

Dual-frequency liquid crystal (DP002-016, DP002-026 and DP022-122) terahertz wave plate [502] is experimentally investigated.

A computationally efficient closed-form integral-equation formulation [503, 504] is proposed to model the director tilting in nematic liquid crystals. A parallel plate waveguide phase shifter filled with E7 is simulated to validate it against CST.

A terahertz achromatic quarter-wave plate consisting of three magnetically controlled liquid crystal (E7) retarders [505] is measured from 0.1 to 1 THz.

Magnetically induced birefringence characteristics of ferromagnetic liquid crystal is experimentally investigated by using THz time domain spectroscopy [506].

A metal-liquid crystal-metal structure with liquid crystal sandwiched by copper comb electrodes and a slotted reflection array [507] is simulated and measured from 105 to 125 GHz.

Phase shifters with liquid crystal sandwiched by microstrip line and defective ground are implemented to develop Ka-band 1×4 Yagi-Uda antenna arrays [508, 509]. Simulation by using CST and measurement from 100 MHz to 50 GHz are presented.

3.4.9.15 Slot

An F-band liquid crystal phase shifter with a slot unit cell [510] is simulated by using finite difference time domain (FDTD). A 30×30 reflectarray is then measured from 110 to 140 GHz.

3.4.9.16 Strip

Three microstrip variable delay lines of fast response are experimentally studied against their conventional counterpart [108, 511]. The polymer-stabilized liquid crystal film [512–514], PTFE membrane impregnated with liquid crystal [106, 515] or dual-frequency switching-mode liquid crystal [52, 107] resides between the ground plane and the cover substrate over which the strip is deposited. Insertion loss of the latter can also be reduced. The setup is later used to characterize five nematic liquid crystal materials (BL006, BL011, BL048, BL005, and MLC11000-100) [516].

The strong interaction between the spontaneous polarization due to the ferroelectric liquid crystal (FLC) molecular alignment and the electric field of the control voltage is utilized to develop an electrically controlled microstrip microwave delay line [517]. The alignment of the conical axes of thick FLC (CS-2005 of Chisso Co.) molecules is stabilized by using aligned submicron diameter polymer fibers. The use of FLC may provide unique features such as low control voltage, high-speed response, and memory operation.

A phase shifter [518] with liquid crystal (Merck 5CB) sandwiched between two fused silica substrates with a gold strip on each substrate was experimentally characterized to have a maximum phase shift of 4.07° at 1.07 THz when the driving electric field 589.3 V/cm.

A phase shifter [519] and the corresponding phased antenna array are demonstrated. Liquid crystal below a microstrip line is controlled by an external electric field.

The response of a microstrip phase shifter with ferroelectric liquid crystal (W128G) [520] to a bias of triangular wave (0.1 Hz, ± 100 V) is experimentally studied at 20 GHz.

A 15 GHz MSL-type meander line phase shifter [521] is developed to demonstrate the characteristics of polymer dispersed liquid crystal.

A microstrip liquid crystal phase shifter in the centimeter and millimeter wavelength range [522] is proposed. The phase shifter simultaneously performs the function of a band-pass filter.

A liquid crystal (GT3-24002) microstrip phase shifter [523] is designed to simultaneously steer beams of a Rotman lens by up to $\pm 7.5^\circ$ from 6 to 10 GHz.

A liquid crystal meander line phase shifter [524, 525] providing a maximum differential phase shift of 38° is simulated. A 4×1 patch antenna array is subsequently designed and simulated from 50 to 70 GHz.

The phase shift of a microwave microstrip nematic liquid crystal phase shifter [526] is calculated and measured at 20 GHz. By replacing the right angled turning

features with semicircular ones, the losses induced by EM wave propagation discontinuity were reduced significantly.

Semicircular turning is proposed to reduce loss of a liquid crystal multiple-folded microstrip line phase shifter [527]. The return loss was reduced by 10 dB and the insertion loss was limited to < 10 dB in the frequency range up to 10 GHz.

A Ka-band liquid crystal stripline phase shifter embedded inside a low temperature cofired ceramic cavity [528] is designed and measured from 20 to 40 GHz.

A demonstrative microstrip meander line phase shifter [529] is presented.

A V-band liquid crystal slow wave microstrip phase shifter, either straight or meander, with a ground plane of porous alumina membrane filled with metallic nanowires, is proposed and measured [530].

3.4.9.17 Substrate Integrated Waveguide

Low-temperature co-fired ceramic (LTCC) substrate integrated waveguide has been implemented for robust packaging and integrating phase shifter [447]. Reliability of the Ka-band LTCC SIW phase shifter [531] is further studied.

3.4.9.18 Wedge

A terahertz liquid crystal wedge with two pairs of electrodes to steer beam [532] is designed and measured by using THz-TDS.

3.4.10 Polarizer

A Feussner-type terahertz polarizer [533] is demonstrated. A nematic liquid crystal layer is sandwiched by two fused-silica prisms.

Liquid crystal immersed membrane film is proposed as an effective solution for alignment and response speed degradation at terahertz frequencies. A polarization control device [534] is fabricated and measured.

A twisted nematic liquid crystal circular waveguide polarizer for continuously tuning the linear polarization of the TE₁₁ mode in the waveguide from 90° to −90° [535] is presented and experimentally verified.

A nematic liquid crystal (GT3-23001) reflection polarizer [536] has been designed, fabricated and measured between 120 and 140 GHz. The polarization of reflected wave can be electrically tuned to right hand circular (RHCP), orthogonal linear or left hand circular (LHCP) polarizations.

A terahertz liquid crystal phase and polarization controller with carbon nanotube film as both alignment layer and transparent electrodes [537] is demonstrated. The output polarization can be controlled by the bias voltage between linear polarization and circular polarization.

A metal grating-liquid crystal-metal grating Fabry–Perot-like terahertz polarization converter [538] is simulated and measured from 325 to 500 GHz.

A terahertz liquid crystal spatially varying axis plate (SVAP) [539] is designed to reshape input wavefront for BrXSiO.

3.4.11 Power Divider

A liquid crystal compact filtering power divider [540] is proposed. It features tunable sharp rejection and good isolation.

A microwave liquid crystal power divider with integrated band-pass filter [541] is simulated by using HFSS and measured.

Compact microwave liquid crystal inverted microstrip line bandpass filter integrated power divider [542] is simulated by using HFSS and measured from 4.5 to 8 GHz.

A liquid crystal power divider by using the edge slope of a low-pass filter to create a defined transmission and reflection [543] is simulated by using CST and measured from 11 to 14 GHz.

3.4.12 Prism

A liquid crystal (LC) prism [337, 544] with a stack-layered structure is prepared using wedge-shaped metal substrates and nematic LC with a positive dielectric anisotropy. The deflection angle of 3° induced by the external applied voltage is measured at 94 GHz.

3.4.13 Q-Plate

A terahertz q-plate to generate vortex beams with a large birefringence liquid crystal sandwiched by two pieces of fused silica glass [545] is proposed and demonstrated.

3.4.14 Resonator

3.4.14.1 Cavity Resonator

To characterize liquid crystal (K15 and novel mixtures), cavity resonators [221, 435, 546–549] based on rectangular waveguide perturbed by two FTFE-tubes

with or without liquid crystal filled through insertion holes are designed. External magnetostatic field is applied to orient the liquid crystal molecules.

Various cylindrical cavity resonators have been used to characterize liquid crystal [550–552].

Effect of polyimide layers is investigated by using a S-band liquid crystal (K15) square cavity resonator [553]. A high performance mixture (GT3-23001) [554] makes the frequency tunable from 2.93 to 2.70 GHz.

Two high Q Ka-band liquid crystal (GT-3) cylindrical waveguide resonators [555] have been designed. A 20 GHz 3-pole bandpass filter with a relative bandwidth of 1% is then constructed and measured. Tunability with magnetic biasing is > 450 MHz.

The microwave properties of nanoparticle-doped nematic liquid crystal materials have been characterized by using [556] cavity perturbation method.

3.4.14.2 Coaxial Resonator

A coaxial resonator [557] is used to characterize nematic liquid crystal materials (5CB and ZhK-440) filling gap between the outer and inner conductors at 1 GHz.

3.4.14.3 Coplanar Resonator

A Ka-band coplanar resonator using polymer dispersed liquid crystal [558] is designed. A half milled Radial SMA connector-open cell is proposed to polymerize liquid crystal and characterize the polymer dispersed liquid crystal.

3.4.14.4 Fabry-Pérot Resonator

A Ka-band Fabry-Pérot tunable resonator [559] has been fabricated. Two partially reflecting surfaces of metallic capacitive meshes sandwich the liquid crystal (E7).

Liquid crystal materials (5CB, 6CB, 7CB, 8CB and E7) are characterized in millimeter wave and terahertz ranges (50–80, 500, and 600 GHz) by using a Fabry-Pérot resonator [560].

3.4.14.5 Half-Wavelength Resonator

A coupled open-circuit half-wavelength microstrip resonator [52] has been proposed. The resonator is compact and convenient for fabrication but suffers undesirable radiation loss. A hairpin resonator is therefore proposed to reduce the radiation loss.

3.4.14.6 Electric-LC Resonator

Electric-LC resonators are made tunable by using liquid crystal through the central capacitive gaps [68, 561].

3.4.14.7 Patch Resonator

A circular patch resonator [562] is devised to measure permittivity of nematic liquid crystal (BI006) from 4.8 to 8.7 GHz.

A liquid crystal rectangular patch resonator [202] is analyzed by a scattering approach based on a variational form of the Helmholtz equation.

3.4.14.8 Ring Resonator

Ring resonators are designed to measure the effective dielectric permittivity of microstrip-line-type liquid crystal devices [563–566]. The inductive coupled ring resonator is also applied to measure the response time of nematic liquid crystal [567] and polymer dispersed liquid crystal [513, 568].

A liquid crystal microstrip circular ring resonator [68] are simulated by using CST and/or ADS and measured.

3.4.14.9 Interdigital Resonator

A microstrip resonant loop with liquid crystal above an interdigital capacitor is used to study the dielectric spectra of n CB and n OCB [569, 570] from 100 MHz to 1 GHz and cyano-containing liquid crystals [571] from 1 MHz to 2 GHz.

2.4 GHz liquid crystal interdigital resonators [68] are simulated by using CST and/or ADS and measured.

3.4.14.10 Plate Resonator

Discrete capacitive parallel plate resonators [572] have been designed to measure the dielectric spectra of liquid crystal (5CB) from 50 MHz to 1 GHz. Similar idea has been applied to characterize MBBA from 1 MHz to 10 GHz [573] and E7 [574] from 20 to 60 GHz.

A split post dielectric resonator is used to determine the effect of AC bias voltage on the complex permittivity of nematic liquid crystal (1825A, 2002, 2002B, and unspecified A, B, and C) up to 8 GHz [575, 576].

A substrate integrated waveguide resonator is proposed to characterize nematic liquid crystal [577] from 10 to 12 GHz.

3.4.15 *Switch*

Sub-terahertz on–off switch based on on–off switching of a sub-terahertz switch [578] is experimentally demonstrate at 91 GHz. The switch is a two-dimensional photonic crystal infiltrated with liquid crystal 5CB.

A 2D photonic crystal waveguide filled with liquid crystal (E7) and controlled by a rotary magnetic coil works as a terahertz switch and filter [579]. Effect of lattice pattern is also studied.

An interference based single-pole double-throw switch with liquid crystal waveguide phase shifters [580] is simulated by using CST and measured from 80 to 110 GHz.

A Ka-band liquid crystal single-pole double-throw (SPDT) with adjustable power splitting ratio in low temperature co-fired ceramic (LTCC) technology [581] is designed and measured between 25 and 35 GHz.

A W-band fully dielectric interference-based single-pole double-throw (SPDT) with liquid crystal phase shifters [582] is simulated by using CST and measured from 75 to 110 GHz.

3.4.16 *Transmission Line*

3.4.16.1 *Coaxial Cable*

The cut back method is used to measure the dielectric permittivity of liquid crystal (BL006, BL048, BL011, BL005 and MLC11000-100) [565] which fills the gap between the inner conductor and outer conductor of a coaxial cable. Similar idea was applied to characterize K15 within 7 and 115 °C between 360 MHz and 23 GHz [583], E7 from 1 to 50 GHz [584], and K15, GT3-23001 and TUD-566 [585] from 3.5 to 30 GHz between 10 and 60 °C. Furthermore, the effect of molecular structure of nematic liquid crystal on dielectric loss [586] is investigated.

A microwave cylindrical cavity spectrometer is applied to study nematic liquid crystal 5CB at 9 GHz [587] and 4'-n-heptyl-4-biphenyl at 20.900 and 29.867 GHz [588].

3.4.16.2 *Coplanar Waveguide*

The dielectric tensor of nematic liquid crystal supported by a coplanar waveguide [589] is numerically extracted in the 1–40 GHz frequency range from S parameters based on the Schwarz-Christoffel transformation (SCT).

A planar waveguide on liquid crystal substrate [169] is invented.

A microwave and millimeter wave coplanar waveguide test cell with a sliding short-circuit is proposed to measure extremely small amount of liquid crystal (K15) [590].

3.4.16.3 Inverted Microstrip Line

A microstrip line on liquid crystal substrate [591] is implemented to characterize liquid crystal JC-M-LC-E7 and QYPD-036 from 2 to 8 GHz.

3.4.16.4 Microstrip

A top grounded microstrip line [386] is used to measure the complex permittivity of commercial liquid crystal (Merck K15). The top ground and the microstrip line form a cavity in which the magnetically controlled liquid crystal under test is filled.

Finite element modal analysis of a sandwiched microstrip on nematic liquid crystal (E7) substrate [592] is carried out to characterize the concerned liquid crystal from 30 to 60 GHz. The numerical result agrees well with experiment result.

Tunability of liquid crystal has been studied using inverted microstrip [593, 594], double grounded slot line [593, 594], and rectangular waveguides [593–595]. Effect of transmission line parameters is considered.

The effect of thickness on liquid crystal characterization using a microstrip line on liquid crystal [596] is comparatively simulated from 30 to 70 GHz. Furthermore, a microstrip device for broadband (15–65 GHz) measurement of dielectric properties of nematic liquid crystal (MDA-00-3506 and GT3-23001) [597] is proposed.

3.4.16.5 Rectangular Waveguide

Commercially available E44, K15, and ZLI-5092 are characterized by filling them in a transmission rectangular waveguide sealed with glass windows [598]. Later, a reflective rectangular waveguide sealed with a glass window and a movable metal tip [599] is prepared to characterize E44, K15, ZLI-1083, ZLI-1132, ZLI-1565, ZLI-4752, ZLI-5092, MLC-6067, MLC-6254, MLC-6608, and MBBA.

HFSS is used to study nematic, smectic and cholesteric liquid crystals [600] in a rectangular waveguide. The effective permittivity from 7.8 to 12.4 GHz frequency range is calculated from the S-parameters.

A rectangular waveguide setup is used to characterize anisotropic liquid crystals (K15) at W-band [601].

3.4.16.6 Open Split Ring Resonator

Bloch impedance and dispersion of an array of liquid crystal open split ring resonators [602] is simulated and measured from 10 to 20 GHz.

3.4.16.7 Stripline

A balanced planar stripline accommodating liquid crystal sample [603, 604] is proposed to measure dielectric constants of liquid crystal materials (E7, K15, E44, E63, and MDA-00-3506) from 57 to 62 GHz.

3.4.16.8 Stripline Waveguide

A strip waveguide [169] with the strip immersed in liquid crystal is invented.

A stripline waveguide is analyzed to characterize liquid crystal by a modified finite difference frequency domain algorithm [605].

3.4.16.9 Dielectric Waveguide

A nonradiative dielectric waveguide using liquid crystal (E7) [519] is proposed. Finite element method based on the edge elements is used to simulate the effective dielectric constant for different applied voltages.

Characterisation and applications of nematic liquid crystals in microwave devices [606]. A method to characterise the dielectric properties of liquid crystal materials at microwave frequencies is presented that utilises a microstrip line with a layer of liquid crystal as a substrate. Accurate modelling of the liquid crystal and microwave fields is used to determine the dielectric properties of the liquid crystal from experimental measurements. The method is applied to a number of liquid crystal materials.

3.4.16.10 Fiber

A terahertz bandgap-guiding nematic liquid crystal fiber [607] is designed and parametrically studied by using finite element method.

3.5 Liquid Crystal Polymer Substrate

Dielectric substrate of low loss is essential for almost all microwave, millimeter wave and terahertz components. Liquid crystal of low loss, flexibility and tunability is therefore inherently beneficial for microwave, millimeter wave and terahertz applications. For this purpose, liquid crystal forms the entire substrate on which the patterned conductors are deposited. The imperative need for low-cost, compact, lightweight, wearable, versatile, adaptive, tunable, and reconfigurable devices for mobile and wireless communication systems makes liquid crystal especially high performance, low cost, and light liquid crystal polymer [608–615] extremely attractive.

3.5.1 Antenna

3.5.1.1 Bowtie Antenna

A bowtie antenna on a liquid crystal polymer substrate [616] is simulated by using HFSS from 18 to 30 GHz. A scaled down prototype is measured is measured from 4.5 to 7.5 GHz. Another bowtie antenna on liquid crystal polymer substrate [617] is designed for vehicle-toanything at cellular and C-V2X bands. Both arms are extended to meander lines.

3.5.1.2 Dipole Antenna

A dipole RFID antenna [618–621] on flexible liquid crystal polymer substrate is presented. The omnidirectional 915 MHz passive tag has a longer read range and wider read power range.

A 24 GHz dipole antenna on liquid crystal polymer substrate [622] is simulated by using HFSS and measured.

A series-fed two-dipole antenna is inkjet-printed on a liquid crystal polymer substrate [623, 624]. The proposed antenna was simulated by using HFSS and measured between 24 and 35 GHz.

A dipole antenna with a pair of meander arms on top and bottom surfaces of the liquid crystal polymer substrate and a 1×8 array [625] are simulated by using CST and measured from 20 to 32 GHz. A director on the top surface is introduced to increase gain and widen bandwidth.

A circularly polarized antenna on liquid crystal polymer substrate [626] is simulated by using HFSS and measured from 2 to 9 GHz. The coplanar waveguide-fed antenna is loaded with stubs, split ring resonators (SRR) and complimentary split ring resonators (CSRR).

3.5.1.3 MIMO Antenna

A co-planar waveguide-fed ultra-wideband multiple-input multiple-output antenna on liquid crystal polymer substrate [627] is simulated by using HFSS and measured from 2 to 15 GHz. The radiator is two vertically placed fan-shaped patches with C-shaped slot.

3.5.1.4 Monopole Antenna

A flexible monopole antenna on liquid crystal polymer substrate for the whole UWB frequency range [628] has been simulated.

An inverse L-shaped monopole antenna printed on liquid crystalline polymer substrate for 5 GHz WLAN/WiMAX applications [629] is designed. The conformal antenna is tightly integrated with a front-end module.

A microfluidically reconfigured liquid metal monopole antenna on liquid crystal polymer substrate [630] is proposed. The resonance frequency of an experimental prototype can be tuned from 1.29 to 5.17 GHz. A 4×1 array that operates from 2.5 to 5 GHz is also designed and measured.

A triple band-notched UWB monopole antenna on ultra-thin liquid crystal polymer substrate based on elliptic single complementary split-ring resonators [631] is presented for flexible electronics. Triple band-notched characteristic is realized by etching different sized elliptic single complementary split-ring resonators on the radiation patch together with capacitance compensation.

A coplanar waveguide-fed monopole antenna with hexagonal patch, rectangular slots, and trapezoid ground on liquid crystal polymer substrate [632] is simulated by using HFSS and measured. The return loss is better than -10 dB from 5.2 to 41 GHz.

3.5.1.5 Patch Antenna

Analytical analysis, CST simulation, and parametric study of a 70 GHz rectangular microstrip patch antenna on liquid crystal polymer substrate [41] have been performed.

A 12 GHz rectangular microstrip patch antenna on liquid crystal polymer substrate [633] is simulated by using HFSS.

An inductively loaded compact patch antenna on a flexible liquid crystalline polymer substrate for a commercially available capsule endoscope [634] is designed. It is wrapped cylindrically and radiates omnidirectionally at 433 MHz. The antenna is not only a radiator but also the EMI shield, mechanically support, and packaging layer for the endoscope.

A W-band aperture coupled stacked patch antenna on Kapton and liquid crystal polymer substrates with substrate embedded air cavity and arrays [635] is simulated and measured. High isolation between vertical and horizontal polarizations is achieved. An 8×1 phased antenna array is subsequently tested.

A W-band aperture coupled stacked patch antenna on Kapton and liquid crystal polymer substrates with substrate embedded air cavity and arrays [635] is simulated and measured. High isolation between vertical and horizontal polarizations is achieved.

A millimeter microstrip patch antenna on liquid crystal polymer substrate [636] is simulated and measured. Causes of discrepancy between simulations and measurements are investigated.

A multiband exponential serrated microstrip antenna on liquid crystal polymer substrate [637] is proposed and simulated from 1 to 4 GHz.

An E-band waveguide-fed patch antenna [638] on liquid crystal polymer substrate together with a slot-coupled waveguide-to-microstrip transition is proposed. The simulated antenna gain is 6.6 dB at 77 GHz and the -10 dB impedance bandwidth lies between 58 and 84 GHz.

A micro-electro-mechanical system patch antenna on liquid crystal polymer substrate with a central frequency of 14 GHz [639] is simulated by using HFSS.

An X-band (9.6–10.8 GHz) liquid crystal (N15) rectangular patch antenna [640] is designed. A 2×2 array is also simulated. Furthermore, a wideband tapered step antenna on liquid crystal polymer substrate with step serrated ground [640, 641] is simulated and measured from 4 to 18 GHz.

A planar inverted-F antenna (PIFA) over uniplanar electromagnetic band gap (EBG) structure with two trapezoidal shaped slots etched on the radiating patch on liquid crystal substrate [642] is proposed. It covers two narrow bands at GSM 1.8 GHz, upper WLAN 5.2 GHz and a wideband from 2.4 to 4 GHz.

A dual-band antenna on liquid crystal polymer substrate with a ring-shaped patch and a circular patch [643] is simulated by using HFSS.

A thick magnetic film loaded microstrip rectangular patch antenna on liquid crystal polymer substrate [644] is simulated by using FEKO and HFSS and measured from 5.5 to 9 GHz.

3.5.1.6 Slot Antenna

A double exponentially tapered slot antenna (DE TSA) on liquid crystal polymer substrate for UWB applications [645] conformal to the longitudinal direction around cylindrical structures is simulated and measured. The effect of cylinder radii on gain, 3 dB beamwidth, cross polarization level, and beam direction is investigated.

A compact tapered slot antenna on liquid crystal polymer substrate [646] working from 53.3 to 69.6 GHz has been proposed.

A flexible, light weight, low profile, linearly flared antipodal slot antenna on liquid crystal polymer substrate [647] is simulated by using HFSS and measured up to 110 GHz. The antenna exhibits high gain, low interconnection loss, narrow beamwidth, low side lobes, and low cross polarization from 75 to 95 GHz.

3.5.1.7 Vivaldi Antenna

A balance antipodal Vivaldi antenna on liquid crystal polymer substrate [640] is simulated and measured from 6 to 18 GHz.

3.5.2 Antenna Arrays

3.5.2.1 Microstrip

A microstrip comb-line array antenna with parasitic elements on liquid crystal polymer substrate [193, 648] is simulated by using HFSS and measured from 55 to 67 GHz.

3.5.2.2 Monopole

A 1×2 single band-notched ultra-wideband MIMO antenna on liquid crystal polymer substrate with U-shaped monopole elements [649] is simulated by using HFSS from 2 to 11 GHz.

3.5.2.3 Patch Antennas

A dual-frequency dual-polarization antenna array [47, 650, 651] is presented. The 14-GHz 2×1 microstrip patch array is embedded between two liquid crystal polymer (LCP) layers while the physically smaller 35-GHz one resides on the top liquid crystal polymer (LCP) layer. The patches are rotated by 45° to have 45° and 135° polarization directions for precipitation radar systems.

Reconfigurable phased array antennas on single layer and multilayer liquid crystal polymer substrate [652] have been demonstrated. The 2×2 patch arrays are integrated with low noise amplifier and RF MEMS phase shifter.

2×1 and 2×2 dual-frequency patch antenna arrays on liquid crystal polymer substrate [653] are simulated and measured.

An 8×8 series fed rectangular patch array on liquid crystal polymer substrate [654] is designed. Simulated impedance bandwidth centered at 93.5 GHz is 11.7% and measured beamwidth at 95 GHz is approximately 13.2° .

A Ka and Q band 4×4 rectangular microstrip patch antenna array on liquid crystal polymer substrate [655] is simulated by using HFSS.

A Ka-band eight-element focal plane array (FPA) on liquid crystal polymer substrate at the back surface of a hemispherical Rexolite lens [656] is proposed. Beam scanning is achieved through microfluidic.

An 8×5 omni-directional cylindrical antenna array of rectangular microstrip patches on liquid crystal polymer substrate [657] is proposed. The 10 dB return loss

bandwidth 0.85 GHz between 23.45 and 24.29 GHz and the measured gain at 24 GHz is 6.9 dB.

A Ka-band linear-phased microstrip-fed slot-coupled patch array with true time-delay multiline phase shifter on thin liquid crystal polymer substrate [658] is proposed. The gain is 15.6 dBi and the beam can be steered up to $33 \pm 1^\circ$ from 31 to 39 GHz.

0.835 THz, 0.635 THz and 0.1 THz 5×1 microstrip patch antenna arrays on liquid crystalline polymer substrate for medical applications [659] have been simulated by using CST. A 0.1 THz prototype is measured.

A bandpass filter or frequency selective surface consisting of periodically patterned capacitive and inductive layers in liquid crystal polymer [193, 194] is simulated by using HFSS and measured between 50 and 70 GHz.

A Q-band 6×6 aperture-coupled patch antenna array [660] is designed and fabricated by using multilayer liquid crystal polymer technology. High front-to-back-ratio is achieved by using substrate integrated coaxial line feeding technique.

28 GHz 1×2 crescent shaped microstrip patch antenna array on liquid crystal polymer substrate [661] is designed and simulated by using CST.

A cylindrically conformal two-element array on liquid crystal polymer substrate [662] is simulated by using CST and measured from 26 to 40 GHz. The rectangular patch element is tapered at its sides with two vertically oriented slots while the coplanar waveguide ground is designed with L-shaped stubs. Laser-milling and inkjet printing are also compared.

3.5.2.4 Phased Array

A 8×8 W-band phased patch array on liquid crystal polymer substrate [663] is simulated by using HFSS.

A 8×2 X-band receiving phased array on liquid crystal polymer substrate [664] is demonstrated and compared with a passive counterpart.

X-band aperture coupled passive 4×1 and phased 8×1 and 8×2 microstrip patch arrays on liquid crystal polymer substrate [55] have been designed and measured.

3.5.2.5 Slot Antenna

An ultra-wide band slot antenna on multilayer liquid crystal polymer substrate from 33 to 60 GHz [665] is presented. Two overlapped tapered slots with different flare angle are introduced to enhancing the bandwidth.

A 4×4 X-band (11 GHz) bidirectional planar polygon slot antenna array with a metamaterial inspired reactive coupling scheme on liquid crystal polymer substrate [666] is proposed for beamforming applications.

3.5.3 Artificial Dielectric

Multilayer W-band artificial dielectric on liquid crystal polymer [667] is designed. Different lattice configurations have been considered.

3.5.4 Balun

Baluns, bandpass filters, and duplexers on liquid crystalline polymer [668, 669] compatible with different communication standards such as 802.11 a/b/g have been designed.

Design of multiband baluns on liquid crystalline polymer (LCP) based substrates [670].

A lumped balun on multilayer liquid crystalline polymer substrate [671] was designed. Good phase and magnitude differences have been achieved.

A low cost low loss millimeter wave wideband balun on multilayer liquid crystal polymer [672] is designed and measured from 30 to 70 GHz.

An extremely compact balun on multilayer liquid crystal polymer substrate operating from 0.9 to 3.6 GHz [673] is designed and measured.

A compact ultra-wideband low loss balun based on stacked-defected ground structure and multilayer liquid crystal polymer [674] is simulated by using HFSS. The measured bandwidth of return loss, insertion loss, amplitude and phase imbalances is from 70 MHz to at least 2.1 GHz.

3.5.5 Capacitor

Compact three-dimensional capacitors on multilayer liquid crystalline polymer substrate [671] were designed and characterized. The capacitance is more than double that of standard capacitors.

3.5.6 Electromagnetic Compatibility

The rapidly deteriorating electromagnetic environment due to rocketing increase of electronic and electrical appliances has made it imperative to address electromagnetic compatibility issue. Otherwise, serious problems such as noise enhancement and malfunction of vulnerable devices might arise.

Electromagnetic shielding is the practice of reducing or blocking electromagnetic fields. It is one of the effective solutions to minimize electromagnetic interference and protect fragile devices. The influence of orientation and weight percentage on

the electromagnetic shielding effectiveness in a liquid crystal polymer composite with conductive carbon-fiber [675] was investigated experimentally and theoretically. Advantages of better shielding effect, lower cost, and easier mass production are confirmed.

3.5.7 Filter

3.5.7.1 Bandpass Filter

A bandpass filter on liquid crystal polymer [676] for a compact C-band module compatible with IEEE802.11a is designed. The coplanar waveguide filter uses a broadside-coupled dual-mode square ring resonator.

Bandpass filters composed of embedded inductors and capacitors in a multilayer liquid crystal polymer substrate have been synthesized by a layout-level technique [677, 678]. The synthesis result agrees fairly well with electromagnetic simulation.

Stripline bandpass filters on multilayer liquid crystalline polymer substrate for 900 MHz and 1.9 GHz [679], 3 GHz [680], and 5 GHz [671] were designed, fabricated, and measured.

A bandpass filter for a WLAN application [681] has been designed based on the low-loss integrated waveguide. The IWG BPF has a bandwidth of 59–64 GHz.

Compact band-pass microstrip filters on both single layer and multilayer liquid crystal polymer [47] are designed and measured.

Ultra wideband filters [682–686] have been fabricated on multilayer liquid crystal polymer substrate. Quasi-lumped elements such as broadside-coupled patches and microstrip radial stubs and high impedance microstrip lines are implemented. A multilayer nonuniform periodical structure [686] generates multiple transmission zeros and therefore improves the selectivity and upper stopband performance of the filter with multiple notch bands.

22–29 [53, 687] and 50–70 GHz [53] dual-mode ultra-wideband microstrip ring resonator filters on liquid crystal polymer substrate are developed for automotive radar systems.

Miniature high- and low-pass filters on multilayer liquid crystal polymer substrate are cascaded to develop ultra-wideband bandpass filter [688]. Similarly, a quasi-elliptic ultra-wideband bandpass filter on multilayer liquid crystal polymer substrate [689] is developed by cascading a few non-uniform periodical structures consisting of broadside coupling patches, slotted ground and embedded quarter-wavelength resonator.

A cascaded coupled line bandpass filter on liquid crystal polymer substrate [690] with reconfigurable bandwidths using LCP multilayer circuit technology. The bandwidth is reconfigurable from 26 to 50%.

Compact quasi-lumped-element bandpass filters on liquid crystal polymer substrate [691] have been designed and measured up to 8 GHz.

A liquid crystal rectangular waveguide bandpass filter for space applications [284] has been demonstrated.

An interdigital coupled line bandpass filter [692] inkjet-printed on liquid crystal polymer substrate is simulated and measured from 10 to 40 GHz. Inkjet-printing is also applied to fabricate a compact bandpass filter [693] together with multilayer liquid crystal polymer technology system on package technology. Three stepped impedance resonators are inkjet-printed on liquid crystal polymer substrates.

A compact self-packaged dual-band filter on multilayer liquid crystal polymer substrate [694] is proposed and experimentally validated.

A microstrip bandpass filter on multilayer liquid crystal polymer substrate [695] is simulated and measured. The integrated microfluidic channel provides frequency tenability from 1 to 1.5 GHz.

Highly reconfigurable bandpass filters on liquid crystal polymer substrate [696] are realized. Microfluidically controlled metallized glass plates is implemented to tune the frequency.

A Chebyshev bandpass filter based on triangular quarter-mode liquid crystal polymer substrate integrated waveguide cavity with a complementary split-ring resonator [697] is designed and measured from 15 to 50 GHz.

A Ku-band bandpass filter with wide upper stopband using multilayer liquid crystal polymer technology [698] is designed and measured up to 50 GHz. The compact filter implements a broadside-coupled H-shape resonator and two open-circuited radial stubs compact.

A bandpass filter with two cascaded substrate integrated waveguide cavities and 24 vias on thin liquid crystal polymer substrate at 94 GHz [699] is designed and measured. The proposed filter has a pass band of 8% centered at 94 GHz.

A compact wearable filter with 0° feed structure and open-ended stub on ultrathin liquid crystal polymer substrate [700] is simulated by using HFSS and measured from 3 to 9 GHz.

Corporate-feed microstrip patch antenna array on liquid crystal polymer substrate for the lower E-band (71–76 GHz) [193, 194] is simulated by using HFSS and measured between 70 and 80 GHz.

A self-packaged miniaturized ultrawideband balanced bandpass filter based on multilayer liquid crystal polymer technology [701] is simulated by using Sonnet and measured up to 14 GHz. Key technologies include transversal signal interference and broadside coupled stripline structure.

A self-packaged bandpass filter using multilayer liquid crystal polymer technology integrating balanced–unbalanced signal conversion and impedance transformation [702] is analyzed by using equivalent circuit model and simulated by using Sonnet. It is also experimentally validated up to 4.5 GHz.

A compact UWB bandpass filter on liquid crystal polymer substrate [703] is simulated by using HFSS and measured up to 20 GHz. It consists of 5 pairs of open- and shorted stubs connected via a uniform microstrip line.

A bandpass filter on liquid crystal polymer substrate [704] is implemented to suppress the local-oscillator leakage signal and spurious frequencies from radio frequency integrated circuit for 5G millimeter wave communications.

A comparative study on liquid crystal polymer (LCP) substrate and polytetrafluoroethylene (PTFE) substrate from 22 to 32 GHz is conducted by using bandpass hairpin and interdigital filters [705].

3.5.7.2 Directional Filter

Slot-coupled traveling-wave directional filters on multilayer liquid crystal polymer substrate at 95 GHz [706] are simulated by using HFSS and measured from 60 to 110 GHz.

3.5.7.3 Dual Band

An asymmetrical dual-band (ISM 2.4–2.5 GHz and UNII 5.15–5.85 GHz) WLAN filter [650, 707] on liquid crystal polymer substrate is designed.

Liquid crystal polymer (LCP) is electrically insensitive with frequency. As such, it is used to develop a single-input single-output (SISO) dual band filter [621] at the WLAN operating frequency bands.

3.5.7.4 Low-Pass

Compact low-pass microstrip filters on single layer liquid crystal polymer [47] are designed and measured.

Two low-pass filters based on the principle of destructive interference [708] are proposed and measured. Both are self-packaged using multilayer liquid crystal polymer technology. The improved one exhibits very high rejection levels better than 40 dB over a wide frequency span.

3.5.8 Inductor

Rectangular and circular spiral inductors on multilayer liquid crystal polymer substrate [676] are designed, modelled, and measured. Effects of radius, ground plane spacing and ground plane width are also studied. The quality factor is about 70. Rectangular spiral inductors with higher quality factor [671, 679] are also presented.

3.5.9 Modulator

A polymer compositions suitable for microwave cooking applications [709] is invented. The microwave susceptible effectively absorbs microwave that appetizing

and palatable food can be more appropriately cooked or heated by using microwave oven.

3.5.10 Oscillator

Low phase noise VCO on liquid crystalline polymer based on transformer core [608] or negative resistance [611] are designed and experimentally characterized.

A low-phase-noise, highly integrated 1.8 GHz modified Colpitt's oscillator on liquid crystalline polymer for UMTS and similar cellular systems [612] was designed and tested.

A signal generator for 802.11a/b/g VoWLAN applications using passive components on liquid crystal polymer substrate [710] is proposed.

3.5.11 Phase Shifters

3.5.11.1 Mems

A compact two-bit X-band phase shifter integrating RF MEMS on multilayer liquid crystal polymer [711] is designed. An area reduction of 22.5% is achieved.

3.5.11.2 Strip

A 5×8 Rotman lens-fed array beamformer on liquid crystal polymer substrate [712] is simulated by using CST and fabricated from 18 to 38 GHz.

3.5.12 Power Divider

A broadband miniaturized Wilkinson power divider on multilayer liquid crystal polymer substrate [713] is developed.

A 4-to-1 power combiner on liquid crystal polymer substrate in a 5G millimeter wave phased array module [704] is measured.

3.5.13 Resistor

Capacitors and resistors integrated on liquid crystal polymer substrate have been designed and experimentally characterized [610]. A cost effective broadband resistor

on liquid crystal polymer [621] is designed. The measured resistance agrees well with simulation.

A 20 W thin film resistor on liquid crystal polymer is implemented to test an integrated microfluidic cooling solution [714].

3.5.14 Resonator

3.5.14.1 Cavity Resonator

Various cylindrical cavity resonators have been used to characterize liquid crystal polymer (LCP) material [715].

A spherical cavity resonator fine tuned using magnetic nanoparticle film deposited on a liquid crystal polymer host substrate [716] is simulated by using HFSS and measured from 7.8 to 8.2 GHz.

3.5.14.2 Ring Resonator

Ring resonators are designed to characterize liquid crystal polymer (LCP) material [715, 717–719]. The thermal stability from 25 to 125 °C of dielectric constant of liquid crystal polymer is measured by microstrip ring resonators with conductor-backed coplanar waveguide (CBCPW)-to-microstrip transitions between 11 to 105 GHz [720].

Microstrip ring resonators on liquid crystal polymer substrate [636] are designed with resonant peaks at 58, 60, 61.5, 63, and 65 GHz and measured to determine the exact relative permittivity of liquid crystal polymer substrate.

A microstrip ring resonator is used to characterize liquid crystal polymer from 110 to 170 GHz [721].

3.5.15 Switch

A GaAs MMIC switch circuit [718, 719] and a low cost RF MEMS switch [722] were fabricated using liquid crystal polymer substrate to demonstrate the concept of system-in-a-package.

Bending effect of a spring-like clamped–clamped coplanar waveguide RF MEMS switch on liquid crystal polymer substrate [723] is simulated by using ANSYS and HFSS and experimentally confirmed up to 20 GHz.

A microfluidically reconfigurable millimeter wave single-pole single-throw switch with patterned copper cladded liquid–crystal polymer [724] is simulated by using ANSYS Workbench 19.1 and Electronics Desktop and measured from 20 to 40 GHz.

3.5.16 Transitions

3.5.16.1 Conductor-Backed Coplanar Waveguide to Stripline

Ultrawide band conductorbacked coplanar waveguide to stripline vertical transition on multilayer liquid crystal polymer substrate [725] is designed.

3.5.16.2 Microstrip Line-To-Microstrip Line

Microstrip line-to-microstrip line transition in multilayer liquid crystal polymer substrate [726] is simulated by using HFSS and measured up to 100 GHz.

3.5.16.3 Microstrip Line-To-Stripline

Vialess microstrip line-to-stripline transition in multilayer liquid crystal polymer substrate [727] is simulated by using HFSS and measured up to 110 GHz.

3.5.16.4 Microstrip Line-To-Waveguide

A low-loss microstrip line-to-post-wall waveguide transition on liquid crystal polymer substrate [193, 194, 728, 729] is simulated by using HFSS and measured between 40 and 70 GHz.

A D-band waveguide transition on liquid crystal polymer substrate [730] is proposed. A slot fed by a microstrip line couples the RF signal to the waveguide perpendicular to its plane.

3.5.16.5 Three-Dimensional Transition

Coplanar waveguide-coplanar waveguide-microstrip and coplanar waveguide-coplanar waveguide-coplanar waveguide transitions 3D transitions on liquid crystal polymer from 60 to 100 GHz [731] substrate are reported. The transitions exhibit superior return loss and insertion loss.

3.5.16.6 Waveguide-To-Waveguide

A grounded-coplanar waveguide-to-post-wall waveguide transition on liquid crystal polymer substrate [193] is simulated by using HFSS and measured between 30 and 70 GHz.

A substrate integrated waveguide-to-waveguide transition in multilayer liquid crystal polymer substrate [732] is simulated by using HFSS and measured from 70 to 110 GHz. The proposed transition is achieved by using a SIW-fed linearly flared antipodal slot line inserted into a WG.

3.5.17 *Transmitting and/or Receiving Module*

Besides a high-Q RF inductors, a single-input-single-output (SISO) dual-band filter, and two dual-polarization 2×1 antenna arrays, a superheterodyne Tx/Rx system [650, 733] on liquid crystal polymer substrate has been fabricated to show the potential of the SOP approach for 3-D-integrated RF and mm waves functions and modules. The compact module compatible with WLAN IEEE 802.11a-compliant integrates two mixers and two bandpass filters. A Ka-band receiver module consisting of a low-noise amplifier, an image-rejection mixer and a driver amplifier [49, 734, 735] was developed using liquid crystal polymer thin-film surface mount packages [736].

A V-band active receiving switched-beam front end on liquid crystal polymer substrate [55] has been presented.

A W-band integrated module with a Yagi-Uda antenna on liquid crystal polymer substrate [737], a silicon-germanium low-noise amplifier, and an optimized flip-chip interconnect on liquid crystal polymer substrate [737, 738] is presented.

A RF front-end receiving module on multilayer liquid crystal polymer substrate for millimeter wave imaging [739] is proposed. A linearly tapered slot antenna, low noise amplifiers, as well as various passive components, including transmission lines, waveguides, filters, and their transitions are integrated into the module.

W-band multilayer liquid crystal polymer front-end receiving module consisting of a high-gain antenna, high-gain low noise amplifiers, bandpass filters, transmission lines, and their transitions for interconnection [61] is developed.

A 95-GHz front-end receiving multichip module on multilayer liquid crystal polymer substrate for passive millimeter-wave imaging [740] is designed and characterized.

3.5.18 *Transmission Line*

3.5.18.1 *Coplanar Waveguide*

Coplanar waveguides [195, 676, 715, 741, 742] and conductor backed coplanar wave guide (CB-CPW) [715, 743] are fabricated to study the electromagnetic properties of liquid crystal polymer substrate.

Low loss D-band conductor-backed coplanar waveguides and the corresponding coplanar waveguide-to-microstrip transitions are aerosol jet printed on liquid crystal polymer substrate [744].

Ground coplanar waveguides are implemented to characterize liquid crystal polymer substrate [745].

3.5.18.2 Integrated Waveguide

Because of the favorable properties of liquid crystal polymer at millimeter wave frequencies, an integrated waveguide on liquid crystal polymer substrate [681, 746] has been developed. The measured insertion loss is only -0.12 dB/mm.

3.5.18.3 Microstrip

The characteristic impedance, effective dielectric constants and losses of microstrip line on liquid crystal polymer is characterized from 220 to 330 GHz [747].

Microstrip lines on liquid crystal polymer substrate and Kapton are by aerosol jet printing [748] are experimentally compared from 10 MHz to 40 GHz.

3.5.18.4 Stripline

A balanced planar stripline accommodating liquid crystal sample [603, 604] is proposed to measure dielectric constants of liquid crystal materials (E7, K15, E44, E63, and MDA-00-3506) from 57 to 62 GHz.

3.5.18.5 Stripline Waveguide

A strip waveguide [169] with the strip immersed in liquid crystal is invented.

A stripline waveguide is analyzed to characterize liquid crystal by a modified finite difference frequency domain algorithm [605].

3.5.18.6 Dielectric Waveguide

A nonradiative dielectric waveguide using liquid crystal (E7) [519] is proposed. Finite element method based on the edge elements is used to simulate the effective dielectric constant for different applied voltages.

Characterisation and applications of nematic liquid crystals in microwave devices [606]. A method to characterise the dielectric properties of liquid crystal materials at microwave frequencies is presented that utilises a microstrip line with a layer of liquid crystal as a substrate. Accurate modelling of the liquid crystal and microwave fields is used to determine the dielectric properties of the liquid crystal from experimental measurements. The method is applied to a number of liquid crystal materials.

3.5.18.7 Fiber

A terahertz bandgap-guiding nematic liquid crystal fiber [607] is designed and parametrically studied by using finite element method.

3.6 Liquid Crystal Polymer for Packaging

Microwave, millimeter wave and terahertz components, circuits, and systems might be very sensitive to contamination and interference that they have to be properly packed. Packaging is a critical part in bringing them into application at an affordable cost.

The low water absorption coefficient and adjustable coefficient of thermal expansion in tandem with low dielectric constant and low loss tangent of liquid crystal polymer [715] has made it a high performance low cost flexible substrate and packaging material in higher frequency operation and fabrication [55, 91–113, 613, 681, 746, 749–765]. The system-on-package with LCP offers an excellent solution to beat the stringent challenge from space constrained emerging 5G communications and forthcoming 6G communications. It can also be used as bonding adhesive [766, 767].

References

1. Ramaseshan S (1996) The centennial of the discovery of millimetre waves by Jagadis Chandra Bose (1858–1937). *Curr Sci* 70(2):172–175
2. Emerson DT (1997) The work of Jagadis Chandra Bose: 100 years of mm-wave research. In: *Proceedings of the 1997 IEEE MTT-S international microwave symposium*, vol 2, Denver, CO, June 8–13, pp 553–556
3. Emerson DT (1997) The work of Jagadis Chandra Bose: 100 years of millimeter-wave research. *IEEE Trans Microw Theory Techn* 45(12):2267–2273
4. Emerson DT (1998) Jagadis Chandra Bose: millimetre wave research in the nineteenth century. In: *Proceedings of the 1998 IEEE TENCON: IEEE region 10 international conference on global connectivity in energy, computer, communication and control*, New Delhi, India, Dec 17–19, pp 282–287
5. Hong S (2001) *Wireless: from marconi's black-box to the audion, series: transformations: studies in the history of science and technology*. The MIT Press, Cambridge
6. Sarkar TK, Mailloux R, Oliner AA, Salazar-Palma M, Sengupta DL (2006) *History of wireless*. Wiley-IEEE Press
7. Woltman SJ, Jay GD, Crawford GP (eds) (2007) *Liquid crystals frontiers in biomedical applications*. World Scientific
8. Woltman SJ, Jay GD, Crawford GP (2007) Liquid-crystal materials find a new order in biomedical applications. *Nat Mater* 6(12):929–938
9. Mitov M (2012) Translated by G. Weiss, *Sensitive matter: foams, gels, liquid crystals, and other miracles*. Harvard University Press, Cambridge
10. Mitov M (2012) Cholesteric liquid crystals with a broad light reflection band. *Adv Mater* 24(47):6260–6276

11. Yang FZ (2008) New directions in recent liquid crystal studies: the progress in foundational research of non-display application of liquid crystals. *Prog Phys* 28(2):107–129
12. Gevorgian S (2009) *Ferroelectrics in microwave devices, circuits and systems: physics, modeling, fabrication and measurement*, series: engineering materials and processes. Springer, Berlin
13. Vieweg N, Deninger A (2013) Terahertz waves and liquid crystals: prospects and challenges. *SPIE Emerg Liq Cryst Technol VIII* 8642:86420K
14. Yaghmaee P, Karabey OH, Bates B, Fumeaux C, Jakoby R (2013) Electrically tuned microwave devices using liquid crystal technology. *Int J Anten Propag* 54:824214
15. Jost M, Gaebler A, Weickhmann C, Strunck S, Hu W, Karabey OH, Jakoby R (2014) Evolution of microwave nematic liquid crystal mixtures and development of continuously tuneable micro- and millimetre wave components. In: *Proceedings of the 2014 25th international liquid crystal conference*
16. Karabey OH (2014) *Electronic beam steering and polarization agile planar antennas in liquid crystal technology*, series: Springer Theses. Springer, Berlin
17. Khoo IC, Zhao S (2014) Multiple time scales optical nonlinearities of liquid crystals for optical-terahertz-microwave applications (invited review). *Prog Electromagnet Res* 147:37–56
18. Yaghmaee P (2014) *Reconfigurable tunable microwave devices using liquid crystal*. Ph. D. Dissertation. The University of Adelaide
19. Carpintero G, Muñoz LEG, Hartnagel HL, Preu S, Räisänen AV (eds) (2015) *Semiconductor terahertz technology: devices and systems at room temperature operation*. Wiley, New York
20. Jost M, Gaebler A, Weickhmann C, Strunck S, Hu W, Karabey OH, Jakoby R (2015) Evolution of microwave nematic liquid crystal mixtures and development of continuously tuneable micro- and millimetre wave components. *Mol Cryst Liq Cryst* 610(1):173–186
21. Maune H, Nikfalazar M, Schuster C, Franke T, Hu W, Nickel M, Kienemund D, Prasetiadi A, Weickhmann C, Jost M, Wiens A, Jakoby R (2016) Tunable microwave component technologies for SatCom-platforms. In: *Proceedings of the 2016 German microwave conference, Bochum, Germany*, pp 23–26
22. Maune H, Jost M, Wiens A, Weickhmann C, Reese R, Nikfalazar M, Schuster C, Franke T, Hu W, Nickel M, Kienemund D, Prasetiadi AE, Jakoby R (2017) Tunable microwave component technologies for SatCom-platforms. *Frequenz* 71(3–4):129–142
23. Camley R, Celinski Z, Garbovskiy Y, Glushchenko A (2018) Liquid crystals for signal processing applications in the microwave and millimeter wave frequency ranges. *Liq Cryst Rev* 6(1):17–52
24. Liu F, Pitilakis A, Mirmoosa MS, Tsilipakos O, Wang X, Tasolamprou AC, Abadal S, Cabellos-Aparicio A, Alarcon E, Liaskos C, Kantartzis NV, Kafesaki M, Economou EN, Soukoulis CM, Tretyakov S (2018) Programmable metasurfaces: state of the art and prospects. In: *Proceedings of the 2018 IEEE international symposium on circuits and systems, Florence, Italy*
25. Shaltout AM, Shalaev VM, Brongersma ML (2019) Spatiotemporal light control with active metasurfaces. *Science* 364(6441):eaat3100
26. Ting TL (2019) Technology of liquid crystal based antenna. *Opt Exp* 27(12):17138–17153
27. Wang L, Xiao RW, Ge SJ, Shen ZX, Lü P, Hu W, Lu YQ (2019) Research progress of terahertz liquid crystal materials and devices. *Acta Phys Sin* 68(8):084205
28. Wang L, Zhang Y, Guo X, Chen T, Liang H, Hao X, Hou X, Kou W, Zhao Y, Zhou T, Liang S, Yang Z (2019) A review of THz modulators with dynamic tunable metasurfaces. *Nanomaterials* 9(7):965
29. Zheng R, Chan EHW, Wang X, Feng X, Guan BO (2019) Microwave photonic devices based on liquid crystal on silicon technology. *Appl Sci* 9(2):260
30. Zografopoulos DC, Ferraro A, Beccherelli R (2019) Liquid-crystal high-frequency microwave technology: materials and characterization. *Adv Mater Technol* 4(2):1800447
31. Jakoby R, Gaebler A, Weickhmann C (2020) Microwave liquid crystal enabling technology for electronically steerable antennas in SATCOM and 5G millimeter-wave systems. *Crystals* 10(6):514

32. Maune H (2020) Microwave liquid crystal technology. *Crystals* 10(8):716
33. Polat E, Tesmer H, Reese R, Nickel M, Wang D, Schumacher P, Jakoby R, Maune H (2020) Reconfigurable millimeter-wave components based on liquid crystal technology for smart applications. *Crystals* 10(5):346
34. Shen ZX, Tang MJ, Chen P, Zhou SH, Ge SJ, Duan W, Wei T, Liang X, Hu W, Lu YQ (2020) Planar terahertz photonics mediated by liquid crystal polymers. *Adv Opt Mater* 8(7):1902124
35. Ferrari P, Jakoby R, Karabey OH, Maune H, Rehder G (eds) (2022) Reconfigurable Circuits and technologies for smart millimeter-wave systems, series: EuMA high frequency technologies series. Cambridge University Press, Cambridge
36. Guan S, Cheng J, Chang S (2022) Recent progress of terahertz spatial light modulators: materials, principles and applications. *Micromachines* 13(10):1637
37. Serrano ALC, Marcati G, Abe I, Palomino GA, Rehder GP (2022) Millimeter-wave wireless integrated systems: what to expect for future solutions. *J Integr Circ Syst* 17(2):627
38. Wu Q, Zhang H, Jia D, Liu T (2022) Recent development of tunable optical devices based on liquid. *Molecules* 27(22):8025
39. Zhou Z, Li W, Qian J, Liu W, Wang Y, Zhang X, Guo Q, Yashchysyn Y, Wang Q, Shi Y, Zhang Y (2022) Flexible liquid crystal polymer technologies from microwave to terahertz frequencies. *Molecules* 27(4):1336
40. Mann GA (1953) The cotton-mouton effect in liquid crystal at microwave frequencies. Master Thesis, California Institute of Technology
41. Khan J (2008) Design of microstrip patch antenna on liquid crystal polymer (LCP) for applications at 70 GHz. Master Thesis, University of Gävle
42. Lin CH (2011) A study of millimeter-wave signals generated by shaped-pulse-excited photonic transmitters. Master Thesis, National Tsing Hua University
43. Cai C (2018) Research on terahertz reflectarray antenna based on liquid crystal. Master Thesis, Hefei University of Technology
44. Xing J (2021) Research on design and characteristics of terahertz reflective scanning array based on electronically controlled liquid crystal. Master Thesis, Harbin Institute of Technology
45. Chen CY (2006) A study of the optical properties and applications of liquid crystals in THz range. Ph. D. Dissertation, National Chiao Tung University
46. Thompson D (2006) Characterization and design of liquid crystal polymer (LCP) based multilayer RF components and packages. Ph. D. Dissertation, Georgia Institute of Technology
47. Bairavasubramanian R (2007) Development of microwave/millimeter-wave antennas and passive components on multilayer liquid crystal polymer (LCP) technology. Ph. D. Dissertation, Georgia Institute of Technology
48. Ismail MY (2007) Reconfigurable reflectarray antenna based on liquid crystal substrate. Ph. D. Dissertation, Queen's University Belfast
49. Aihara K (2008) Development of liquid crystalline polymer (LCP) surface mount packages for Ka-band applications. Ph. D. Dissertation, University of California, Davis
50. Marin R (2008) Investigation on liquid crystal reconfigurable unit cells for mm-wave reflectarrays. Ph. D. Dissertation, Technischen Universität Darmstadt
51. Lapanik A (2009) Liquid crystal systems for microwave applications: single compounds and mixtures for microwave applications dielectric, microwave studies on selected systems. Ph. D. Dissertation, Technische Universität Darmstadt
52. Mirfatah A (2009) Study on a tuneable microwave resonator based on liquid crystal. École Polytechnique de Montréal
53. Zhang X (2009) Design, fabrication and characterization of microwave passive devices on liquid crystal polymer substrates. Ph. D. Dissertation, Chalmers University
54. Gölden F (2010) Flüssigkristall-basierte Mikrowellenkomponenten mit schnellen Schaltzeiten: material, technologie, Leistungsverträglichkeit/liquid crystal based microwave components with fast response times: material, technology, power handling capability. Ph. D. Dissertation, Technischen Universität Darmstadt
55. Patterson CE (2012) Exploration of liquid crystal polymer packaging techniques for RF wireless systems. Ph. D. Dissertation, Georgia Institute of Technology

56. Parras MR (2015) Tunable metamaterial leaky wave antenna based on microwave liquid crystal technology. Ph. D. Dissertation, Universität Darmstadt
57. Rosell JT (2015) Design and characterization of new tunable devices based on liquid crystal technology for microwave applications. Ph. D. Dissertation, Universidad Carlos III de Madrid
58. Maasch M (2016) Tunable microwave metamaterial structures, series: Springer Theses. Springer, Berlin
59. Mavrona E (2016) Functionlised liquid crystals for manipulating terahertz radiation. Ph. D. Dissertation, University of Southampton
60. Nasserddine V (2016) Millimeter-wave phase shifters based on tunable transmission lines in MEMS technology post-CMOS process/Déphaseurs en bande millimétrique basés sur des lignes à ondes lentes accordables en technologie MEMS dans un process post-CMOS. Ph. D. Dissertation, Université Grenoble Alpes
61. Zhang Y (2016) Development of multilayer liquid crystal polymer based radio frequency front-end receiving module at W-band. Ph. D. Dissertation, University of Delaware
62. Prasetiadi AE (2017) Tunable substrate integrated waveguide bandpass filter and amplitude tuner based on microwave liquid crystal technology. Ph. D. Dissertation, Technische Universität Darmstadt
63. Weickmann CJM (2017) Liquid crystals towards terahertz: characterisation and tunable waveguide phase shifters for millimetre-wave and terahertz beamsteering antennas. Ph. D. Dissertation, Technischen Universität Darmstadt
64. Jost M (2018) Liquid crystal mixed beam-switching and beam-steering network in hybrid metallic and dielectric waveguide technology. Ph. D. Dissertation, Technische Universität Darmstadt
65. Li J (2018) Structure and optimisation of liquid crystal based phase shifter for millimetre-wave applications, University of Cambridge. Ph. D. Dissertation
66. Tebbe M (2018) Analytical and experimental characterization of a liquid crystal based phased array. Ph. D. Dissertation, Technische Universität München
67. Almhadi RAM (2019) Optical true time delay device for mm-wave antenna array beamforming. Ph. D. Dissertation, The Ohio State University
68. Lei M (2019) Design and evaluation of tunable microstrip liquid crystal devices. Ph. D. Dissertation, University College London
69. Yang Y (2019) Terahertz reflective electronically controlled scanning antenna based on liquid crystal. Master Thesis, Hefei University of Technology
70. Nobles JE (2020) Optimization of liquid crystal based devices operating in the microwave region. Ph. D. Dissertation, University of Colorado Colorado Springs
71. Gomes L (2022) Voltage-controlled oscillator for high-performance MMW beam-steering front-end. Ph. D. Dissertation, Université Grenoble Alpes
72. Cotton A, Mouton H (1905) Sur le phénomène de Majorana. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* 141:317–319
73. Cotton A, Mouton H (1905) Sur la biréfringence magnétique. *Nouveaux Liq. Actifs* 141:349–351
74. Dolfi D, Huignard JP, Baril M (1989) Optically controlled true time delays for phased array antenna. *SPIE Opt Technol Microw Appl IV* 1102:152–161
75. Dolfi D, Michel-Gabriel F, Bann S, Huignard JP (1991) Two dimensional optical architecture for time delay beamforming in a phased array antenna. *Opt Lett* 16(4):255–257
76. Riza NA (1991) A transmit/receive time delay optical beamforming architecture for phased array antennas. *Appl Opt* 30(32):4594–4596
77. Dolfi D, Bann S, Huignard JP, Roger J (1992) Two dimensional optical architecture for phase and time delay beamforming in a phased array antenna. *SPIE Opt Technol Microw Appl VI Optoelectr Sig Process Phased-Array Antennas III* 1703:481–489
78. Riza NA (1992) Liquid crystal-based optical time delay control system for wideband phased arrays. *SPIE Anal Photon* 1790:171–183
79. Riza NA (1992) Liquid crystal-based optical control of phased array antennas. *J Lightw Technol* 10(12):1974–1984

80. Riza NA (1993) Three dimensional optical time delay units for radar. *SPIE Photon Process Neural Netw Memor* 2026:227–237
81. Riza NA (1994) Liquid-crystal-based optical controllers for phased-array antennas. *SPIE Optoelectr Sig Process Phased-Array Antennas IV* 2155:169–180
82. Riza NA (1994) Acousto-optic liquid-crystal analog beam former for phased-array antennas. *Appl Opt* 33(17):3712–3724
83. Bendix Corporation Research Laboratories (1970) Development of liquid crystal microwave power density meter. Report BRH/DEP 70-8, Bureau of Radiological Health, U.S. Government Document No. PB-191–396
84. Keilmann F, Renk KF (1971) Visual observation of submillimeter wave laser beams. *Appl Phys Lett* 18(10):452–457
85. Swicord ML (1971) Microwave measurements and new types of detectors for evaluation of health hazards. Report BRH/DEP 71-1, Bureau of Radiological Health, U.S. Government Document No. PB-197–715
86. Tolmachev AV, Kuz'michev VM (1971) Use of liquid crystals make infrared radiation visible. *Soviet J Exp Theor Phys Lett* 14(4):144–146
87. Brown GH (1973) Structure, properties, and some applications of liquid crystals. *J Opt Soc Am* 63(12):1505–1514
88. Tolmachev AV, Govorun EY, Kuz'michev VM (1973) Visualization of radiation in the millimeter and submillimeter range by means of liquid crystals. *Soviet Phys J Exp Theor Phys* 36(2):309–310
89. Fanslow GE (1974) Liquid crystal mapping of slotted waveguide fields. *J Microw Power* 9(3):173–175
90. Rozzell TC, Johnson CC, Durney CH, Lords JL, Olsen RG (1974) A non-perturbing temperature sensor for measurement in electromagnetic fields. *J Microw Power* 9(3):241–249
91. Meier G, Sackmann E, Grabmaier JG (1975) Applications of liquid crystals. Springer, New York
92. Fanslow GE (1976) A liquid crystal calorimeter for radiation monitoring. In: *Proceedings of the 1976 11th annual microwave power symposium*, Katholieke Universiteit, Leuven
93. Fanslowt G (1977) Liquid crystal electromagnetic radiation monitor. *J Microw Power* 12(1):87–91
94. Kovshev EI, Blinov LM, Titov VV (1977) Thermotropic liquid crystals and their applications. *Russian Chem Rev* 46(5):395–419
95. Wang L, Qiu H, Phan TNK, Kato K, Kang B, Takano K, Lu Y, Chen L, Lv P, Yu K, Wei W, Jin B, Nakajima M (2018) Visible measurement of terahertz power based on capsulized cholesteric liquid crystal film. *Appl Sci* 8(12):2580
96. Kojima M, Tsai CY, Suzuki Y, Sasaki K, Tasaki T, Taki M, Watanabe S, Sasaki H (2019) Ocular response to millimeter wave exposure under different levels of humidity. *J Infrared Millimeter Terahertz Waves* 40(5):574–584
97. Lim KC, Margerum JD (1992) Liquid-crystal optical properties and applications in the millimeter-wave range. *SPIE Disp Technol* 1815:99–105
98. Lim KC, Margerum JD, Lackner AM, Miller LJ (1992) Microwave phase modulation with liquid crystals. European Patent No. EP0472403A2, Raytheon Co
99. Lim KC, Margerum JD, Lackner AM (1993) Liquid crystal millimeter wave electronic phase shifter. *Appl Phys Lett* 62(10):1065–1067
100. Lim KC, Margerum JC, Lackner AM, Miller LJ, Sherman E, Smith WH (1993) Liquid crystal birefringence for millimeter wave radar. *Liq Cryst* 14(2):327–337
101. Dolfi D, Labeyrie M, Joffre P, Huignard JP (1993) Liquid crystal microwave phase shifter. *Electr Lett* 29(10):926–928
102. Dolfi D, Labeyrie M, Joffre P, Huignard JP (1994) Liquid-crystal microwave phase shifter. *SPIE Optoelectr Sig Process Phased-Array Antennas IV* 2155:420–425
103. Lim KC (1996) Liquid crystal millimeter wave open transmission lines modulators. Patent No. US5537242, DirecTV Group Inc

104. Guérin F, Chappe JM, Joffre P, Dolfi DDD (1997) Modeling, synthesis and characterization of a millimeter-wave multilayer microstrip liquid crystal phase shifter. *Jpn J Appl Phys* 36(7R):4409–4413
105. Lim KC, Margerum JD, Lackner AM, Sherman E, Ho MS, Fung BM, Genetti WB, Grady BP (1997) A liquid crystal based polymer for applications in MMW modulation devices. *Mol Cryst Liq Cryst Sci Technol A Mol Cryst Liq Cryst* 302(1):187–197
106. Kuki T, Fujikake H, Kamoda H, Nomoto T (2002) Microwave variable delay line using a membrane impregnated with liquid crystal. In: *Proceedings of the 2002 IEEE MTT-S international microwave symposium*, Seattle, WA, pp 363–366
107. Kuki T, Fujikake H, Nomoto T (2002) Microwave variable delay line using dual-frequency switching-mode liquid crystal. *IEEE Trans Microw Theory Techn* 50(11):2604–2609
108. Kuki T, Fujikake H, Nomoto T, Utsumi Y (2002) Design of a microwave variable delay line using liquid crystal, and a study of its insertion loss. *Electr Commun Jpn* 85(2):36–42
109. Busch K, John S (1999) Liquid-crystal photonic-band-gap materials: the tunable electromagnetic vacuum. *Phys Rev Lett* 83(5):967–970
110. Ye W, Xing H, Zhou X, Sun Y, Zhang Z (2015) Influence of rubbing-alignment on microwave modulation induced by liquid crystal. *AIP Adv* 5(6):067145
111. Luukkonen O, Costa F, Monorchio A, Tretyakov SA (2009) A thin electromagnetic absorber for wide incidence angles and both polarizations. *IEEE Trans Antennas Propag* 57(10):3119–3125
112. Spada LL, Vegni L (2016) Metamaterial-based wideband electromagnetic wave absorber. *Opt Exp* 24(6):5763–5772
113. Duan Y, Guan H (2017) *Microwave absorbing materials*. Pan Stanford Publishing
114. Jiang W, Yan L, Ma H, Fan Y, Wang J, Feng M, Qu S (2018) Electromagnetic wave absorption and compressive behavior of a three-dimensional metamaterial absorber based on 3D printed honeycomb. *Sci Rep* 8:4817
115. Kotsuka Y (2019) *Electromagnetic wave absorbers: detailed theories and applications*. Wiley, Amsterdam
116. Tirkey MM, Gupta N (2019) Electromagnetic absorber design challenges. *IEEE Electromagn Compat Mag* 8(1):59–65
117. Tirkey MM, Gupta N (2019) The quest for perfect electromagnetic absorber: a review. *Int J Microw Wireless Technol* 11(2):151–167
118. Zhang M, Cao MS, Shu JC, Cao WQ, Li L, Yuan J (2021) Electromagnetic absorber converting radiation for multifunction. *Mater Sci Eng R Rep* 145:100627
119. Kishk A (2022) *Recent topics in electromagnetic compatibility*. Intech
120. Dunn A, Zhang Z, Horbury ME, Nuttall E, Han Y, Salih M, Li L, Saleh E, Harris R, Daghestani N, Pardo D, Ellison D, Burnett A, Gleeson H, Valavanis A (2021) Development of advanced terahertz optics using liquid crystals. In: *Proceedings of the 2021 46th international conference on infrared, millimeter, and terahertz waves*, Chengdu, China
121. Honma M, Sase T, Ito R, Nose T (2021) Millimeter-wave single-pixel imaging using liquid crystal mask cell with matrix electrode structure. In: *Proceedings of the 2021 international display workshops*, vol 28
122. Honma M, Sase T, Ito R, Nose T (2023) Millimeter-wave single-pixel imaging using electrically-switchable liquid-crystal mask. *IEICE Trans Electr* 106(2):34–40
123. Fusco VF, Cahill R, Hu W, Simms S (2008) Ultra-thin tunable microwave absorber using liquid crystals. *Electr Lett* 44(1):37–38
124. Seman FC, Cahill R, Fusco VF (2009) Electronically tunable liquid crystal based Salisbury screen microwave absorber. In: *Proceedings of the 2009 Loughborough antennas propagation conference*, Loughborough, pp 93–96
125. Shrekenhamer D, Chen WC, Padilla WJ (2013) Liquid crystal tunable metamaterial absorber. *Phys Rev Lett* 110(17):177403
126. Nemati A, Wang Q, Hong M, Teng J (2018) Tunable and reconfigurable metasurfaces and metadevices. *Opto-Electr Adv* 1(5):180009

127. Savo S, Shrekenhamer D, Padilla WJ (2014) Liquid crystal metamaterial absorber spatial light modulator for THz applications. *Adv Opt Mater* 2(3):275–279
128. Isić G, Vasić B, Zografopoulos DC, Beccherelli R, Gajić R (2015) Electrically tunable critically coupled terahertz metamaterial absorber based on nematic liquid crystals. *Phys Rev Appl* 3(6):064007
129. Wang L, Ge S, Chen Z, Hu W, Lu Y (2016) Liquid crystal based tunable terahertz metamaterial absorbers. In: Proceedings of the 2016 conference COMSOL conference, Shanghai
130. Wang L, Ge S, Chen Z, Hu W, Lu Y (2016) Bridging the terahertz near-field and far-field observations of liquid crystal based metamaterial absorbers. *Chin Phys B* 25(9):094222
131. Deng G, Xia T, Jing S, Yang J, Lu H, Yin Z (2017) A tunable metamaterial absorber based on liquid crystal intended for F frequency band. *IEEE Antennas Wireless Propag Lett* 16:2062–2065
132. Lu HB, Jing SC, Xia TY, Yang J, Yin Z, Deng G (2001) Measurement of LC dielectric constant at lower terahertz region based on metamaterial absorber. *IEICE Electr Exp* 14(12):2017
133. Hokmabadi MP, Tareki A, Rivera E, Kung P, Lindquist RG, Kim SM (2017) Investigation of tunable terahertz metamaterial perfect absorber with anisotropic dielectric liquid crystal. *AIP Adv* 7(1):015102
134. Wang L, Ge S, Hu W, Nakajima M, Lu Y (2017) Graphene-assisted high-efficiency liquid crystal tunable terahertz metamaterial absorber. *Opt Exp* 25(20):23873–23879
135. Deng G, Lu Y, Yin Z, Lai W, Lu H, Yang J, Yang A, Ye Y, Liu D, Chi B (2018) A tunable polarization-dependent terahertz metamaterial absorber based on liquid crystal. *Electronics* 7(3):27
136. Deng G, Zhao T, Lu Y, Yang J, Yin Z (2018) A liquid crystal based tunable metamaterial absorber with wide incident angle stability. In: Proceedings of the 2018 international conference on microwave and millimeter wave technology, Chengdu, China
137. Yin Z, Lu Y, Xia T, Lai W, Yang J, Lu H, Deng G (2018) Electrically tunable terahertz dual-band metamaterial absorber based on a liquid crystal Check for updates. *Roy Soc Chem Adv* 8(8):4197–4203
138. Yin Z, Wan C, Deng G, Zheng A, Wang P, Yang Y, Gao S, Yang J, Cai F, Li Z, Lu H (2018) Fast-tunable terahertz metamaterial absorber based on polymer network liquid crystal. *Appl Sci* 8(12):2454
139. Kuznetsov SA, Nikolaev NA, Trashkeev SI, Lazorskiy PA, Arzhannikov AV (2019) Application of the concept of ultra-thin resonant absorbers for controlling millimeter-wave radiation by means of liquid crystals. *Siberian J Phys* 14(2):86–102
140. Deng G, Hu H, Mo H, Xu J, Yin Z, Lu H, Hu M, Li J, Yang J (2021) Tunable terahertz metamaterial wideband absorber with liquid crystal. *Opt Mater Exp* 11(12):4026–4035
141. Lv JF, Ding C, Meng FY, Han JQ, Jin T, Wu Q (2021) A tunable metamaterial absorber based on liquid crystal with the compact unit cell and the wideband absorption. *Liq Cryst* 48(10):1438–1447
142. Deng G, Hu H, Mo H, Yin Z, Lu H, Hu M, Li J, Yang J (2022) Liquid crystal-based wide-angle metasurface absorber with large frequency tunability and low voltage. *Opt Exp* 30(13):22550–22561
143. Ning R, Wang F, Huang W, Jiao Z (2023) Dual controlled cross-shaped broadband terahertz absorber based on vanadium oxide—liquid crystal metamaterial. *J Opt* 12:1–7
144. Zhou S, Shen Z, Kang R, Ge S, Hu W (2018) Liquid crystal tunable dielectric metamaterial absorber in the terahertz range. *Appl Sci* 8(11):2211
145. Madhav BTP, Pisipati VGKM, Khan H, Prasad VGNS, Praveen Kumar K, Bhavani KVL, Ravi Kumar M (2011) Liquid crystal bow-tie microstrip antenna for wireless communication applications. *J Eng Sci Technol Rev* 4(2):131–134
146. Damm C, Maasch M, Gonzalo R, Jakoby R (2010) Tunable composite right/left-handed leaky wave antenna based on a rectangular waveguide using liquid crystals. In: Proceedings of the 2010 IEEE MTT-S international microwave symposium, Anaheim, CA, pp 13–16
147. Roig M, Maasch M, Damm C, Jakoby R (2013) Steerable Ka-Band leaky wave antenna based on liquid crystal material. In: Proceedings of the 2013 7th international congress on advanced

- electromagnetic materials in microwaves and optics (METAMATERIALS), Talence, France, pp 540–545
148. Roig M, Maasch M, Damm C, Karabey OH, Jakoby R (2013) Liquid crystal based tunable composite right/left-handed leaky-wave antenna for Ka-Band applications. In: Proceedings of the 2013 43rd European microwave conference, Nuremberg, Germany, pp 759–762
 149. Roig M, Maasch M, Damm C, Jakoby R (2014) Liquid crystal-based tunable CRLH-transmission line for leaky wave antenna applications at Ka-band. *Int J Microw Wirel Technol* 6(3–4):325–330
 150. Roig M, Maasch M, Damm C, Jakoby R (2014) Dynamic beam steering properties of an electrically tuned liquid crystal based CRLH leaky wave antenna. In: Proceedings of the 2014 8th international congress on advanced electromagnetic materials in microwaves and optics, Copenhagen, pp 253–255
 151. Roig M, Maasch M, Damm C, Jakoby R (2014) Electrically tunable liquid crystal based composite right/left-handed leaky-wave antenna at 26.7 GHz. In: Proceedings of the 2014 44th European microwave conference, Rome, Italy, pp 331–334
 152. Roig M, Maasch M, Damm C, Jakoby R (2015) Investigation and application of a liquid crystal loaded varactor in a voltage tunable CRLH leaky-wave antenna at Ka-band. *Int J Microw Wirel Technol* 7(3–4):361–367
 153. Che BJ, Meng FY, Lyu YL, Wu Q (2016) A novel liquid crystal based leaky wave antenna. In: Proceedings of the 2016 IEEE MTT-S international microwave workshop series on advanced materials and processes for RF and THz applications, Chengdu
 154. Che BJ, Jin T, Erni D, Meng FY, Lyu YL, Wu Q (2017) Electrically controllable composite right/left-handed leaky-wave antenna using liquid crystals in PCB technology. *IEEE Trans Comp Pack Manuf Technol* 7(8):1331–1342
 155. Ma S, Wang PY, Zhang FL, Meng FY, Wu Q (2016) Electrically controlled leaky wave antenna with wide-angle scanning based on liquid crystal. In: Proceedings of the 2016 IEEE international conference on electronic information and communication technology, Harbin, pp 603–605
 156. Papanicolaou NC, Christou MA, Polycarpou AC, Nestoros M, Tchema R (2020) Electromagnetic modeling and simulation of microwave and mm-wave devices based on liquid crystal compounds. *AIP Confer Proceed* 2302(1):110006
 157. Tchema RB, Polycarpou AC (2020) Quasi-periodic leaky-wave antenna based on substrate integrated waveguide and liquid crystal technologies. In: Proceedings of the 2020 14th European conference on antennas and propagation, Copenhagen
 158. Tchema R, Papanicolaou NC, Polycarpou AC (2021) An investigation of the dynamic beam-steering capability of a liquid-crystal-enabled leaky-wave antenna designed for 5G applications. *Appl Phys Lett* 119(13):034104
 159. Reese R, Jost M, Polat E, Tesmer H, Strobl J, Schuster C, Nickel M, Jakoby R, Maune H (2019) A millimeter-wave beam-steering lens antenna with reconfigurable aperture using liquid crystal. *IEEE Trans Antennas Propag* 67(8):5313–5324
 160. Stevenson R, Sazegar M, Bily A, Johnson M, Kundtz N (2016) Metamaterial surface antenna technology: commercialization through diffractive metamaterials and liquid crystal display manufacturing. In: Proceedings of the 2016 10th international congress on advanced electromagnetic materials in microwaves and optics, Chania, pp 349–351
 161. Stevenson RA, Fotheringham D, Freeman T, Noel T, Shafie S (2018) High-throughput satellite connectivity for the constant contact vehicle. In: Proceedings of the 2018 48th European microwave conference, Madrid, pp 316–319
 162. Bily A, Kundtz N, Johnson M (2023) Dynamic polarization and coupling control from a steerable cylindrically fed holographic antenna. Patent No. US11545747B2, Kymeta Corp
 163. Martin N, Laurent P, Person C, Huret F (2003) Patch antenna adjustable in frequency using liquid crystal. In: Proceedings of the 2003 33rd European microwave conference, Munich, pp 699–702
 164. Martin N, Laurent P, Person C, Gelin P, Huret F (2004) Size reduction of a liquid crystal-based, frequency-adjustable patch antenna. In: Proceedings of the 2004 34th European microwave conference, vol 2, Amsterdam, pp 825–828

165. Bernigaud JP, Laur V, Laurent P, Martin N, Tanne G, Huret F (2008) Ferroelectrics- and liquid crystal-based microwave agile devices. In: Proceedings of the 2008 German microwave conference, Hamburg-Harburg
166. Christou MA, Papanicolaou NC, Polycarpou AC (2014) A nematic liquid crystal tunable patch antenna. In: Proceedings of the 2014 8th European conference on antennas and propagation, The Hague, pp 1875–1878
167. Kitatani K, Tsuji T, Okamura Y (2005) Circular polarized tunable patch antenna using liquid crystal. In: Proceedings of the 2005 international symposium on antennas and propagation, Seoul, pp 989–992
168. Martin N, Laurent P, Person C, Le Roy M, Perennec A, Gelin P, Huret F (2005) Influence of design liquid crystal-based devices on the agility capability. In: Proceedings of the 2005 IEEE MTT-S international microwave symposium, Long Beach, pp 1835–1838
169. Crossland WA, Collings N, Robertson PA (2007) Liquid crystal devices. World intellectual property organization Patent No. WO2007122409A1
170. Liu L, Langley RJ (2008) Liquid crystal tunable microstrip patch antenna. *Electr Lett* 44(20):1179–1181
171. Christodoulou CG, Tawk Y, Lane SA, Erwin SR (2013) Reconfigurable antennas for wireless and space applications. *Proceed IEEE* 101(7):2250–2261
172. Polycarpou AC, Christou MA, Papanicolaou NC (2014) Tunable patch antenna printed on a biased nematic liquid crystal cell. *IEEE Trans Antennas Propag* 62(10):4980–4987
173. Papanicolaou NC, Christou MA, Polycarpou AC (2016) Electromagnetic modeling of printed antennas on nematic liquid crystal cells. In: Proceedings of the 2016 10th European conference on antennas and propagation, Davos
174. Missaoui S, Gharbi A, Kaddour M (2011) Design and simulation reconfigurable liquid crystal patch antennas on foam substrate. *J Chem Eng Mater Sci* 2(7):96–102
175. Fritzsch C, Bildik S, Jakoby R (2012) Ka-band frequency tunable patch antenna. In: Proceedings of the 2012 IEEE antennas and propagation society international symposium, Chicago, IL
176. Missaoui S, Missaoui S, Kaddour M (2013) Compact circularly polarized low-profile agility GPS antenna based on liquid crystals. *Adv Microelectr Eng* 1(3):67–71
177. Woehrle CD, Ayoub FN, Doyle DT, Christodoulou CG (2014) Liquid crystal reconfigurable circularly polarized patch antenna. In: Proceedings of the 2014 IEEE antennas and propagation society international symposium, Memphis, TN, pp 561–562
178. Papanicolaou NC, Christou MA, Polycarpou AC (2015) Frequency-agile microstrip patch antenna on a biased liquid crystal substrate. *Electr Lett* 51(3):202–204
179. Liu Y, Agrawal A, Natarajan A (2016) Millimeter-wave IC-antenna cointegration for integrated transmitters and receivers. *IEEE Antennas Wireless Propag Lett* 15:1848–1852
180. Missaoui S, Missaoui S, Kaddour M (2016) Reconfigurable microstrip patch antenna based on liquid crystals for microwave applications. In: Proceedings of the 2016 3rd international conference on green energy and environmental engineering, pp 23–28
181. Bily A, Kundtz N, Johnson M (2018) Dynamic polarization and coupling control from a steerable cylindrically fed holographic antenna, Patent No. US9887456B2. Kymeta Corp
182. Bily A, Kundtz N, Johnson M (2019) Dynamic polarization and coupling control from a steerable, multi-layered cylindrically fed holographic antenna. Patent No. US10431899B2, Kymeta Corp
183. Posthuma B, Nonis A, Lammé D (2019) Portable flat-panel satellite antenna. EP 3:537–538
184. Kim D, Kim K, Kim H, Choi M, Na JH (2021) Design optimization of reconfigurable liquid crystal patch antenna. *Materials* 14(4):932
185. Srinivas AS, Poorna Priya P, Khan H (2008) A novel microstrip T-slot antenna on liquid crystal substrate for X-band applications. *Int J Innov Res Technol Sci* 2(2):102–107
186. Mohamad S, Cahill R (2017) Spiral antenna with reconfigurable HIS using liquid crystals for monopulse radar application. In: Proceedings of the 2017 IEEE conference on antenna measurements and applications, Tsukuba, pp 55–58

187. Kumar TA, Devi YU, Madhav BTP, Kotamraju SK, Rajesh V (2019) High gain flexible liquid crystal polymer based 8-element printed antenna for millimetric wave applications. *Int J RF Microw Comput Aided Eng* 29(7):e21744
188. Madhav BT, Devi YU, Anilkumar T (2019) Defected ground structured compact MIMO antenna with low mutual coupling for automotive communications. *Microw Opt Technol Lett* 61(3):794–800
189. Tebbe M, Hoehn A, Nathrath N, Weickhmann C (2016) Simulation of an electronically steerable horn antenna array with liquid crystal phase shifters. In: *Proceedings of the 2016 IEEE aerospace conference, Big Sky, MT*
190. Kamei T, Yokota M, Ozaki R, Moritake H, Onodera N (2011) Microstrip array antenna with liquid crystals loaded phase shifter. *Mol Cryst Liq Cryst* 542(1):167–175
191. Madhav BTP, Pisipati VGKM, Khan H, Prasad VGNS, Praveen K, Bhavani KVL, Prasad PVD (2011) Microstrip 2×2 square patch array antenna on K15 liquid crystal substrate. *Int J Appl Eng Res* 6(9):1099–1104
192. Ayoub FN, Woehrle CD, Tawk Y, Doyle DT, Christodoulou CG, Costantine J (2014) Frequency-tunable patch array using highly anisotropic liquid crystal. In: *Proceedings of the 2014 USNC-URSI radio science meeting/2014 IEEE antennas and propagation society international symposium, Memphis, TN*, pp 1664–1665
193. Hosono R, Uemichi Y, Hasegawa Y, Nakatani Y, Kobayashi K, Guan N (2017) Development of millimeter-wave devices based on liquid crystal polymer (LCP) substrate. *IEICE Electr Exp* 14(20):1–13
194. Hosono R, Uemichi Y, Hasegawa Y, Kobayashi K, Nakatani Y, Guan N (2018) Development for LCP-based millimeter-wave devices. *Fujikura Tech Rev* 48:23–27
195. Nose T, Ito R, Honma M (2018) Potential of liquid-crystal materials for millimeter-wave application. *Appl Sci* 8(12):2544
196. Ma S, Zhang SQ, Ma LQ, Meng FY, Erni D, Zhu L, Fu JH, Wu Q (2018) Compact planar array antenna with electrically beam steering from backfire to endfire based on liquid crystal. *IET Microw Antennas Propag* 12(7):1140–1146
197. Hassan AEH, Fadlallah N, Rammal M, El Nashef GZ, Rachid E (2021) Wideband reconfigurable millimeter-wave linear array antenna using liquid crystal for 5G networks. *Wireless Eng Technol* 12(1):1–14
198. Karabey OH, Bildik S, Fritzsche C, Strunck S, Gaebler A, Jakoby R, Manabe A (2010) Liquid crystal based reconfigurable antenna arrays. In: *Proceedings of the 2010 32nd ESA antenna workshop on antennas for space applications, Noordwijk*
199. Wolff I (2010) Integrated beam steerable antennas in LTCC-technology. In: *Proceedings of the 2010 international workshop on antenna technology, Lisbon*
200. Deo P, Mirshekar-Syahkal D, Seddon L, Day SE, Aníbal Fernández F (2013) 60 GHz liquid crystal phased array using reflection-type phase shifter. In: *Proceedings of the 2013 7th European conference on antennas and propagation, Gothenburg*, pp 927–929
201. Deo P, Mirshekar-Syahkal D, Seddon L, Day SE, Fernandez FA (2014) Beam steering 60 GHz slot antenna array using liquid crystal phase shifter. In: *Proceedings of the 2014 8th European conference on antennas and propagation, The Hague*, pp 1005–1007
202. Fernández FA, Seddon L, James R, Day SE, Bulja S, Deo P, Mirshekar-Syahkal D (2015) Accurate modelling of liquid crystal-based microwave devices. *Mol Cryst Liq Cryst* 619(1):19–27
203. Zhao Y, Qing A (2016) Reconfigurable antenna based on liquid crystal (LC) technology. In: *Proceedings of the 2016 progress in electromagnetic research symposium, Shanghai*, p 4019
204. Zhao Y, Qing A, Lin C (2016) Frequency reconfigurable antenna based on liquid crystal material, invention patent CN 201610096052.2
205. Zhao Y, Huang C, Qing A, Luo X (2017) A frequency and pattern reconfigurable antenna based on liquid crystal technology. *IEEE Photon J* 9(3):4600307
206. Foo S (2018) Liquid-crystal reconfigurable, lens-enhanced, millimeter-wave phased array. In: *Proceedings of the 2018 12th European conference on antennas and propagation, London*

207. Barzegari S, Dadashzadeh GR, Tahanian E (2015) Improvement of the reflection coefficient of waveguide-fed phased-array antenna using liquid crystal. *J Commun Eng* 4(1):41–54
208. Dehghani MR, Akgiray AH, Mehmood A, Karabey OH (2020) Liquid crystals: a power and cost-efficient electronically steerable antenna solution for 5G. *Microw J* 63(5):110–120
209. Xiu W, Han Y, Pang C, Li Y, Wang X, Tian H, Wu D (2022) Design and implementation of one-dimensional liquid crystal holographic coding phased array antenna. *Chin J Radio Sci* 37(4):610–618
210. Ismail MY, Cahill R (2005) Beam steering reflectarrays using liquid crystal substrate. In: Proceedings of the 2005 IEEE high frequency postgraduate colloquium, Leeds, pp 62–65
211. Ismail MY, Cahill R (2005) Application of liquid crystal technology for electronically scanned Reflectarrays. In: Proceedings of the 2005 Asia-Pacific conference on applied electromagnetics, Johor, pp 82–85
212. Hu W, Ismail MY, Cahill R, Dickie R, Gamble HS, Fusco VF, Linton D, Grant N (2006) Integrated liquid crystal phase shifter for reflectarray antennas. In: Proceedings of the 2006 Loughborough antennas propagation conference, Loughborough, pp 173–176
213. Hu W, Ismail MY, Cahill R, Gamble HS, Dickie R, Fusco VF, Linton D, Rea SP, Grant N (2006) Tunable liquid crystal reflectarray patch element. *Electr Lett* 42(9):509–511
214. Ismail MY, Zain AFM (2009) Phase tunability of reflectarray patch elements using tunable dielectric substrate of nematic liquid crystal. In: Proceedings of the 2009 international workshop on antenna technology, Santa Monica, CA
215. Marin R, Mossinger A, Freese J, Muller S, Jakoby R (2005) Basic investigations of 35 GHz reflectarrays and tunable unit-cells for beamsteering applications. In: Proceedings of the 2005 European radar conference, Paris, pp 291–294
216. Marin R, Mossinger A, Freese J, Muller S, Jakoby R (2005) Basic investigations of 35 GHz reflectarrays and tunable unit-cells for beamsteering applications. In: Proceedings of the 2005 European radar conference, Paris, pp 307–310
217. Marin R, Mossinger A, Freese J, Muller S, Jakoby R (2005) Basic investigations of 35 GHz reflectarrays and tunable unit-cells for beam steering applications. In: Proceedings of the 2005 35th European microwave conference, Paris, pp 2018–2021
218. Marin R, Moessinger A, Freese J, Jakoby R (2006) Characterisation of 35 GHz tunable reflectarray unit-cells using highly anisotropic liquid crystal. In: Proceedings of the 2006 German microwave conference, Universität Karlsruhe
219. Marin R, Mossinger A, Freese J, Manabe A, Jakoby R (2006) Realization of 35 GHz steerable reflectarray using highly anisotropic liquid crystal. In: Proceedings of the 2006 IEEE antennas and propagation society international symposium, Albuquerque, NM, pp 4307–4310
220. Moessinger A, Marin R, Mueller S, Freese J, Jakoby R (2006) Electronically reconfigurable reflectarrays with nematic liquid crystals. *Electr Lett* 42(16):899–900
221. Mueller S, Moessinger A, Marin R, Goelden F, Lapanik A, Haase W, Jakoby R (2007) Liquid crystals: microwave characterization and tunable devices. *Frequenz* 61(9–10):217–223
222. Moessinger A, Eicher D, Gaebler A, Marin R, Mueller S, Jakoby R, Schlaak HF (2008) Electronically reconfigurable LC-reflectarray with 2D scanning capability and SU-8 structured cavity. *Frequenz* 62(3–4):62–66
223. Dieter S, Moessinger A, Mueller S, Jakoby R, Menzel W (2009) Characterization of reconfigurable LC-reflectarrays using near-field measurements. In: Proceedings of the 2009 German microwave conference, Munich
224. Moessinger A, Marin R, Freese J, Mueller S, Manabe A, Jakoby R (2006) Investigations on 77 GHz tunable reflectarray unit cells with liquid crystal. In: Proceedings of the 2006 1st European conference on antennas and propagation, Nice
225. Marin R, Moessinger A, Goelden F, Mueller S, Jakoby R (2007) 77 GHz reconfigurable reflectarray with nematic liquid crystal. In: proceedings of the 2007 2nd European conference on antennas and propagation, Edinburgh
226. Gaebler A, Moessinger A, Goelden F, Manabe A, Goebel M, Follmann R, Koether D, Modes C, Kipka A, Deckelmann M, Rabe T, Schulz B, Kuchenbecker P, Lapanik A, Mueller S, Haase W, Jakoby R (2009) Liquid crystal-reconfigurable antenna concepts for space applications at microwave and millimeter waves. *Int J Antennas Propag* 14:876989

227. Hu W, Ismail MY, Cahill R, Encinar JA, Fusco VF, Gamble HS, Linton D, Dickie R, Grant N, Rea SP (2007) Liquid-crystal-based reflectarray antenna with electronically switchable monopulse patterns. *Electr Lett* 43(14):744–745
228. Hu W, Cahill R, Encinar JA, Dickie R, Gamble H, Fusco V, Grant N (2008) Design and measurement of reconfigurable millimeter wave reflectarray cells with nematic liquid crystal. *IEEE Trans Antennas Propag* 56(10):3112–3117
229. Hu W, Arrebola M, Cahill R, Encinar JA, Fusco V, Gamble HS, Alvarez Y, Las-Heras F (2009) 94 GHz dual-reflector antenna with reflectarray subreflector. *IEEE Trans Antennas Propag* 57(10):3043–3050
230. Bildik S, Fritzsche C, Moessinger A, Jakoby R (2010) Tunable liquid crystal reflectarray with rectangular elements. In: *Proceedings of the 2010 German microwave conference, Berlin*, pp 1–4
231. Bildik S, Dieter S, Fritzsche C, Frei M, Fischer C, Menzel W, Jakoby R (2011) Reconfigurable liquid crystal reflectarray with extended tunable phase range. In: *Proceedings of the 2011 41st European microwave conference, Manchester*, pp 1292–1295
232. Bildik S, Dieter S, Fritzsche C, Frei M, Fischer C, Menzel W, Jakoby R (2011) Reconfigurable liquid crystal reflectarray with extended tunable phase range. In: *proceedings of the 2011 8th European radar conference, Manchester*, pp 404–407
233. de Valorització U (2011) Reconfigurable beam reflectarray antenna for frequencies in the range of terahertz and millimeter wave. *Universitat Politècnica de Catalunya Patent MKT2011/0026-1*
234. Dieter S, Feil P, Menzel W (2011) Folded reflectarray antenna using a modified polarization grid for beam-steering. In: *Proceedings of the 2011 5th European conference on antennas and propagation, Rome*
235. Perez-Palomino G, Encinar JA, Barba M (2011) Accurate electromagnetic modeling of liquid crystal cells for reconfigurable reflectarrays. In: *Proceedings of the 2011 5th European conference on antennas and propagation, Rome*, pp 997–1001
236. Perez-Palomino G, Encinar JA, Barba M, Carrasco E (2012) Design and evaluation of multi-resonant unit cells based on liquid crystals for reconfigurable reflectarrays. *IET Microw Antennas Propag* 6(3):348–354
237. Perez-Palomino G, Encinar JA, Barba M, Dickie R, Baine P, Cahill R, Florencio R, Boix RR (2012) Wideband unit-cell based on liquid crystals for reconfigurable reflectarray antennas in f-band. In: *Proceedings of the 2012 IEEE antennas and propagation society international symposium, Chicago, IL*
238. Perez-Palomino G, Baine P, Dickie R, Bain M, Encinar JA, Cahill R, Barba M, Toso G (2013) Design and experimental validation of liquid crystal-based reconfigurable reflectarray elements with improved bandwidth in F-band. *IEEE Trans Antennas Propag* 61(4):1704–1713
239. Perez-Palomino G, Encinar JA, Barba M, Cahill R, Dickie R, Baine P, Bain M (2015) Millimeter-wave beam-scanning antennas using liquid crystals. In: *Proceedings of the 2015 9th European conference on antennas and propagation, Lisbon*
240. Gao H, Yin M, Chu X, Gao S, Zhao Z, Yang J, Yin Z, Deng G (2021) Terahertz reflective beam scanning antenna based on liquid crystal. *J Terahertz Sci Electr Inform Technol* 19(4):642–647
241. Yang J, Xu L, Zhang G, Li Y, Hu M, Li J, Lu H, Deng G, Yin Z (2022) Electrically active control of terahertz waves in a hybrid metasurface–grating structure with a liquid crystal. *Appl Opt* 61(29):8704–8710
242. Yang J, Xu L, Zhang G, Li X, Li Y, Hu M, Li J, Lu H, Deng G, Yin Z (2022) Rapid terahertz wave manipulation in a liquid-crystal-integrated metasurface structure. *Opt Exp* 30(18):33014–33021
243. Guirado R, de la Rosa P, Perez-Palomino G, Caño-García M, Carrasco E, Quintana X (2023) Characterization and application of dual frequency liquid crystal mixtures in mm-wave reflectarray cells to improve their temporal response. *TechRxiv*
244. Ismail MY, Abbasi MI, Dahri MH (2013) Phase characterization of reconfigurable reflectarray antennas. *Int J Electr Eng Inform* 5(4):447–453

245. Ismail MY, Inam M (2014) Design of liquid crystal based tunable reflectarray antenna using slot embedded patch element configurations. *World Acad Sci Eng Technol Int J Electr Comput Energ Electr Commun Eng* 8(10):1515–1520
246. Bildik S, Dieter S, Fritzsche C, Menzel W, Jakoby R (2015) Reconfigurable folded reflectarray antenna based upon liquid crystal technology. *IEEE Trans Antennas Propag* 63(1):122–132
247. Perez-Palomino G, Barba M, Encinar JA, Cahill R, Dickie R, Baine P, Bain M (2015) Design and demonstration of an electronically scanned reflectarray antenna at 100 GHz using multiresonant cells based on liquid crystals. *IEEE Trans Antennas Propag* 63(8):3722–3727
248. Ismail MY, Inam M (2016) Liquid crystal based reconfigurable reflectarray antenna design. *World Acad Sci Eng Technol Int J Electr Commun Eng* 10(1):52–56
249. Yang J, Cai C, Yin Z, Xia T, Jing S, Lu H, Deng G (2018) Reflective liquid crystal terahertz phase shifter with tuning range of over 360°. *IET Microw Antennas Propag* 12(9):1466–1469
250. Yang J, Xia T, Jing S, Deng G, Lu H, Fang Y, Yin Z (2018) Electrically tunable reflective terahertz phase shifter based on liquid crystal. *J Infrared Millimeter Terahertz Waves* 39(5):439–446
251. Sun SY, Yu X, Wang PJ, Wan CF, Yang J, Yin Z, Deng G, Lu HB (2020) Electronically tunable liquid-crystal-based F-band phase shifter. *IEEE Access* 8:151065–151071
252. Yang J, Gao S, Wang P, Yin Z, Lu H, Lai W, Li Y, Deng G (2020) Design and experimental verification of a liquid crystal-based terahertz phase shifter for reconfigurable reflectarrays. *J Infrared Millimeter Terahertz Waves* 41(6):665–674
253. Yang J, Wang P, Sun S, Li Y, Yin Z, Deng G (2020) A novel electronically controlled two-dimensional terahertz beam-scanning reflectarray antenna based on liquid crystals. *Front Phys* 8:576045
254. Mao R, Xu J, Li X, Sun S, Li X, Yang J, Yin Z, Deng G, Lu H (2021) Design and fabrication of a liquid crystal-based 94 GHz 360 phase shifter for reflectarray antennas. *Prog Electromagnet Res Lett* 100:145–150
255. Yang J, Xu L, Zhang G, Mao R, Yin Z, Lu H, Deng G, Li Y (2022) Active continuous control of terahertz wave based on a reflectarray element-liquid crystal-grating electrode hybrid structure. *Opt Exp* 30(10):17361–17370
256. Meng X, Nekovee M, Wu D (2019) Reconfigurable liquid crystal reflectarray metasurface for THz communications. *arXiv1908.02736v1*
257. Meng X, Nekovee M, Wu D (2019) Reconfigurable liquid crystal reflectarray metasurface for THz communications. In: *Proceedings of the 2019 institute of engineering and technology antennas and propagation conference*, Birmingham, pp 45–50
258. Meng X, Nekovee M, Wu D (2011) The design and analysis of electronically reconfigurable liquid crystal-based reflectarray metasurface for 6G beamforming, beamsteering, and beamsplitting. *IEEE Access* 9:155564–155575
259. Abbasi MI, Ismail MY, Kamarudin MR, Abbasi QH (2021) Reconfigurable reflectarray antenna: a comparison between design using PIN diodes and liquid crystals. *Wireless Commun Mob Comput* 12:2835638
260. Zhang W, Li Y, Zhang Z (2022) A reconfigurable reflectarray antenna with an 8 μm -thick layer of liquid crystal. *IEEE Trans Antennas Propag* 70(4):2770–2778
261. Aghabeyki P, Cai Y, Deng G, Tan ZH, Zhang S (2023) A dual-polarized reconfigurable reflectarray with a thin liquid crystal layer and 2D beam scanning. *IEEE Trans Antennas Propag* 20:10036445
262. Sanadgol B, Holzwarth S, Kassner J (2009) 30 GHz liquid crystal phased array. In: *Proceedings of the 2009 Loughborough antennas propagation conference*, Loughborough, pp 589–592
263. Shi H, Li J, Zhu S, Zhang A, Xu Z (2018) Radiation pattern reconfigurable waveguide slot array antenna using liquid crystal. *Int J Antennas Propag* 32:2164065
264. Mueller S, Koeberle M, Moessinger A, Goelden F, Gaebler A, Jakoby R (2008) Liquid crystal based electronically steerable 4×4 antenna array with single horn feed at Ka-Band. In: *Proceedings of the 2008 IEEE antennas and propagation society international symposium*, San Diego, CA

265. Hoefle M, Koeberle M, Chen M, Penirschke A, Jakoby R (2010) Reconfigurable Vivaldi antenna array with integrated antipodal finline phase shifter with liquid crystal for W-band applications. In: Proceedings of the 2010 35th international conference on infrared, millimeter, and terahertz waves, Rome
266. Hoefle M, Koeberle M, Penirschke A, Jakoby R (2011) Millimeterwave Vivaldi antenna with liquid crystal phase shifter for electronic beam steering. In: Proceedings of the 2011 6th ESA workshop on millimetre-wave technology and applications, Espoo
267. Hoefle M, Koeberle M, Penirschke A, Jakoby R (2011) Improved millimeter wave Vivaldi antenna array element with high performance liquid crystals. In: Proceedings of the 2011 36th international conference on infrared, millimeter, and terahertz waves, Huston, TX
268. Xia Y, Yuan M, Dobrea A, Li C, Heidari H, Mottram N, Ghannam R (2022) Reconfigurable wearable antenna for 5G applications using nematic liquid crystals
269. Yeh JA, Chang CA, Cheng CC, Huang JY, Hsu SSH (2005) Microwave characteristics of liquid-crystal tunable capacitors. *IEEE Electr Dev Lett* 26(7):451–453
270. Goelden F, Gaebler A, Mueller S, Lapanik A, Haase W, Jakoby R (2008) Liquid-crystal varactors with fast switching times for microwave applications. *Electr Lett* 44(7):480–481
271. Goelden F, Lapanik A, Gaebler A, Mueller S, Haase W, Jakoby R (2008) Characterization and application of liquid crystals at microwave frequencies. *Frequenz* 62(3–4):57–61
272. Xu H, Trushkevych O, Collings N, Crossland WA (2009) Measurement of dielectric anisotropy of some liquid crystals for microwave applications. *Mol Cryst Liq Cryst* 502(1):235–244
273. Karabey OH, Bausch S, Bildik S, Strunck S, Gaebler A, Jakoby R (2012) Design and application of a liquid crystal varactor based tunable coupled line for polarization agile antennas. In: proceedings of the 2012 42nd European microwave conference, Amsterdam, pp 739–742
274. Karabey OH, Bausch S, Bildik S, Strunck S, Gaebler A, Jakoby R (2012) Design and application of a liquid crystal varactor based tunable coupled line for polarization agile antennas. In: Proceedings of the 2012 9th European radar conference, Amsterdam, pp 413–416
275. Hu W, Karabey OH, Gäbler A, Prasetiadi AE, Jost M, Jakoby R (2014) Liquid crystal varactor loaded variable phase shifter for integrated compact and fast beamsteering antenna systems. In: Proceedings of the 2014 9th European microwave integrated circuit conference, Rome, pp 660–663
276. Bernigaud JF, Martin N, Laurent P, Quendo C, Tanne G, Della B, Huret F, Gelin P (2006) Liquid crystal tunable filter based on DBR topology. In: Proceedings of the 2006 36th European microwave conference, Manchester, pp 368–371
277. Chen CY, Pan CL, Hsieh CF, Lin YF, Pan RP (2006) A liquid-crystal-based terahertz tunable lyot filter. *Appl Phys Lett* 88(10):101107
278. Pan CL, Pan RP (2006) Recent progress in liquid crystal THz optics. *SPIE Liq Cryst Mater Dev Appl XI* 6135:61350D
279. Pan CL, Pan RP (2007) Liquid-crystal-based devices manipulate terahertz-frequency radiation. *SPIE Newsroom*
280. Jewell SA, Hendry E, Issac TH, Sambles JR (2008) Tuneable Fabry-Perot etalon for terahertz radiation. *New J Phys* 10:033012
281. Gobel T, Meissner P, Gaebler A, Koeberle M, Mueller S, Jakoby R (2009) Dual-frequency switching liquid crystal based tunable THz filter. In: Proceedings of the 2009 conference on lasers and electro-optics and 2009 conference on quantum electronics and laser science, Baltimore, MD
282. Goelden F, Gaebler A, Karabey O, Goebel M, Manabe A, Jakoby R (2010) Tunable band-pass filter based on liquid crystal. In: Proceedings of the 2010 German microwave conference, Berlin, pp 98–101
283. Yazdanpanahi M, Mirshekar-Syahkal D (2012) Millimeter-wave liquid-crystal-based tunable bandpass filter. In: Proceedings of the 2012 IEEE radio and wireless symposium, Santa Clara, CA, pp 139–142
284. Follmann R, Köther D, Arias Campo M, Franke T, Gabler A, Jakoby R, Manabe A, Rabe T, Heunisch A, Rauch A, Kässer T (2013) Liquida-Sky: a tunable liquid crystal filter for space applications. In: Proceedings of the 2013 IEEE-APS topical conference on antennas and propagation in wireless communications, Torino, pp 90–93

285. Torrecilla J, Marcos C, Urruchi V, Sánchez-Pena JM (2013) Tunable dual-mode bandpass filter based on liquid crystal technology. In: Proceedings of the 2013 43rd European microwave conference, Nuremberg, pp 806–809
286. Torrecilla J, Urruchi V, Sánchez-Pena JM, Bennis N, García A, Segovia D (2014) Improving the pass-band return loss in liquid crystal dual-mode bandpass filters by microstrip patch reshaping. *Materials* 7(6):4524–4535
287. Jost M, Weickhmann C, Franke T, Prasetiadi AE, Hu W, Nickel M, Karabey OH, Jakoby R (2015) Tuneable hollow waveguide devices for space applications based on liquid crystal. In: Proceedings of the 2015 SBMO/IEEE MTT-S international microwave and optoelectronics conference, Porto de Galinhas
288. Prasetiadi AE, Karabey OH, Weickhmann C, Franke T, Hu W, Jost M, Nickel M, Jakoby R (2015) Continuously tunable substrate integrated waveguide bandpass filter in liquid crystal technology with magnetic biasing. *Electr Lett* 51(20):1584–1585
289. Prasetiadi AE, Jost M, Schulz B, Quibeldey M, Rabe T, Follmann R, Jakoby R (2018) Liquid-crystal-based amplitude tuner and tunable SIW filter fabricated in LTCC technology. *Int J Microw Wirel Technol* 10(5–6):674–681
290. Shen M, Huang Y, Shao Z (2015) A tunable microstrip dual-mode bandpass filter based on liquid crystal technology. In: Proceedings of the 2015 IEEE international conference on communication problem-solving, Guilin, pp 464–466
291. Jiang D, Liu Y, Cao W, Guo Z (2016) A compact novel microwave liquid crystal tunable band-pass filter. *Optik* 127(20):8374–8378
292. Liu Y, Jiang D, Cao W, Yang T, Xia L, Xu R (2016) Microwave tunable split ring resonator bandpass filter using nematic liquid crystal materials. *Optik* 127(21):10216–10222
293. Li X, Shao Z, He Z, Shen M (2016) A miniaturized electrically tunable dual-mode bandpass filter based on liquid crystal technology for microwave applications. *Microw Opt Technol Lett* 58(7):1686–1689
294. Cai L, Xu H, Chu D (2017) Compact liquid crystal based tunable band-stop filter with an ultra-wide stopband by using wave interference technique. *Int J Antennas Propag* 32:9670965
295. Economou EC, Lovejoy J, Harward I, Nobles JE, Kula P, Herman J, Glushchenko A, Celinski Z (2017) Electrically tunable open-stub bandpass filters based on nematic liquid crystals. *Phys Rev Appl* 8(6):064012
296. Guo Z, Liu Y, Jiang D (2017) A compact tunable microwave band-pass filter using liquid crystal material. *Optik* 135:134–138
297. Polat E, Reese R, Jost M, Schuster C, Nickel M, Jakoby R, Maune H (2019) Tunable liquid crystal filter in nonradiative dielectric waveguide technology at 60 GHz. *IEEE Microw Wirel Comp Lett* 29(1):44–46
298. Divsalar A, Salarian S, Mirshekar-Syahkal D (2022) MMW 60 GHz tunable periodic filter. In: Proceedings of the 2022 8th international conference on antennas and electromagnetic systems, Marrakesh
299. Missaoui S, Missaoui S, Kaddour M (2017) Tunable SIW bandpass filter-combined microstrip antenna based on liquid crystals. *Int J Hydr Energy* 42(13):8804–8812
300. Wilk R, Vieweg N, Kopschinski O, Koch M (2009) Liquid crystal based electrically Bragg structure for THz waves. *Opt Exp* 17(9):7377–7382
301. Skulski J, Szymańska A (2013) Liquid crystal tunable microwave band stop filters. *SPIE Electr Technol Confer* 8902:89022E
302. Torrecilla J, Avila-Navarro E, Marcos C, Urruchi V, Sanchez-Pena JM, Arias J, Sanchez-Lopez MM (2013) Microwave tunable notch filter based on liquid crystal using spiral spurline technology. *Microw Opt Technol Lett* 55(10):2420–2423
303. Urruchi V, Marcos C, Torrecilla J, Sánchez-Pena JM, Garbat K (2013) Note: Tunable notch filter based on liquid crystal technology for microwave applications. *Rev Sci Instrum* 84(2):026102
304. Cai L, Xu H, Pivnenko M, Chu D (2014) A tunable wideband microstrip bandstop filter based on liquid crystal materials. In: Proceedings of the 2014 IEEE international conference on communication problem-solving, Beijing, pp 656–657

305. Jiang D, Liu Y, Cao W, Chen H, Luo W, Ding M (2016) A novel tunable inverted microstrip filter based on liquid crystal. *Microw Opt Technol Lett* 58(7):1626–1628
306. Economou EC, Lovejoy J, Harward I, Nobles JE, Kula P, Herman J, Glushchenko A, Celinski Z (2018) Liquid crystal based tunable spurline filters with notch frequencies at 50 and 85 GHz. *Microw Opt Technol Lett* 60(3):672–679
307. Tanaka M, Sato S (2002) Focusing properties of liquid crystal lens cells with stack-layered structure in the millimeter-wave region. *IEEE Microw Wirel Compon Lett* 12(5):163–165
308. Tanaka M, Sato S (2002) Electrically controlled millimeter-wave focusing properties of liquid crystal lens. *Jpn J Appl Phys Reg Papers Short Notes* 41(8):5332–5333
309. Nose T, Seno T, Yuri R, Ito R, Honma M (2011) Fundamental properties of Fresnel lens in MMW region for liquid crystal lens applications. In: *Proceedings of the 2011 36th international conference on infrared, millimeter, and terahertz waves*, Huston, TX
310. Nose T, Ohno S, Masaka M, Ito K, Ito R, Honma M (2017) Basic performance of a liquid crystal millimeter wave Fresnel lens fabricated using machinable porous polymethylmethacrylate materials. *Mol Cryst Liq Cryst* 647(1):341–350
311. Nose T, Watanabe Y, Kon A, Ito R, Honma M (2018) Quasi-optic millimeter-wave device application of liquid crystal material by using porous PMMA matrix. *SPIE Emerg Liq Cryst Technol XIII* 10555:105550T
312. Shen Z, Zhou S, Ge S, Duan W, Ma L, Lu Y, Hu W (2019) Liquid crystal tunable terahertz lens with spin-selected focusing property. *Opt Exp* 27(6):8800–8807
313. Bao L, Cui TJ (2020) Tunable, reconfigurable, and programmable metamaterials. *Microw Opt Technol Lett* 62(1):9–32
314. Tsilipakos O, Tasolamprou AC, Pitilakis A, Liu F, Wang X, Mirmoosa MS, Tzarouchis DC, Abadal S, Taghvaei H, Liaskos C, Tsioliaridou A, Georgiou J, Cabellos-Aparicio A, Alarcón E, Ioannidis S, Pitsillides A, Akyildiz IF, Kantartzis NV, Economou EN, Soukoulis CM, Kafesaki M, Tretyakov S (2020) Toward intelligent metasurfaces: the progress from globally tunable metasurfaces to software-defined metasurfaces with an embedded network of controllers. *Adv Opt Mater* 8(17):2000783
315. Fan Y, Zhao Q, Zhang F, Shen N (2021) Tunable and reconfigurable optical metamaterials. *Front Phys*
316. Xu J, Yang R, Fan Y, Fu Q, Zhang F (2021) A review of tunable electromagnetic metamaterials with anisotropic liquid crystals. *Front Phys* 9:633104
317. Liang YC, Chen J, Long R, He ZQ, Lin X, Huang C, Liu S, Shen XS, Renzo MD (2021) Reconfigurable intelligent surfaces for smart wireless environments: channel estimation, system design and applications in 6G networks. *Sci China Inform Sci* 64(10):200301
318. Basharat S, Khan M, Iqbal M, Hashmi US, Zaidi SAR, Robertson I (2022) Exploring reconfigurable intelligent surfaces for 6G: State-of-the-art and the road ahead. *IET Commun* 16(13):1458–1474
319. Jiménez-Sáez A, Asadi A, Neuder R, Wang D, Jakoby R (2022) Liquid crystals: the way to scalable and practical reconfigurable intelligent surfaces in 6G. *TechRxiv* 21335733
320. Yang F, Pitchappa P, Wang N (2022) Terahertz reconfigurable intelligent surfaces (RISs) for 6G communication links. *Micromachines* 13(2):285
321. Khoo IC, Werner DH, Liang X, Diaz A, Weiner B (2006) Nanosphere dispersed liquid crystals for tunable negative-zero-positive index of refraction in the optical and terahertz regimes. *Opt Lett* 31(17):2592–2594
322. Amanaganti S, Chowdhury DR, Ravník M, Dontabaktuni J (2018) Electromagnetic response of dielectric nanostructures in liquid crystals. *SPIE Emerg Liq Cryst Technol XIII* 10555:105551F
323. Kundtz N (2014) Next generation communications for next generation satellites. *Microw J* 57(8):56–64
324. Novin SN, Jarchi S, Yaghmaee P (2017) Tunable frequency selective surface based on IDC-loaded electric-LC resonator incorporated with liquid crystal. In: *Proceedings of the 2017 conference on microwave techniques*, Brno, pp 80–89

325. Chang CL, Wang WC, Lin HR, Hsieh FJ, Pun YB, Chan CH (2013) Tunable terahertz fishnet metamaterial. *Appl Phys Lett* 102(15):151903
326. Maasch M, Roig M, Damm C, Jakoby R (2014) Realization of a voltage tunable gradient-index fishnet loaded with liquid crystal. In: *Proceedings of the 2014 8th international congress on advanced electromagnetic materials in microwaves and optics*, Copenhagen, pp 196–198
327. Maasch M, Roig M, Damm C, Jakoby R (2014) Voltage-tunable artificial gradient-index lens based on a liquid crystal loaded fishnet metamaterial. *IEEE Antennas Wirel Propag Lett* 13:1581–1584
328. Zografopoulos DC, Beccherelli R (2015) Tunable terahertz fishnet metamaterials based on thin nematic liquid crystal layers for fast switching. *Sci Rep* 5:13137
329. Algorri JF, Zografopoulos D, Bennis N, Morawiak P, Urruchi V, Sánchez-Pena JM, Beccherelli R (2018) Active metasurface at THz based on liquid crystals. In: *Proceedings of the 2018 22nd conference on liquid crystals: chemistry, physics and applications*, Jastrzębia Góra
330. Tanaka M, Nose T, Sato S (2000) Millimeter-wave transmission properties of nematic liquid-crystal cells with a grating-patterned electrode structure. *Jpn J Appl Phys Regul Papers Short Notes* 39(11):6393–6396
331. Lin CJ, Li YT, Hsieh CF, Pan RP, Pan CL (2008) Manipulating terahertz wave by a magnetically tunable liquid crystal phase grating. *Opt Exp* 16(5):2995–3001
332. Lin CJ, Lin CH, Li YT, Pan RP, Pan CL (2009) Electrically controlled liquid crystal phase grating for terahertz waves. *IEEE Photon Technol Lett* 21(11):730–732
333. Choudhury PK (ed) (2018) *Liquid crystals: recent advancements in fundamental and device technologies*. Intech
334. Yang F, Sambles J (2001) Microwave liquid crystal wavelength selector. *Appl Phys Lett* 79(22):3717–3719
335. Yang F, Sambles JR (2002) A liquid crystal microwave wavelength selector. *Liq Cryst Today* 11(4):1–2
336. Yang F, Sambles JR (2004) Microwave liquid-crystal variable phase grating. *Appl Phys Lett* 85(11):2041–2043
337. Sambles JR, Kelly R, Yang Z (2006) Metal slits and liquid crystals at microwave frequencies. *Philos Trans R Soc Lond A* 364(1847):2733–2746
338. Yang F, Sambles JR (2002) Determination of the microwave permittivities of nematic liquid crystals using a single-metallic slit technique. *Appl Phys Lett* 81(11):2047–2049
339. Yang F, Sambles JR (2003) Determination of the permittivity of nematic liquid crystals in the microwave region. *Liq Cryst* 30(5):599–602
340. Tanaka M, Sato S (2001) Electrically controlled millimeter-wave transmission properties of stack-layered liquid crystal cells with metal substrates. *Jpn J Appl Phys* 40(6A):4131–4135
341. Kamoda H, Kuki T, Fujikake H, Nomoto T (2003) Millimeter-wave beam former using liquid crystal. In: *Proceedings of the 2003 28th international conference on infrared and millimeter waves*, Otsu, pp 259–260
342. Kamoda H, Kuki T, Fujikake H, Nomoto T (2004) Millimeter-wave beam former using liquid crystal. In: *Proceedings of the 2004 34th European microwave conference*, Amsterdam, pp 1141–1144
343. Kamoda H, Kuki T, Fujikake H, Nomoto T (2005) Millimeter-wave beam former using liquid crystal. *Electr Commun Jpn* 88(8):10–18
344. Kamoda H, Kuki T, Nomoto T (2005) Conductor loss reduction for liquid crystal millimeter-wave beam former. *IEICE Electr Exp* 2(18):471–476
345. Yuan Y, He J, Liu J, Yao J (2010) Proposal of an electrical controlled terahertz switch based on liquid-crystal-filled dual-metallic grating structures. *Appl Opt* 49(31):6092–6097
346. Xu S, Fan F, Cao H, Wang Y, Chang S (2021) Liquid crystal integrated metamaterial for multi-band terahertz linear polarization conversion. *Chin Opt Lett* 19(9):093701
347. Pan CL, Hsieh CF, Pan RP, Tanaka M, Miyamaru F, Tani M, Hangyo M (2005) Control of enhanced THz transmission through metallic hole arrays using nematic liquid crystal. *Opt Exp* 13(11):3921–3930

348. Yang J, Li J, Xia T, Deng G, Yin Z (2016) Design of 340 GHz liquid crystal modulator based on double-layer metal hole arrays. In: Proceedings of the 2016 IEEE international conference on microwave and millimeter wave technology, Beijing, pp 943–945
349. Zheng A, Xia X, Gao S, Yang J, Lu H, Deng G, Yin Z (2020) Dielectric properties of two high birefringence liquid crystal mixtures in the Sub-THz band. *Liq Cryst* 47(1):83–88
350. Mao R, Zhang G, Xu L, Gao H, Yang J, Yin Z, Deng G, Lu H (2022) Dielectric properties of liquid crystal polymer substrates in the region from 90 to 140 GHz. *Crystals* 12(2):170
351. Deng G, Mo H, Kou Z, Yang J, Yin Z, Li Y, Lu H (2023) A polyimide-free configuration for tunable terahertz liquid-crystal-based metasurface with fast response time. *Opt Laser Technol* 161:109127
352. Foo S (2017) Liquid-crystal-tunable metasurface antennas. In: Proceedings of the 2017 11th European conference on antennas and propagation, Paartis, pp 3026–3030
353. Foo S (2017) Liquid-crystal reconfigurable metasurface reflectors. In: Proceedings of the 2017 IEEE international symposium on antennas and propagation and USNC/URSI National Radio Science Meeting, San Diego, pp 2069–2070
354. Wang Q, Zhang XG, Tian HW, Jiang WX, Bao D, Jiang HL, Luo ZJ, Wu LT, Cui TJ (2019) Millimeter-wave digital coding metasurfaces based on nematic liquid crystals. *Adv Theory Simul* 2(12):1900141
355. Lv JF, Meng FY, Zhang K, Ding C, Han JQ, Liu YH, Wu Q (2022) Tunable liquid crystal metasurface with polarization selection characteristic. *J Phys D Appl Phys* 55(37):375001
356. Matsuno H, Ohto T, Amano Y, Okita M, Suzuki D, Matsunaga K, Oka S (2022) Development of a direction-variable liquid crystal meta-surface reflector. In: Proceedings of the 2022 IEEE international conference on communication workshop on advances in software defined and context aware cognitive networks, Seoul, pp 4854–4859
357. Ohto T, Matsuno H, Amano Y, Okita M, Suzuki D, Matsunaga K, Oka S (2022) Reconfigurable meta-surface reflectors: practical phase adjustment method and experimental validation. In: Proceedings of the 2022 95th IEEE vehicular technology conference, Helsinki
358. Rea S (2007) Liquid crystal tunable mm wave frequency selective surface. *IEEE Microw Wirel Compon Lett* 17(9):667–669
359. Bossard JA, Liang X, Li L, Yun S, Werner DH, Weiner B, Mayer TS, Cristman PF, Diaz A, Khoo IC (2008) Tunable frequency selective surfaces and negative-zero-positive index index metamaterials based on liquid crystals. *IEEE Trans Antennas Propag* 56(5):1308–1320
360. Wu J, Shen Z, Ge S, Chen B, Shen Z, Wang T, Zhang C, Hu W, Fan K, Padilla W, Lu Y, Jin B, Chen J, Wu P (2020) Liquid crystal programmable metasurface for terahertz beam steering. *Appl Phys Lett* 116(13):131104
361. Zhao Q, Kang L, Du B, Li B, Zhou J, Tang H, Liang X, Zhang B (2007) Electrically tunable negative permeability metamaterials based on nematic liquid crystals. *Appl Phys Lett* 90(1):011112
362. Zhang F, Zhao Q, Kang L, Gaillot DP, Zhao X, Zhou J, Lippens D (2008) Magnetic control of negative permeability metamaterials based on liquid crystals. *Appl Phys Lett* 92(19):193104
363. Zhang F, Zhao Q, Kang L, Gaillot DP, Zhao X, Zhou J, Lippens D (2008) Magnetic control of negative permeability metamaterials based on liquid crystals. In: Proceedings of the 2008 38th European microwave conference, Amsterdam, pp 801–804
364. Kowordzie R, Olifierczuk M, Parka J, Jaroszewicz L (2012) Simulation of tunable meta-material with nematic liquid crystal layers. In: Proceedings of the 2012 19th international conference on microwaves, radar and wireless communications, Warsaw, pp 343–345
365. Liu Z, Huang CY, Liu H, Zhang X, Lee C (2013) Resonance enhancement of terahertz metamaterials by liquid crystals/indium tin oxide interfaces. *Opt Exp* 21(5):6519–6525
366. Chikhi N, Lisitskiy M, Papari G, Tkachenko V, Andreone A (2016) A hybrid tunable THz metadvice using a high birefringence liquid crystal. *Sci Rep* 6:34536
367. Yang J, Wang P, Gao S, Deng G, Lu H, Lai W, Yin Z, Li Y, Hu Y (2019) Tunable terahertz transmission properties of double-layered metal hole-loop arrays using nematic liquid crystal. *J Infrared Millimeter Terahertz Waves* 40(3):276–287

368. Zheng A, Chu X, Wang P, Wang P, Gao S, Yang J, Lu H, Deng G, Yin Z (2020) The characterization and application of two liquid crystal mixtures in the low THz region. *Crystals* 10(2):99
369. Yang J, Wang P, Shi T, Gao S, Lu H, Yin Z, Lai W, Deng G (2019) Electrically tunable liquid crystal terahertz device based on double-layer plasmonic metamaterial. *Opt Exp* 27(19):27039–27045
370. Buchnev O, Podoliak N, Kaltenecker K, Walther M, Fedotov VA (2020) Metasurface-based optical liquid crystal cell as an ultrathin spatial phase modulator for THz applications. *ACS Photon* 7(11):3199–3206
371. Yang J, Yin M, Wang P, Wang P, Yin Z, Deng G (2020) Liquid crystal terahertz modulator based on double-layer plasmonic metamaterial. In: *Proceedings of the 2020 international conference on microwave and millimeter wave technology*, Shanghai
372. Shih YH, Lin XY, Silalahi HM, Lee CR, Huang CY (2021) Optically tunable terahertz metasurfaces using liquid crystal cells coated with photoalignment layers. *Crystals* 11(9):1100
373. Fu X, Shi L, Yang J, Fu Y, Liu C, Wu JW, Yang F, Bao L, Cui TJ (2022) Flexible terahertz beam manipulations based on liquid-crystal-integrated programmable metasurfaces. *ACS Appl Mater Interf* 14(19):22287–22294
374. Perivolari E, Fedotov VA, Parka J, Kaczmarek M, Apostolopoulos V (2022) Anomalous resonance frequency shift in liquid crystal-loaded THz metamaterials. *Nanophotonics* 11(10):2341–2348
375. Zhuang X, Zhang W, Wang K, Gu Y, An Y, Zhang X, Gu J, Luo D, Han J, Zhang W (2023) Active terahertz beam steering based on mechanical deformation of liquid crystal elastomer metasurface. *Nat Light Sci Appl* 12:14
376. Zhang F, Zhao Q, Zhang W, Sun J, Zhou J, Lippens D (2010) Voltage tunable short wire-pair type of metamaterial infiltrated by nematic liquid crystal. *Appl Phys Lett* 97(13):131403
377. Shen Z, Zhou S, Ge S, Duan W, Chen P, Wang L, Hu W, Lu Y (2018) Liquid-crystal-integrated metadevice: towards active multifunctional terahertz wave manipulations. *Opt Lett* 43(19):4695–4698
378. Shen ZX, Zhou SH, Ge SJ, Hu W, Lu YQ (2019) Liquid crystal enabled dynamic cloaking of terahertz Fano resonators. *Appl Phys Lett* 114(4):041106
379. Vogel W, Berroth M (2001) Polarisation independent liquid crystal 360° phase shifter for optically generated RF-signals. In: *Proceedings of the 2001 31st European microwave conference*, London, pp 31–34
380. Chakam GA, Vogel W, Yilmaz H, Berroth M, Freude W (2002) Microstrip phased array patch antenna based on a liquid crystal phase shifter for optically generated RF-signals. In: *Proceedings of the 2002 international topical meeting on microwave photonics*, Awaji, pp 265–268
381. Sahoo AK, Yen CL, Lu YC, Pan CL, Yang CS, Lin HC, Lin YH, Wada O (2018) Liquid crystal based terahertz spatial light modulator for imaging application. In: *Proceedings of the 2018 43rd international conference on infrared, millimeter, and terahertz waves*, Nagoya
382. Maune H, Jost M, Reese R, Polat E, Nickel M, Jakoby R (2018) Microwave liquid crystal technology. *Crystals* 8(9):355
383. Ji Y, Fan F, Chang S (2021) Review of terahertz phase control devices based on liquid crystal integrated with microstructures or nanomaterials. In: *proceedings of the SPIE tenth international symposium on ultrafast phenomena and terahertz waves (ISUPTW 2021)*, vol 11909
384. Zeng H, Gong S, Wang L, Zhou T, Zhang Y, Lan F, Cong X, Wang L, Song T, Zhao Y, Yang Z, Mittleman DM (2022) A review of terahertz phase modulation from free space to guided wave integrated devices. *Nanophotonics* 11(3):415–437
385. You B, Lu JY (eds) (2022) *Terahertz technology*. Intech
386. Splingart B, Tentillier N, Huret F, Legrand C (2001) Liquid crystals applications to RF and microwave tunable components. *Mol Cryst Liq Cryst* 368:183–190
387. Martin N, Tentillier N, Laurent P, Splingart B, Huret F, Gelin P, Legrand C (2002) Electrically microwave tunable components using liquid crystals. In: *Proceedings of the 2002 32nd European microwave conference*, Milan, pp 393–396

388. Sahbani F, Tentillier N, Gharsallah A, Gharbi A, Legrand C (2008) New tunable coplanar microwave phase shifter with nematic crystal liquid. In: *Proceedings of the 2008 3rd international design and test workshop*, Monastir, pp 78–81
389. Missaoui S, Kaddour M, Gharbi A (2011) Design and simulation of tunable phase shifters based on liquid crystals. *Electromagnetics* 31(4):285–293
390. Li J, Chu D (2019) Liquid crystal-based enclosed coplanar waveguide phase shifter for 54–66 GHz applications. *Crystals* 9(12):650
391. Dubois F, Krasinski F, Splingart B, Tentillier N, Legrand C, Spadlo A, Dabrowski R (2008) Large microwave birefringence liquid-crystal characterization for phase-shifter applications. *Jpn J Appl Phys* 47(5R):3564–3567
392. Nose T, Saito S, Yanagihara S, Honma M (2006) Potential applications of nematic liquid crystal materials in the millimeter wave region. *SPIE Liq Cryst Mater Dev Appl XI* 6135:61350A
393. Nose T, Yanagihara S, Honma M (2006) Molecular orientation effects in the CPW type LC devices for MMW phase shifting. *SPIE Liq Cryst Mater Dev Appl XI* 6135:61350F
394. Nose T, Yanagihara S, Honma M (2007) Operational mode of millimeter-wave phase shifter using liquid crystal materials with coplanar waveguide. *Jpn J Appl Phys* 46(3R):1114–1117
395. Morita S, Ozaki R, Moritake H, Kamei T, Utsumi Y (2007) Microwave variable phase shifter of coplanar waveguide using ferroelectric liquid crystal. *Mol Cryst Liq Cryst* 476(1):105–113
396. Moritake H, Morita S, Ozaki R, Kamei T, Utsumi Y (2007) Fast-switching microwave phase shifter of coplanar waveguide using ferroelectric liquid crystal. *Jpn J Appl Phys* 46(2L):L519–L521
397. Utsumi Y, Kamei T, Maeda T, Dinh NQ (2007) Microwave high-speed liquid crystal devices using CPW with floating electrode. *Mol Cryst Liq Cryst* 476(1):3–13
398. Utsumi Y, Bach NT, Kamei T, Ozaki R, Moritake H (2009) Comparison of microwave measurements and theoretical calculations of dielectric birefringence for a liquid crystal loaded CPW-FE phase shifter. *Mol Cryst Liq Cryst* 510(1):197–213
399. Kamei T, Moritake H, Utsumi Y (2010) Microwave and light-wave measurements for nematic-liquid-crystal-loaded phase shifter using coplanar waveguide with floating electrode. *Jpn J Appl Phys* 49(1S):01AF03
400. Moritake H, Morita S, Ozaki R, Kamei T, Utsumi Y (2008) Microwave variable phase shifter of coplanar waveguide using ferroelectric liquid crystal. *Jpn J Appl Phys* 47(2S):1367–1370
401. Moritake H, Ozaki R, Kamei T, Utsumi Y (2011) Effective dielectric permittivity of coplanar waveguide type microwave phase shifter using ferroelectric liquid crystal. *Mol Cryst Liq Cryst* 542(1):158–166
402. Nose T, Yanagihara S, Sato Y, Ito R, Honma M (2008) Improvement of phase-shifting properties in coplanar waveguide-type liquid crystal millimeter-wave phase shifter by introducing a resonant phenomenon. *Jpn J Appl Phys* 47(11R):8483–8486
403. Goelden F, Gaebler A, Goebel M, Manabe A, Mueller S, Jakoby R (2009) Tunable liquid crystal phase shifter for microwave frequencies. *Electr Lett* 45(13):686–687
404. Fritzsche C, Giacomozzi F, Karabey OH, Goelden F, Moessinger A, Bildik S, Colpo S, Jakoby R (2011) Continuously tunable W-band phase shifter based on liquid crystals and MEMS technology. In: *Proceedings of the 2011 European microwave integrated circuits conference*, Manchester, pp 522–525
405. Fritzsche C, Giacomozzi F, Karabey OH, Goelden F, Moessinger A, Bildik S, Colpo S, Jakoby R (2011) Continuously tunable W-band phase shifter based on liquid crystals and MEMS technology. In: *Proceedings of the 2011 41st European microwave conference*, Manchester, pp 1083–1086
406. Sahbani F, Tentillier N, Legrand C, Blary K, Gharsallah A, Gharbi A (2011) Coplanar liquid crystal reconfigurable phase-shifters. *Mol Cryst Liq Cryst* 542(1):204–212
407. Bulja S, Mirshekar-Syahkal D, James R, Day SE, Aníbal-Fernández F (2013) Effective dielectric constant of top grounded coplanar waveguide on liquid crystal substrate. *Microw Opt Technol Lett* 55(6):1416–1418

408. Franc A, Karabey OH, Rehder G, Pistono E, Jakoby R, Ferrari P (2013) Compact and broadband millimeter-wave electrically tunable phase shifter combining slow-wave effect with liquid crystal technology. *IEEE Trans Microw Theory Techn* 61(11):3905–3915
409. Nguyen T, Umeno S, Higuchi H, Kikuchi H, Moritake H (2014) Improvement of decay time in nematic-liquid-crystal-loaded coplanar-waveguide-type microwave phase shifter by polymer stabilizing method. *Jpn J Appl Phys* 53(1S):01AE08
410. Attoui A, Boualleg H (2015) External command study of the phase shifter for applications to array antenna with nematic liquid crystal. *Metall Min Ind* 7:134–140
411. Reese R, Jost M, Maune H, Jakoby R (2017) Design of a continuously tunable W-band phase shifter in dielectric waveguide topology. In: *Proceedings of the 2017 IEEE MTT-S international microwave symposium*, Honolulu, HI, pp 180–183
412. Reese R, Polat E, Jost M, Nickel M, Jakoby R, Maune H (2017) Liquid crystal based phase shifter in a parallel-plate dielectric waveguide topology at V-band. In: *Proceedings of the 2017 European microwave integrated circuit conference*, Nuremberg, pp 353–356
413. Bui VB, Inoue Y, Moritake H (2019) NRD waveguide-type terahertz phase shifter using nematic liquid crystal. *Jpn J Appl Phys* 58(2):022001
414. Lang TN, Bui VB, Inoue Y, Moritake H (2020) Response improvement of liquid crystal-loaded NRD waveguide type terahertz variable phase shifter. *Crystals* 10(4):307
415. Zhu K, Jiang D, Bai T, Zhang W, Zhang T, Gao J, Qi K (2021) Design of a terahertz phase shifter based on liquid crystal. In: *Proceedings of the 2021 14th UK-Europe-China workshop on millimetre-waves and terahertz technologies (UCMMT)*, Lancaster
416. Jost M, Reese R, Weickhmann C, Schuster C, Karabey OH, Maune H, Jakoby R (2016) Tunable dielectric delay line phase shifter based on liquid crystal technology for a SPDT in a radiometer calibration scheme at 100 GHz. In: *Proceedings of the 2016 IEEE MTT-S international microwave symposium*, San Francisco
417. Mueller S, Felber C, Scheele P, Wittek M, Hock C, Jakoby R (2005) Passive tunable liquid crystal finline phase shifter for millimeter waves. In: *Proceedings of the 2005 35th European microwave conference*, Paris
418. Koeberle M, Hoeffle M, Mo C, Penirschke A, Jakoby R (2011) Electrically tunable liquid crystal phase shifter in antipodal fin-line technology for reconfigurable W-Band Vivaldi antenna array concepts. In: *Proceedings of the 2011 5th European conference on antennas and propagation*, Rome, pp 1536–1539
419. Lu YQ, Hu W, Liang X (2014) 34.4: invited paper: THz devices based on high birefringence liquid crystals. In: *Society for information display symposium digest of technical papers*, pp 491–494
420. Wang L, Lin XW, Hu W, Shao GH, Chen P, Liang LJ, Jin BB, Wu PH, Qian H, Lu YN, Liang X, Zheng ZG, Lu YQ (2015) Broadband tunable liquid crystal terahertz waveplates driven with porous graphene electrodes. *Nat Light Sci Appl* 4:e253
421. Wang L, Ge S, Hu W, Nakajima M, Lu Y (2017) Tunable reflective liquid crystal terahertz waveplates. *Opt Mater Exp* 7(6):2023–2029
422. Zhang X, Fan F, Zhang CY, Ji YY, Wang XH, Chang SJ (2020) Tunable terahertz phase shifter based on dielectric artificial birefringence grating filled with polymer dispersed liquid crystal. *Opt Mater Exp* 10(2):282–292
423. Nozokido T, Maede S, Miyasaka N, Okada H, Nose T, Murai T (2010) A millimeter-wave quasi-optical grid phase shifter using liquid crystal. *IEICE Electr Exp* 7(2):67–72
424. Tamayo-Domínguez A, Fernández-González JM, Sierra-Castañer M (2018) Additive manufacturing and liquid crystals for new millimeter-wave devices. In: *Proceedings of the 2018 IEEE MTT-S Latin America microwave conference*, Arequipa
425. Weil C, Luessem G, Jakoby R (2002) Tunable inverted-microstrip phase shifter device using nematic liquid crystals. In: *Proceedings of the 2002 IEEE MTT-S international microwave symposium*, Seattle, WA, pp 367–371
426. Weil C, Müller S, Scheele P, Kryvoschapka Y, Lüssem G, Best P, Jakoby R (2003) Ferroelectric and liquid crystal-tunable microwave phase shifters. In: *Proceedings of the 2003 33rd European microwave conference*, Munich, pp 1431–1434

427. Jakoby R, Scheele P, Müller S, Weil C (2004) Nonlinear dielectrics for tunable microwave components. In: Proceedings of the 2004 15th international conference on microwaves, radar and wireless communications, Warsaw, pp 369–378
428. Weil C, Muller S, Scheele P, Jakoby R (2004) A comparative study of paraelectrics and novel liquid crystals for tunable microwave devices. *Frequenz* 58(7–8):162–168
429. Martin N, Laurent P, Prigent G, Gelin P, Huret F (2003) Improvement of an inverted microstrip line-based microwave tunable phase-shifter using liquid crystals. In: Proceedings of the 2003 33rd European microwave conference, Munich, pp 1417–1420
430. Martin N, Laurent P, Prigent G, Gelin P, Huret F (2004) Technological evolution and performances improvements of a tunable phase-shifter using liquid crystal. *Microw Opt Technol Lett* 43(4):338–341
431. Karabey OH, Goelden F, Gaebler A, Strunck S, Jakoby R (2011) Tunable loaded line phase shifters for microwave applications. In: Proceedings of the 2011 IEEE MTT-S international microwave symposium, Baltimore, MD
432. Karabey OH, Saavedra BG, Fritzsche C, Strunck S, Gaebler A, Jakoby R (2011) Methods for improving the tuning efficiency of liquid crystal based tunable phase shifters. In: Proceedings of the 2011 European microwave integrated circuits conference, Manchester, pp 494–497
433. Weil C, Müller S, Scheele P, Best P, Lüssem G, Jakoby R (2003) Highly-anisotropic liquid-crystal mixtures for tunable microwave devices. *Electr Lett* 39(24):1732–1734
434. Müller S, Scheele P, Weil C, Wittek M, Hock C, Jakoby R (2004) Tunable passive phase shifter for microwave applications using highly anisotropic liquid crystals. In: Proceedings of the 2004 IEEE MTT-S international microwave symposium, Fort Worth, pp 1153–1156
435. Penirschke A, Müller S, Scheele P, Weil C, Wittek M, Hock C, Jakoby R (2004) Cavity perturbation method for characterization of liquid crystals up to 35 GHz. In: Proceedings of the 2004 34th European microwave conference, Amsterdam, pp 545–548
436. Goelden F, Mueller S, Scheele P, Wittek M, Jakoby R (2006) IP3 measurements of liquid crystals at microwave frequencies. In: Proceedings of the 2006 36th European microwave conference, Manchester, pp 971–974
437. Goelden F, Lapanik A, Mueller S, Gaebler A, Haase W, Jakoby R (2007) Investigations on the behavior of ferroelectric liquid crystals at microwave frequencies. In: Proceedings of the 2007 37th European microwave conference, Munich, pp 106–109
438. Bulja S, Mirshekar-Syahkal D (2010) Meander line millimetre-wave liquid crystal based phase shifter. *Electr Lett* 46(11):769–770
439. Ito Y, Kawakami T, Sasamori T, Isota Y, Ito R, Honma M, Nose T (2011) MMW liquid crystal phase shifter by using novel microstrip structure. In: Proceedings of the 2011 36th international conference on infrared, millimeter, and terahertz waves, Huston, TX
440. Garbovskiy Y, Zagorodnii V, Krivosik P, Lovejoy J, Camley RE, Celinski Z, Glushchenko A, Dziaduszek J, Dąbrowski R (2012) Liquid crystal phase shifters at millimeter wave frequencies. *J Appl Phys* 111(5):054504
441. Ito R, Kawakami T, Ito Y, Sasamori T, Isota Y, Honma M, Nose T (2012) Fundamental properties of novel design microstrip line type of liquid crystal phase shifter in microwave region. *Jpn J Appl Phys* 51(4):044104
442. Nose T, Chien LC, Catanescu O, Golvin A, Ito Y, Sasamori T, Isota Y, Ito R, Honma M (2013) Improvement high-frequency performance of microstrip-line-type liquid crystal phase shifter. *Jpn J Appl Phys* 52(9R):091701
443. Nose T, Isaka T, Ito Y, Sasamori T, Isota Y, Ito R, Honma M, Watanabe T, Ito K (2013) Planar type liquid crystal phase shifter based on the microstripline structure. In: Proceedings of the 2013 38th international conference on infrared, millimeter, and terahertz waves, Mainz
444. Nose T, Ito Y, Isaka T, Chien LC, Catanescu O, Golvin A, Isota Y, Sasamori T, Ito R, Honma M (2013) High frequency performance extending to millimeter-waves in inverted-microstrip-line-type LC phase shifter. *SPIE Emerg Liq Cryst Technol VIII* 8642:864206
445. Karabey OH, Gaebler A, Strunck S, Jakoby R (2012) A 2-D electronically steered phased-array antenna with 2×2 elements in LC display technology. *IEEE Trans Microw Theory Techn* 60(5):1297–1306

446. Karabey H, Maasch M, Jakoby R (2012) Stable satellite link by liquid crystal based phased array antennas. *ATZelektronik Worldwide* 7(4):46–50
447. Strunck S, Karabey OH, Weickmann C, Gaebler A, Jakoby R (2013) Continuously tunable phase shifters for phased arrays based on liquid crystal technology. In: *Proceedings of the 2013 IEEE international symposium on phased array systems and technology*, Waltham, MA, pp 82–88
448. Karabey OH, Bildik S, Bausch S, Strunck S, Gaebler A, Jakoby R (2013) Continuously polarization agile antenna by using liquid crystal-based tunable variable delay lines. *IEEE Trans Antennas Propag* 61(1):70–76
449. Jiang D, Xu H, Pivnenko M, Chu D (2014) Compact phase shifter based on highly anisotropic liquid crystals for microwave frequency. *Electr Lett* 50(7):525–526
450. Karabey OH, Mehmood A, Ayluctarhan M, Braun H, Letz M, Jakoby R (2014) Liquid crystal based phased array antenna. *Electr Lett* 50(6):426–428
451. Mehmood A, Karabey OH, Ayluctarhan M, Zheng Y, Braun H, Hovhannisyan M, Letz M, Jakoby R (2014) Dielectric resonator antenna phased array with liquid crystal based phase shifters. In: *Proceedings of the 2014 8th European conference on antennas and propagation*, The Hague, pp 2436–2439
452. Nose T, Komuro T, Sasamori T, Isota Y, Watanabe T, Ito K, Ito R, Honma M (2014) Fundamental performance of liquid crystal millimeter-wave phase shifter using negative dielectric anisotropic material. In: *Proceedings of the 2014 39th international conference on infrared, millimeter, and terahertz waves*, Tucson, AZ
453. Yang T, Zhan M, Jiang D (2015) A novel tunable inverted microstrip phase shifter based on liquid crystal. In: *Proceedings of the 2015 IEEE international conference on communication problem-solving*, Guilin, pp 575–577
454. Cai L, Xu H, Li J, Chu D (2017) High figure-of-merit compact phase shifters based on liquid crystal material for 1–10 GHz applications. *Jpn J Appl Phys* 56(1):011701
455. Wang Q, Su Z, Li S, Zhao H, Yin X (2022) Electrically tunable liquid crystal phase shifter with excellent phase shift capability per wavelength based on opposed coplanar waveguide. *J Phys D Appl Phys* 55(40):405001
456. Wei L, Xue W, Chen Y, Alkeskjold TT, Bjarklev A (2009) Compact optically-fed microwave true-time delay using liquid crystal photonic bandgap fiber device. In: *Proceedings of the 2009 advances in optical sciences congress*, Honolulu, HI
457. Wei L, Xue W, Chen Y, Alkeskjold TT, Bjarklev A (2009) Optically fed microwave true-time delay based on a compact liquid-crystal photonic-band-gap-fiber device. *Opt Lett* 34(18):2757–2759
458. Gaebler A, Goelden F, Manabe A, Goebel M, Mueller S, Jakoby R (2009) Investigation of high performance transmission line phase shifters based on liquid crystal. In: *Proceedings of the 2009 European microwave conference*, Rome, pp 594–597
459. Hoehn A, Hager PB, Harder JT (2013) Design characterization of an electronic steerable Ka-band antenna using liquid crystal phase shifters. In: *Proceedings of the 2013 IEEE aerospace conference*, big sky, MT
460. Weickmann C, Nathrath N, Gehring R, Gaebler A, Jost M, Jakoby R (2013) A light-weight tunable liquid crystal phase shifter for an efficient phased array antenna. In: *Proceedings of the 2013 43rd European microwave conference*, Nuremberg, pp 428–431
461. Maune H, Weickmann C, Jost M, Reese R, Nickel M, Fritzsche C, Jakoby R (2017) Liquid crystal technology for reconfigurable satcom applications. In: *Proceedings of the 2017 topical workshop on internet of space*, Phoenix, AZ
462. Tebbe M, Hoehn A, Nathrath N, Weickmann C (2017) Manufacturing and testing of liquid crystal phase shifters for an electronically steerable array. In: *Proceedings of the 2017 IEEE aerospace conference*, Big Sky, MT
463. Weickmann C, Jost M, Laemmle D, Jakoby R (2014) Design and fabrication considerations for a 250 GHz liquid crystal phase shifter. In: *Proceedings of the 2014 39th international conference on infrared, millimeter, and terahertz waves*, Tucson, AZ

464. Heunisch A, Schulz B, Rabe T, Strunck S, Follmann R, Manabe A (2012) LTCC antenna array with integrated liquid crystal phase shifter for satellite communication. In: Proceedings of the 2012 international microelectronics assembly and packaging society (iMAPS) CICMT, Erfurt, pp 97–102
465. Jost M, Weickhmann C, Strunck S, Gäbler A, Fritzsche C, Karabey OH, Jakoby R (2013) Liquid crystal based low-loss phase shifter for W-band frequencies. *Electr Lett* 49(23):1460–1462
466. Jost M, Weickhmann C, Strunck S, Gaebler A, Hu W, Franke T, Prasetyadi AE, Karabey OH, Jakoby R (2014) Electrically biased W-band phase shifter based on liquid crystal. In: Proceedings of the 2014 39th international conference on infrared, millimeter, and terahertz waves, Tucson, AZ
467. Mueller S, Goelden F, Scheele P, Wittek M, Hock C, Jakoby R (2006) Passive phase shifter for W-band applications using liquid crystals. In: Proceedings of the 2006 36th European microwave conference, Manchester, pp 306–309
468. Alhmadi R, Sertel K (2017) Frozen modes in all-dielectric 3-way-coupled ridge waveguides. In: Proceedings of the 2017 IEEE international symposium on antennas and propagation and USNC/URSI national radio science meeting, San Diego, CA
469. Alhmadi R, Sertel K (2019) Tunable true time delay engine for UWB mm-wave beam-forming. In: Proceedings of the 2019 United States national committee of URSI national radio science meeting (USNC-URSI NRSM), Boulder, CO
470. Alhmadi R, Sertel K (2019) Frozen-light modes in 3-way coupled silicon ridge waveguides. In: Proceedings of the 2019 United States national committee of URSI national radio science meeting (USNC-URSI NRSM), Boulder, CO
471. Nickel M, Jiménez-Sáez A, Agrawal P, Gadallah A, Malignaggi A, Schuster C, Reese R, Tesmer H, Polat E, Wang D, Schumacher P, Jakoby R, Kissinger D, Maune H (2020) Ridge gap waveguide based liquid crystal phase shifter. *IEEE Access* 8:77833–77842
472. Moessinger A, Fritzsche C, Bildik S, Jakoby R (2010) Compact tunable Ka-band phase shifter based on liquid crystals. In: Proceedings of the 2010 IEEE MTT-S international microwave symposium, Anaheim, CA, pp 1020–1023
473. Weickhmann C, Gaebler A, Jost M, Gehring R, Nathrath N, Jakoby R (2013) Recent measurements of compact electronically tunable liquid crystal phase shifter in rectangular waveguide topology. *Electr Lett* 49(21):1345–1347
474. Chen CY, Tsai TR, Pan CL, Pan RP (2003) Room temperature terahertz phase shifter based on magnetically controlled birefringence in liquid crystals. *Appl Phys Lett* 83(22):4497–4499
475. Pan CL, Chao RP, Chen CY (2005) Terahertz phase shifter or retarder based on magnetically controlled birefringence in liquid crystals. Application No. US20050024359, National Chiao Tung University
476. Chen CY, Hsieh CF, Lin YF, Pan RP, Pan CL (2004) Magnetically tunable room-temperature 2π liquid crystal terahertz phase shifter. *Opt Exp* 12(12):2625–2630
477. Pan RP, Chen CY, Tsai TR, Pan CL (2004) Terahertz phase shifter with nematic liquid crystal in a magnetic field. *Mol Cryst Liq Cryst* 421(1):157–164
478. Wu HY, Hsieh CF, Tang TT, Pan RP, Pan CL (2006) Electrically tunable room-temperature 2π liquid crystal terahertz phase shifter. *IEEE Photon Technol Lett* 18(14):1488–1490
479. Pan CL, Pan RP (2007) Liquid-crystal-based electrically tunable THz optical devices. *SPIE Emerg Liq Cryst Technol II* 6487:648709
480. Hsieh CF, Pan RP, Tang TT, Chen HL, Pan CL (2006) Voltage-controlled liquid-crystal terahertz phase shifter and quarter-wave plate. *Opt Lett* 31(8):1112–1114
481. Koeberle M, Hoeffle M, Gaebler A, Penirschke A, Jakoby R (2011) Liquid crystal phase shifter for terahertz frequencies with quasi-orthogonal electrical bias field. In: Proceedings of the 2011 36th international conference on infrared, millimeter, and terahertz waves, Houston, TX
482. Pan CL, Pan RP (2012) Characterization and applications of liquid crystals in the THz frequency range. *SPIE Emerg Liq Cryst Technol VII* 8279:82790I
483. Altmann K, Reuter M, Garbat K, Koch M, Dabrowski R, Dierking I (2013) Polymer stabilized liquid crystal phase shifter for terahertz waves. *Opt Exp* 21(10):12395–12400

484. Karwin CM, Livesey KL (2013) Liquid crystal phase shifters with a twist. *Appl Phys Lett* 103(6):063508
485. Sahoo AK, Yang CS, Wada O, Pan CL (2019) Twisted nematic liquid crystal based terahertz phase shifter with crossed indium tin oxide finger type electrodes. *IEEE Trans Terahertz Sci Technol* 9(4):399–408
486. Karwin CM, Livesey KL (2014) Microwave properties of twisted and supertwisted nematic liquid crystals with weak anchoring. *Liq Cryst* 41(5):707–716
487. Wu Y, Ruan X, Chen CH, Shin YJ, Lee Y, Niu J, Liu J, Chen Y, Yang KL, Zhang X, Ahn JH, Yang H (2013) Graphene/liquid crystal based terahertz phase shifters. *Opt Exp* 21(18):21395–21402
488. Yang CS, Kuo C, Tang CC, Chen JC, Pan RP, Pan CL (2015) Liquid-crystal terahertz quarter-wave plate using chemical-vapor-deposited graphene electrodes. *IEEE Photon J* 7(6):2200808
489. Yang CS, Pan RP, Pan CL (2015) Liquid crystal terahertz photonics with indium tin oxide nanowhiskers and graphene as functional electrodes. *SPIE Emerg Liq Cryst Technol X* 9384:93840Q
490. Jiang SL, Ji YY, Fan F (2022) Terahertz liquid crystal phase shifter controlled by graphene transparent electrode. In: *SPIE seventeenth national conference on laser technology and optoelectronics*, vol 12501
491. Yang CS, Pan RP, Yu P, Pan CL (2014) Voltage-controlled 2π liquid-crystal terahertz phase shifter with indium-tin-oxide (ITO) nanowhiskers as transparent electrodes. In: *Proceedings of the 2014 31st URSI general assembly and scientific symposium*, Beijing
492. Yang CS, Tang TT, Pan RP, Yu P, Pan CL (2014) Liquid crystal terahertz phase shifters with functional indium-tin-oxide nanostructures for biasing and alignment. *Appl Phys Lett* 104(14):141106
493. Yang CS, Kuo C, Chen PH, Wu WT, Pan RP, Yu P, Pan CL (2019) High-transmittance 2π electrically tunable terahertz phase shifter with CMOS-compatible driving voltage enabled by liquid crystals. *Appl Sci* 9(2):271
494. Ung BSY, Yang Y, Parrott EPJ, Srivastava A, Park H, Chigrinov VG, Pickwell-MacPherson E (2014) Terahertz in plane and terahertz out of plane (TIP-TOP) switching of a liquid crystal spatial light modulator. In: *Proceedings of the 2014 39th international conference on infrared, millimeter, and terahertz waves*, Tucson, AZ
495. Macpherson E, Park H, Fan F, Chigrinov VG, Parrott EPJ (2016) Terahertz in plane and terahertz out-of-plane (TIP-TOP) switching liquid crystal devices. Patent No. US9298050B2, Chinese University of Hong Kong CUHK Hong Kong University of Science and Technology HKUST
496. Ung BSY, Liu X, Parrott EPJ, Srivastava AK, Park H, Chigrinov VG, Pickwell-MacPherson E (2018) Towards a rapid terahertz liquid crystal phase shifter: terahertz in-plane and terahertz out-plane (TIP-TOP) switching. *IEEE Trans Terahertz Sci Technol* 8(2):209–214
497. Oh-e M, Zheng DY (2022) Newly discovered dimensional effects of electrodes on liquid crystal THz phase shifters enable novel switching between in-plane and out-of-plane. *Sci Rep* 12:5482
498. Du Y, Tian H, Cui X, Wang H, Zhou ZX (2016) Electrically tunable liquid crystal terahertz phase shifter driven by transparent polymer electrodes. *J Mater Chem C* 4(19):4138–4142
499. Sahoo AK, Yang CS, Yen CL, Lin HC, Wang YJ, Lin YH, Wada O, Pan CL (2019) Twisted nematic liquid-crystal-based terahertz phase shifter using pristine PEDOT: PSS transparent conducting electrodes. *Appl Sci* 9(4):761
500. Ito R, Honma M, Nose T (2018) Electrically tunable hydrogen-bonded liquid crystal phase control device. *Appl Sci* 8(12):2478
501. Jakoby R, Hamza Karabey O, Hu W (2018) Phase shift device. Patent No. US20150380789, Alcan Systems GmbH
502. Yu JP, Chen S, Fan F, Cheng JR, Xu ST, Wang XH, Chang SJ (2018) Tunable terahertz wave-plate based on dual-frequency liquid crystal controlled by alternating electric field. *Opt Exp* 26(2):663–673

503. Alex-Amor A, Palomares-Caballero Á, Palomares A, Tamayo-Domínguez A, Fernández-González JM, Padilla P (2019) Generalized director approach for liquid-crystal-based reconfigurable RF devices. *IEEE Microw Wirel Compon Lett* 29(10):634–637
504. Alex-Amor A, Tamayo-Domínguez A, Palomares-Caballero Á, Fernández-González JM, Padilla P, Valenzuela-Valdés J, Palomares A (2019) Analytical approach of director tilting in nematic liquid crystals for electronically tunable devices. *IEEE Access* 7:14883–14893
505. Hsieh CF, Yang CS, Shih FC, Pan RP, Pan CL (2019) Liquid-crystal-based magnetically tunable terahertz achromatic quarter-wave plate. *Opt Exp* 27(7):9933–9940
506. Ji Y, Fan F, Xu S, Yu J, Chang S (2019) Manipulation enhancement of terahertz liquid crystal phase shifter magnetically induced by ferromagnetic nanoparticles. *Nanoscale* 11(11):4933–4941
507. Yang J, Chu X, Gao H, Wang P, Deng G, Yin Z, Lu H (2021) Fully electronically phase modulation of millimeter-wave via comb electrodes and liquid crystal. *IEEE Antennas Wirel Propag Lett* 20(3):342–345
508. Wang D, Polat E, Tesmer H, Jakoby R, Maune H (2021) A compact and fast 1×4 continuously steerable endfire phased-array antenna based on liquid crystal. *IEEE Antennas Wirel Propag Lett* 20(10):1859–1862
509. Wang D, Polat E, Tesmer H, Maune H, Jakoby R (2022) Switched and steered beam end-fire antenna array fed by wideband via-less butler matrix and tunable phase shifters based on liquid crystal technology. *IEEE Trans Antennas Propag* 70(7):5383–5392
510. Gao S, Yang J, Wang P, Zheng A, Lu H, Deng G, Lai W, Yin Z (2018) Tunable liquid crystal based phase shifter with a slot unit cell for reconfigurable reflectarrays in F-band. *Appl Sci* 8(12):2528
511. Kamei T, Utsumi Y, Moritake H, Toda K, Suzuki H (2003) Measurements of the dielectric properties of nematic liquid crystals at 10 kHz to 40 GHz and application to a variable delay line. *Electr Commun Jpn* 86(8):49–60
512. Fujikake H, Kuki T, Nomoto T, Tsuchiya Y, Utsumi Y (2001) Thick polymer-stabilized liquid crystal films for microwave phase control. *J Appl Phys* 89(10):5295–5298
513. Utsumi Y, Kamei T, Saito K, Moritake H (2005) Increasing the speed of microstrip-line-type polymer-dispersed liquid-crystal loaded variable phase shifter. *IEEE Trans Microw Theory Techn* 53(11):3345–3353
514. Bui VB, Inoue Y, Higuchi H, Kikuchi H, Moritake H (2018) Response improvement of microstrip line microwave and millimeter wave phase shifter utilizing polymer stabilized nematic liquid crystal with UV polymerization. *Electr Commun Jpn* 101(3):49–57
515. Kuki T, Fujikake H, Kamoda H, Nomoto T (2003) Microwave variable delay line using a membrane impregnated with liquid crystal. *IEICE Trans Electr* 86(8):1699–1703
516. Utsumi Y, Kamei T (2005) Birefringence of nematic liquid crystal in microwave and light wave region. *Mol Cryst Liq Cryst* 434(1):1–7
517. Fujikake H, Kuki T, Kamoda H, Sato F, Nomoto T (2003) Voltage-variable microwave delay line using ferroelectric liquid crystal with aligned submicron polymer fibers. *Appl Phys Lett* 83(9):1815–1817
518. Tsai TR, Chen CY, Pan RP, Pan CL, Zhang XC (2004) Electrically controlled room temperature terahertz phase shifter with liquid crystal. *IEEE Microw Wirel Comp Lett* 14(2):77–79
519. Wang H, Zheng L, Chen J, Wu TX, Wu ST (2004) Smart millimeter-wave devices using liquid crystal. In: *SPIE smart structures and materials 2004: smart electronics, MEMS, BioMEMS, and nanotechnology*, vol 5389, pp 476–485
520. Moritake H, Toda K, Kamei T, Utsumi Y, Haase W (2005) Microwave phase shifter with ferroelectric liquid crystal having large tilt angle. *Mol Cryst Liq Cryst* 434(1):199–207
521. Kamei T, Dinh NQ, Utsumi Y (2007) Microwave polymer dispersed liquid crystal loaded variable phase shifter. *Mol Cryst Liq Cryst* 476(1):15–30
522. Belyaev BA, Leksikov AA, Serzhantov AM, Shabanov VF (2008) Controllable liquid-crystal microwave phase shifter. *Tech Phys Lett* 34(6):463–466

523. Christie S, Cahill R, Mitchell N, Munro Y, Manabe A (2013) Electronically scanned Rotman lens antenna with liquid crystal phase shifters. *Electr Lett* 49(7):445–447
524. Deo P, Mirshekar-Syahkal D, Seddon L, Day SE, Aníbal Fernández F (2013) Liquid crystal based patch antenna array for 60 GHz applications. In: *Proceedings of the 2013 IEEE radio and wireless symposium*, Austin, TX, pp 127–129
525. Fernandez FA, Seddon L, James R, Day SE, Mirshekar-Syahkal D, Bulja S, Deo P (2014) Accurate modelling of liquid crystal-based microwave devices. In: *Proceedings of the 2014 5th workshop on liquid crystals for photonics*, Erice
526. Nguyen T, Nguyen BT, Ozaki R, Moritake H (2013) Analyses of nematic liquid crystal molecule motion and response characteristics in microstripline-type microwave phase shifter. *Jpn J Appl Phys* 52(12R):121701
527. Xu H, Jiang D, Cai L, Pivnenko M, Chu D (2014) Minimising the losses due to EM field discontinuities in a compact LC tunable microstrip line phase shifter. In: *Proceedings of the 2014 IEEE international conference on communication problem-solving*, Beijing, pp 658–660
528. Jost M, Strunck S, Heunisch A, Wiens A, Prasetiadi AE, Weickhmann C, Schulz B, Quibeldey M, Karabey OH, Rabe T, Follmann R, Koether D, Jakoby R (2015) Continuously tuneable liquid crystal based stripline phase shifter realised in LTCC technology. In: *Proceedings of the 2015 45th European microwave conference*, Paris, pp 1260–1263
529. Seddon L, James R, Day SE, Fernandez FA, Deo P, Mirshekar-Syahkal D (2017) Accurate modelling for the analysis and design of liquid-crystal-based microwave devices. In: *Proceedings of the 2017 IEEE international workshop on electromagnetics: applications and student innovation competition*, London, pp 105–107
530. Jost M, Gautam JSK, Gomes LG, Reese R, Polat E, Nickel M, Pinheiro JM, Serrano ALC, Maune H, Rehder GP, Ferrari P, Jakoby R (2018) Miniaturized liquid crystal slow wave phase shifter based on nanowire filled membranes. *IEEE Microw Wirel Compon Lett* 28(8):681–683
531. Strunck S, Gaebler A, Karabey OH, Heunisch A, Schulz B, Rabe T, Follmann R, Kassner J, Koether D, Manabe A, Jakoby R (2015) Reliability study of a tunable Ka-band SIW-phase shifter based on liquid crystal in LTCC-technology. *Int J Microw Wirel Technol* 7(5):521–527
532. Scherger B, Reuter M, Scheller M, Altmann K, Vieweg N, Dabrowski R, Deibel JA, Koch M (2012) Discrete terahertz beam steering with an electrically controlled liquid crystal device. *J Infrared Millimeter Terahertz Waves* 33(11):1117–1122
533. Hsieh CF, Lai YC, Pan RP, Pan CL (2008) Polarizing terahertz waves with nematic liquid crystals. *Opt Lett* 33(11):1174–1176
534. Ito R, Kumagai T, Yoshida H, Takeya K, Ozaki M, Tonouchi M, Nose T (2011) THz nematic liquid crystal devices using stacked membrane film layers. *Mol Cryst Liq Cryst* 543(1):77/843-84/850
535. Strunck S, Karabey OH, Gaebler A, Jakoby R (2012) Reconfigurable waveguide polariser based on liquid crystal for continuous tuning of linear polarization. *Electr Lett* 48(8):441–443
536. Doumanis E, Goussetis G, Dickie R, Cahill R, Baine P, Bain M, Fusco V, Encinar JA, Toso G (2014) Electronically reconfigurable liquid crystal based mm-wave polarization converter. *IEEE Trans Antennas Propag* 62(4):2302–2307
537. Ji Y, Fan F, Zhang Z, Cheng J, Chang S (2022) Active terahertz liquid crystal device with carbon nanotube film as both alignment layer and transparent electrodes. *Carbon* 190:376–383
538. Yang J, Zhang G, Xu L, Li Y, Deng G, Yin Z, Lu H (2022) Highly efficient and tunable terahertz polarization converter based on double subwavelength metallic gratings infiltrated with liquid crystal. *Appl Opt* 61(28):8265–8272
539. Piccirillo B, Paparo D, Rubano A, Andreone A, Conti MR, Giove D, Vicuña-Hernández V, Koral C, Masullo MR, Mettievier G, Opromolla M, Papari G, Passarelli A, Pesce G, Petrillo V, Piedipalumbo E, Ruijter M, Russo P, Serafini L (2023) Liquid crystal-based geometric phase-enhanced platform for polarization and wavefront analysis techniques with the short-teraHertz FEL oscillator TerRa@BriXSInO. *Symmetry* 15(1):103
540. Jiang D, Chen H, Li X, He Z, Shen M (2015) A novel tunable microwave filter integrated power divider using liquid crystal. *Microw Opt Technol Lett* 57(11):2539–2543

541. Liu Y, Jiang D, Xia L, Xu R (2015) A novel microwave tunable band-pass filter integrated power divider based on liquid crystal. *Int J Antennas Propag* 42:320910
542. Liu Y, Liu Y, Li H, Jiang D, Cao W, Chen H, Xia L, Xu R (2016) Tunable microwave bandpass filter integrated power divider based on the high anisotropy electro-optic nematic liquid crystal. *Rev Sci Instrum* 87(7):074709
543. Nickel M, Müh M, Reese R, Polat E, Jost M, Damm C, Jakoby R, Maune H (2018) Liquid crystal based tunable reflection-type power divider. In: *Proceedings of the 2018 48th European microwave conference, Madrid*, pp 45–48
544. Tanaka M, Sato S (2001) Millimeter-wave deflection properties of liquid crystal prism cells with stack-layered structure. *Jpn J Appl Phys* 40(10B):L1123–L1125
545. Ge S, Chen P, Shen Z, Sun W, Wang X, Hu W, Zhang Y, Lu Y (2017) Terahertz vortex beam generator based on a photopatterned large birefringence liquid crystal. *Opt Exp* 25(11):12349–12356
546. Goelden F, Lapanik A, Gaebler A, Mueller S, Haase W, Jakoby R (2007) Systematic investigation of nematic liquid crystal mixtures at 30 GHz. In: *Proceedings of the 2007 IEEE/LEOS summer topical meeting, Portland, OR*, pp 202–203
547. Gaebler A, Goelden F, Mueller S, Jakoby R (2008) Triple-mode cavity perturbation method for the characterization of anisotropic media. In: *Proceedings of the 2008 38th European microwave conference, Amsterdam*, pp 909–912
548. Lapanik A, Goelden F, Lapanik V, Mueller S, Penirschke A, Jakoby R, Haase W (2011) Nematic LCs mixtures with high birefringence in the microwave region. *Frequenz* 65(1–2):15–19
549. Lapanik A, Haase W, Golden F, Muller S, Jakoby R (2011) Highly birefringent nematic mixtures at room temperature for microwave applications. *Opt Eng* 50(8):081208
550. Parka J, Krupka J, Dąbrowski R, Wosik J (2007) Measurements of anisotropic complex permittivity of liquid crystals at microwave frequencies. *J Eur Ceram Soc* 27(8–9):2903–2905
551. Sánchez JR, Nova V, Bachiller C (2019) Characterization of nematic liquid crystal at microwave frequencies using split-cylinder resonator method. *IEEE Trans Microw Theory Techn* 67(7):2812–2820
552. Sánchez JR, Nova V, Bachiller C, Villacampa B, de la Rua A, Kronberger R, Peñaranda F, Boria VE (2019) Measurement of the dielectric properties of liquid crystal material for microwave applications. In: *Proceedings of the 2019 17th international conference on microwave and high frequency heating, Valencia*, pp 506–510
553. Yaghmaee P, Kaufmann T, Bates B, Fumeaux C (2012) Effect of polyimide layers on the permittivity tuning range of liquid crystals. In: *Proceedings of the 2012 6th European conference on antennas and propagation, Prague*, pp 3579–3582
554. Yaghmaee P, Fumeaux C, Bates B, Manabe A, Karabey OH, Jakoby R (2012) Frequency tunable S-band resonator using nematic liquid crystal. *Electr Lett* 48(13):798–800
555. Franke T, Gaebler A, Prasertiadi AE, Jakoby R (2014) Tunable Ka-band waveguide resonators and a small band band-pass filter based on liquid crystals. In: *Proceedings of the 2014 44th European microwave conference, Rome*, pp 339–342
556. Karabey OH (2015) Microwave material properties of nanoparticle-doped nematic liquid crystals. *Frequenz* 69(3–4):105–109
557. Kukhtin MP, Kocherzhin AI, Lisetski LN, Nerukh AG, Fedoryako AP, Kukhtina NN (2007) Electrophysical properties of nematic liquid crystals under stationary and microwave electric and magnetic fields. In: *Proceedings of the 2007 6th international conference on antenna theory and techniques, Sevastopol*, pp 170–172
558. Krasinski F, Splingart B, Dubois F, Maschke U, Legrand C (2011) Dielectric characterization of polymer dispersed liquid crystal in microwave range: material integration in specific electronic devices. *Mol Cryst Liq Cryst* 542(1):227–236
559. Tentillier N, Krasinski F, Sauleau R, Splingart B, Lhermite H, Coquet P (2009) A liquid-crystal tunable ultra-thin fabry-perot resonator in KA band. *IEEE Antennas Wirel Propag Lett* 8:701–704

560. Meriakri VV, Nikitin IP, Pan CL, Pan RP, Parkhomenko MP, Chigryai EF (2010) Experimental investigation of liquid crystals in the millimetre frequency range. *Liq Cryst* 37(11):1453–1457
561. Yaghmaee P, Withayachumnankul W, Horestani AK, Ebrahimi A, Bates B, Fumeaux C (2013) Tunable electric-LC resonators using liquid crystal. In: *Proceedings of the 2013 IEEE antennas and propagation society international symposium*, Orlando, FL, pp 382–383
562. Schaub DE, Oliver DR (2011) A circular patch resonator for the measurement of microwave permittivity of nematic liquid crystal. *IEEE Trans Microw Theory Techn* 59(7):1855–1862
563. Naito R, Kamei T, Utsumi Y (2002) Measurement of liquid crystal's dielectric permittivity in the microwave range using inductive coupled ring resonator. Technical report IEICE MW2002-76
564. Utsumi Y, Kamei T, Naito R (2003) Measurements of effective dielectric permittivity of microstrip-line-type liquid crystal devices using inductive coupled ring resonator. *Electr Lett* 39(11):849–850
565. Utsumi Y, Kamei T (2004) Dielectric permittivity measurements of liquid crystal in the microwave and millimeter wave ranges. *Mol Cryst Liq Cryst* 409(1):355–370
566. Utsumi Y, Kamei T, Naito R (2004) Dielectric properties of microstrip-line adaptive liquid crystal devices. *Electr Commun Jpn* 87(10):13–24
567. Utsumi Y, Kamei T, Naito R, Saito K (2005) Measurement methods of nematic liquid crystal response time. *Mol Cryst Liq Cryst* 434(1):9–24
568. Utsumi Y, Kamei T, Saito K, Moritake H (2005) Increasing the speed of microstrip line-type PDLC devices. In: *Proceedings of the 2005 IEEE MTT-S international microwave symposium*, Long Beach, CA, pp 1831–1834
569. Belyaev BA, Drokin NA, Shabanov VF, Shepov VN (2002) High-frequency dielectric spectra from liquid crystals of series nCB and nOCB. *Techn Phys* 47(4):470–473
570. Belyaev BA, Drokin NA, Shabanov VF, Shepov VN (2003) Specific features of the approximation of the dielectric spectra of alkylcyanobiphenyl liquid crystals. *Phys Solid State* 45(3):598–602
571. Belyaev BA, Drokin NA, Shabanov VF, Baranova VA (2004) Dielectric properties of liquid crystals of the cyano derivative compounds with different fragments in the molecular core. *Phys Solid State* 46(3):574–578
572. Belyaev BA, Drokin NA, Shabanov VF, Shepov VN (1997) Specific features of the dielectric spectra of the liquid crystal 5CB in the decimeter wavelength range. *J Exp Theor Phys Lett* 66(4):271–274
573. Belyaev BA, Drokin NA, Shabanov VF (2006) Resonance sensors for measuring dielectric spectra of liquid crystals in a wide frequency range. *Instrum Exp Techn* 49(5):696–702
574. Yazdanpanahi M, Bulja S, Mirshekar-Syahkal D, James R, Day SE, Aníbal-Fernández F (2010) Measurement of dielectric constants of nematic liquid crystals at mm-wave frequencies using patch resonator. *IEEE Trans Instrum Measur* 59(12):3079–3085
575. Kowrdziej R, Krupka J, Nowinowski-Kruszelnicki E, Olifierczuk M, Parka J (2013) Microwave complex permittivity of voltage-tunable nematic liquid crystals measured in high resistivity silicon transducers. *Appl Phys Lett* 102(10):102904
576. Kowrdziej R, Parka J, Krupka J, Olifierczuk M, Nowinowski-Kruszelnicki E, Jaroszewicz L, Chojnowska O (2013) Dielectric properties of highly anisotropic nematic liquid crystals for tunable microwave components. *Appl Phys Lett* 103(17):172902
577. Nova V, Bachiller C, Villacampa B, Kronberger R, Boria VE (2020) Characterization of nematic liquid crystals at microwave frequencies. *Crystals* 10(12):1106
578. Ghattan Z, Hasek T, Wilk R, Shahabadi M, Koch M (2008) Sub-terahertz on-off switch based on a two-dimensional photonic crystal infiltrated by liquid crystals. *Opt Commun* 281(18):4623–4625
579. Zhang H, Guo P, Chen P, Chang S, Yuan J (2009) Liquid-crystal-filled photonic crystal for terahertz switch and filter. *J Opt Soc Am B* 26(1):101–106
580. Jost M, Reese R, Nickel M, Schmidt S, Maune H, Jakoby R (2017) Interference based W-band single-pole double-throw with tunable liquid crystal based waveguide phase shifters. In: *Proceedings of the 2017 IEEE MTT-S international microwave symposium*, Honolulu, HI, pp 184–187

581. Jost M, Heunisch A, Prasetiadi AE, Schulz B, Reese R, Nickel M, Polat E, Quibeldey M, Maune H, Rabe T, Follmann R, Jakoby R (2018) Liquid crystal based SPDT with adjustable power splitting ratio in LTCC technology. In: Proceedings of the 2018 48th European microwave conference, Madrid, pp 612–615
582. Jost M, Reese R, Nickel M, Maune H, Jakoby R (2018) Fully dielectric interference-based SPDT with liquid crystal phase shifters. *IET Microw Antennas Propag* 12(6):850–857
583. Mueller S, Penirschke A, Damm C, Scheele P, Wittek M, Weil C, Jakoby R (2005) Broad-band microwave characterization of liquid crystals using a temperature-controlled coaxial transmission line. *IEEE Trans Microw Theory Techn* 53(6):1937–1945
584. Karabey OH, Goelden F, Gaebler A, Jakoby R (2010) Precise broadband microwave material characterization of liquids. In: Proceedings of the 2010 40th European microwave conference, Paris, pp 1591–1594
585. Hu W, Karabey OH, Prasetiadi AE, Jost M, Jakoby R (2014) Temperature controlled artificial coaxial line for microwave characterization of liquid crystal. In: Proceedings of the 2014 German microwave conference, Aachen
586. Murakami Y, Shibata Y, Sato H, Ishinabe T, Chen Q, Fujikake H (2020) Systematic investigation of molecular structure of nematic-phase liquid crystals for reduction of dielectric loss in microwave control applications. *ITE Trans Media Technol Appl* 8(4):218–223
587. Johri M, Saxena A, Johri S, Saxena S, Singh DP (2011) Dielectric relaxation studies in 5CB nematic liquid crystal at 9 GHz under the influence of external magnetic field using microwave cavity spectrometer. *Pramana J Phys* 76(4):621–628
588. Singh DP, Saxena S, Johri S, Paudyal H, Johri M (2011) Microwave cavity technique to study the dielectric response in 4'-n-heptyl-4-biphenyl nematic liquid crystal at 20.900 and 29.867 GHz. *Measurement* 44(4):605–610
589. Hinojosa J (2005) Broad band electromagnetic characterization method of nematic liquid crystals using a coplanar waveguide. In: Proceedings of the 2005 IEEE international conference on dielectric liquids, Coimbra, pp 441–444
590. Ito R, Yanagihara S, Ito K, Watanabe T, Nose T, Honma M (2011) Basic performance of refractive index measurement method for LC materials in super high frequency region by using coplanar wave guide. *Mol Cryst Liq Cryst* 543(1):92–100
591. Peng H, Zhang Y, Zhu S, Temiz M, El-Makadema A (2022) Determining dielectric properties of nematic liquid crystals at microwave frequencies using inverted microstrip lines. *Liq Cryst* 49(15):2069–2081
592. James R, Aníbal-Fernández F, Day SE, Bulja S, Mirshekar-Syahkal D (2009) Accurate modeling for wideband characterization of nematic liquid crystals for microwave applications. *IEEE Trans Microw Theory Techn* 57(12):3293–3297
593. Gaebler A, Goelden F, Mueller S, Jakoby R (2008) Efficiency considerations of tuneable liquid crystal microwave devices. In: Proceedings of the 2008 German microwave conference, Hamburg-Harburg
594. Gaebler A, Goelden F, Mueller S, Jakoby R (2008) Multiphysics simulations for tunability efficiency evaluation of liquid crystal based RF. *Frequenz* 62(9–10):240–245
595. Gaebler A, Goelden F, Mueller S, Jakoby R (2008) Modeling of electrically tunable transmission line phase shifter based on liquid crystal. In: Proceedings of the 2008 IEEE antennas and propagation society international symposium, San Diego, CA
596. Deo P, Yazdanpanahi M, Mirshekar-Syahkal D (2012) Effect of test device thickness on liquid crystal characterisation. In: Proceedings of the 2012 Asia-Pacific microwave conference, Kaohsiung, pp 1280–1282
597. P. Deo, D. Mirshekar-Syahkal, L. Seddon, S. E. Day, and F. Aníbal Fernández, Microstrip device for broadband (15–65 GHz) measurement of dielectric properties of nematic liquid crystals. *IEEE Trans Microw Theory Techn* 63(4), 1388–1398, 2015
598. Nose T, Honma M, Nozokido T, Mizuno K (2004) Determination of the insertion loss and refractive index anisotropy in nematic liquid crystal materials using a V-band waveguide transmission cell. *Mol Cryst Liq Cryst* 409(1):199–207

599. Nose T, Honma M, Nozokido T, Mizuno K (2005) Simple method for the determination of refractive indices and loss parameters for liquid-crystal materials in the millimeter-wave region. *Appl Opt* 44(7):1150–1155
600. Ionescu D, Alexandru ND (2005) Study of effective permittivity for thermotropic liquid crystals in 7.8–12.4 GHz frequency range. In: *Proceedings of the 2005 international symposium on signals, circuits and systems*, Lasi, pp 737–740
601. Mueller S, Koeberle M, Goelden F, Penirschke A, Gaebler A, Lapanik A, Haase W, Jakoby R (2008) W-band characterization of anisotropic liquid crystals at room temperature. In: *Proceedings of the 2008 38th European microwave conference*, Amsterdam, pp 119–122
602. Maasch M, Groudas A, Karabey O, Damm C, Jakoby R (2012) Electrically tunable open splitting resonators based on liquid crystal material. In: *Proceedings of the 2012 6th international congress on advanced electromagnetic materials in microwaves and optics*, pp 270–272
603. Bulja S, Mirshekar-Syahkal D, James R, Day SE, Anfbal Fernández F (2009) Planar transmission line method for measurement of dielectric constants of liquid crystals in 60 GHz band. In: *Proceedings of the 2009 Asia Pacific microwave conference*, Singapore, pp 341–344
604. Bulja S, Mirshekar-Syahkal D, James R, Day SE, Anfbal-Fernandez F (2010) Measurement of dielectric properties of nematic liquid crystals at millimeter wavelength. *IEEE Trans Microw Theory Techn* 58(12):3493–3501
605. Gaebler A, Goelden F, Karabey OH, Jakoby R (2010) A FDFD based eigen-dielectric formulation of the Maxwell equations for material characterization in arbitrary waveguide structures. In: *Proceedings of the 2010 IEEE MTT-S international microwave symposium*, Anaheim, CA, pp 1656–1659
606. James R, Anfbal-Fernández F, Day SE, Bulja S, Mirshekar-Syahkal D (2011) Characterisation and applications of nematic liquid crystals in microwave devices. *Mol Cryst Liq Cryst* 542(1):196–203
607. Wang D, Mu C, Li B, Yang J (2018) Electrically tunable propagation properties of the liquid crystal-filled terahertz fiber. *Appl Sci* 8(12):2487
608. Bavisi A, Sundaram V, Swaminathan M (2005) Design of a system-in-package based low-phase-noise VCO using 3D integrated passives on a multilayer LCP substrate. In: *Proceedings of the 2005 35th European microwave conference*, Paris
609. Govind V, Yun W, Dalmia S, Sundaram V, White G, Swaminathan M (2005) Analysis and design of compact wideband baluns on multilayer liquid-crystalline polymer-based substrates. In: *Proceedings of the 2005 IEEE MTT-S international microwave symposium*, Long Beach, CA, pp 543–546
610. Zou G, Grönqvist H, Liu J (2005) Integrated capacitors and resistors on liquid crystal polymer substrate. In: *Proceedings of the 2005 conference on high density microsystem design and packaging and component failure analysis*, Shanghai
611. Bavisi A, Dalmia S, Swaminathan M, Sundaram V, White G (2006) Chip-package codesign of integrated voltage controlled oscillator in LCP substrate. *IEEE Trans Adv Pack* 29(3):390–402
612. Bavisi A, Swaminathan M, Sundaram V, Dalmia S, White G (2006) A novel miniaturized feedback LC oscillator for UMTS-type applications in 3D stacked liquid crystalline polymer technology. *Int J RF Microw Comput Aided Eng* 16(3):227–237
613. Arabi B, Shamim A (2015) Three-dimensional RF SoP technologies: LTCC versus LCP. *Microw Opt Technol Lett* 57(2):434–441
614. Gu X, Liu D, Sadhu B (2021) Packaging and antenna integration for silicon-based millimeter-wave phased arrays: 5G and beyond. *IEEE J Microw* 1(1):123–134
615. Khan MUA, Raad R, Tubbal F, Theoharis PI, Liu S, Foroughi J (2021) Bending analysis of polymer-based flexible antennas for wearable, general IoT applications: a review. *Polymers* 13(3):357
616. Marnat L, Shamim A (2012) Liquid crystal polymer (LCP) based antenna for flexible system on package (SoP) applications. In: *Proceedings of the 2012 15th international symposium on antenna technology and applied electromagnetics*, Toulouse

617. Chletsou A, He Y, Locke JF, Papapolymerou J (2020) Multi-band, flexible, lightweight antenna on LCP for automotive applications. In: Proceedings of the 2020 IEEE international symposium on antennas and propagation and North American radio science meeting, pp 1507–1508
618. Basat S, Bhattacharya S, Rida A, Johnston S, Yang L, Tentzeris MM, Laskar J (2004) Fabrication and assembly of a novel high-efficiency UHF RFID tag on flexible LCP substrate. In: Proceedings of the 2006 56th electronic components and technology conference, Las Vegas, NV, pp 1352–1355
619. Serkan Basat S, Bhattacharya S, Yang L, Rida A, Tentzeris MM, Laskar J (2006) Design of a novel high efficiency UHF RFID antenna on flexible LCP substrate with high read-range capability. In: Proceedings of the 2006 IEEE antennas and propagation society international symposium, Albuquerque, NM, pp 1031–1034
620. Bhattacharya SK, Tentzeris MM, Yang L, Basat S, Rida A (2007) Flexible LCP and paper-based substrates with embedded actives, passives, and RFIDs. In: Proceedings of the 2007 6th international conference on polymers and adhesives in microelectronics and photonics, Tokyo, pp 159–166
621. Vyas R, Rida A, Bhattacharya S, Tentzeris MM (2007) Liquid crystal polymer (LCP): the ultimate solution for low-cost RF flexible electronics and antennas. In: Proceedings of the 2007 IEEE antennas and propagation society international symposium, Honolulu, HI, pp 1729–1732
622. Madhav BTP, Pisipati VGKM, Latha DM, Prasad PVD (2011) Planar dipole antenna on liquid crystal polymer substrate at 2.4 GHz. *Solid State Phenom* 181–182:289–292
623. Kao HL, Cho CL, Zhang XY, Chang LC, Wei BH, Dai X, Chiu HC (2014) Bending effect of an inkjet-printed series-fed two-dipole antenna on a liquid crystal polymer substrate. *IEEE Antennas Wireless Propag Lett* 13:1172–1175
624. Kao HL, Yeh CS, Zhang XY, Cho CL, Dai X, Wei BH, Chang LC, Chiu HC (2014) Inkjet printed series-fed two-dipole antenna comprising a balun filter on liquid crystal polymer substrate. *IEEE Trans Compon Pack Manuf Technol* 4(7):1228–1236
625. Wu S, Zhao A, Zhao Y (2019) Wideband dipole antenna and array based on liquid crystal polymer for 5G applications. In: Proceedings of the 2019 Asia-Pacific microwave conference, Singapore, pp 438–440
626. Rao MV, Madhav M, Tirunagari A, Badugu P (2020) Circularly polarized flexible antenna on liquid crystal polymer substrate material with metamaterial loading. *Microw Opt Technol Lett* 62(2):866–874
627. Du C, Yang Z, Jin G, Zhong S (2022) Design of a co-planar waveguide-fed flexible ultra-wideband-multiple-input multiple-output antenna with dual band-notched characteristics for wireless body area network. *Int J RF Microw Comput Aided Eng* 32(3):e22997
628. Kim B, Nikolaou S, Ponchak GE, Kim YS, Papapolymerou J, Tentzeris MM (2006) A curvature CPW-fed ultra-wideband monopole antenna on liquid crystal polymer substrate using flexible characteristic. In: Proceedings of the 2006 IEEE antennas and propagation society international symposium, Albuquerque, NM, pp 1667–1670
629. Altunyurt N, Rieske R, Swaminathan M, Sundaram V (2009) Conformal antennas on liquid crystalline polymer based rigid-flex substrates integrated with the front-end module. *IEEE Trans Adv Pack* 32(4):797–808
630. Dey A, Guldiken R, Mumcu G (2016) Microfluidically reconfigured wideband frequency-tunable liquid-metal monopole antenna. *IEEE Trans Antennas Propag* 64(6):2572–2576
631. Xiao W, Mei T, Lan Y, Wu YQ, Xu R, Xu YH (2017) Triple band-notched UWB monopole antenna on ultra-thin liquid crystal polymer based on ESCSRR. *Electr Lett* 53(2):57–58
632. Du C, Li K, Zhong S (2021) A novel flexible hexagon wideband CPW-fed monopole antenna for UWB applications. *Microw Opt Technol Lett* 63(7):1899–1905
633. Madhav BTP, Pisipati VGKM, Bhavani KVL, Sreekanth P, Rakesh-Kumar P (2010) Rectangular microstrip patch antenna on liquid crystal polymer substrate. *J Theor Appl Inform Technol* 18(1):62–66

634. Cheng X, Wu J, Blank R, Senior DE, Yoon YK (2012) An omnidirectional wrappable compact patch antenna for wireless endoscope applications. *IEEE Antennas Wirel Propag Lett* 11:1667–1670
635. Chieh JCS, Pham B, Pham AV, Kannell G, Pidwebetsky A (2013) Millimeter-wave dual-polarized high-isolation antennas and arrays on organic substrates. *IEEE Trans Antennas Propag* 61(12):5948–5957
636. Huang M, Herben M, Reniers A, Amulders P (2013) Causes of discrepancies between measurements and EM simulations of millimeter-wave antennas. *IEEE Antennas Propag Mag* 55(6):139–149
637. Kotamraju SK, Rama Krishna TV, Madhav BTP, Khan H, Bhavani KVL (2013) Exponential multiband serrated microstrip antenna on LCP substrate In: Proceedings of the 2013 international conference on advanced research in engineering and technology, Andhra Pradesh, pp 732–736
638. Zhang Y, Shi S, Prather DW (2013) Slot-coupled waveguide-to-microstrip transition and waveguide-fed patch antenna at E-band. In: Proceedings of the 2013 IEEE antennas and propagation society international symposium, Orlando, FL, pp 1858–1859
639. Lin C, Lixin X, Qi H (2015) Radiation characteristics of a flexible micro-electro-mechanical system antenna on a liquid crystal polymer substrate. *Mater Res Innov* 19(s9):290–294
640. Madhav BTP (2015) Substrate permittivity effects on the performance of compact and wideband microstrip antennas. Ph. D. Dissertation, Koneru Lakshmaiah Education Foundation
641. Madhav BTP, Kaza H, Kaza V, Manikanta P, Dhulipala S, Konijeti SK, Bonagiri A, Shaik F (2015) Liquid crystal polymer substrate based wideband tapered step antenna. *Leonardo Electr J Pract Technol* 26:103–114
642. Soliman AM, Elsheakh DM, Abdallah EA, El-Hennawy H (2015) Design of planar inverted-F antenna over uniplanar EBG structure for laptop mimo applications. *Microw Opt Technol Lett* 57(2):277–285
643. Wang Q, Du CZ, Zheng YY, Liu PC, Yang FH (2018) A novel dual-band antenna based on liquid crystal polymer. In: Proceedings of the 2018 11th UK-Europe-China workshop on millimeter waves and terahertz technologies (UCMMT), Hangzhou
644. He Y, Drew E, Zhang ZJ, Papapolymerou J (2021) Compact patch antenna on thick (> 800 m) NiFe_2O_4 magnetic film. *IET Microw Antennas Propag* 15(1):12–20
645. Nikolaou S, Ponchak GE, Papapolymerou J, Tentzeris MM (2006) Conformal double exponentially tapered slot antenna (DETTSA) on LCP for UWB applications. *IEEE Trans Antennas Propag* 54(5):1663–1669
646. Pazin L, Leviatan Y (2010) A compact 60-GHz tapered slot antenna printed on LCP substrate for WPAN applications. *IEEE Antennas Wirel Propag Lett* 9:272–275
647. Zhang Y, Shi S, Martin RD, Prather DW (2016) High-gain linearly tapered antipodal slot antenna on LCP substrate at E- and W-bands. *IEEE Antennas Wirel Propag Lett* 15:1357–1360
648. Hosono R, Uemichi Y, Han X, Guan N, Nakatani Y (2014) A bandwidth-enhanced millimeter-wave microstrip comb-line array antenna with parasitic elements on liquid crystal polymer substrate. In: Proceedings of the 2014 USNC-URSI radio science meeting/2014 IEEE antennas and propagation society international symposium, Memphis, TN, pp 1726–1727
649. Du CZ, Ma TC, Wang X, Yang ZP, Liu HY, Nie Y (2019) Flexible single band-notched ultra-wideband MIMO antenna. In: Proceedings of the 2019 19th IEEE international conference on communication technology (ICCT), Xi'an, pp 839–842
650. Palazzari V, Thompson D, Papageorgiou N, Pinel S, Lee JH, Sarkar S, Pratap R, DeJean G, Bairavasubramanian R, Li RL, Tentzeris M, Laskar J, Papapolymerou J, Roselli L (2004) Multi-band RF and mm-wave design solutions for integrated RF functions in liquid crystal polymer system-on-package technology. In: Proceedings of the 2004 54th electronic components and technology conference, Las Vegas, NV, pp 1658–1663
651. Dejean G, Bairavasubramanian R, Thompson D, Ponchak GE, Tentzeris MM, Papapolymerou J (2005) Liquid crystal polymer (LCP): a new organic material for the development of multi-layer dual-frequency/dualpolarization flexible antenna arrays. *IEEE Antennas Wirel Propag Lett* 4:22–26

652. Kingsley N, Ponchak GE, Papapolyerou J (2008) Reconfigurable RF MEMS phased array antenna integrated within a liquid crystal polymer (LCP) system-on-package. *IEEE Trans Antennas Propag* 56(1):108–118
653. Missaoui S, Kaddour M, Gharbi A (2010) Development and design of multilayer antennas based on liquid crystals. *IOP Conf Ser Mater Sci Eng* 13(1):012028
654. Chieh JCS, Pham B, Pham AV (2012) A W-band 8×8 series fed patch array detector on liquid crystal polymer. In: *Proceedings of the 2012 IEEE antennas and propagation society international symposium*, Chicago, IL
655. Govardhani I, Narayana MV (2012) Rectangular patch array antenna with liquid crystal substrate for Ka and Q band applications. *Int J Comput Sci Commun Netw* 2(1):16–21
656. Gheethan AA, Jo MC, Guldiken R, Mumcu G (2013) Microfluidic based ka-band beam-scanning focal plane array. *IEEE Antennas Wirel Propag Lett* 12:1638–1641
657. Zhou Y, Lin B, Zhu F, Shen D, Liu Y, Wang M (2014) Omni-directional cylindrical patch array antenna using liquid crystal polymer technology. In: *Proceedings of the 2014 IEEE international conference on communication problem-solving*, Beijing, pp 269–272
658. Zhang Y, Bai J, Shi S, Prather DW (2016) Ka-band phased patch array antenna integrated with a PET-controlled phase shifter. *Int J RF Microw Comput Aided Eng* 26(3):199–208
659. Rabbani MS, Ghafouri-Shiraz H (2017) Liquid crystalline polymer substrate-based THz microstrip antenna arrays for medical applications. *IEEE Antennas Wirel Propag Lett* 16:1533–1536
660. Xing K, Liu B, Guo Z, Wei X, Zhao R, Ma Y (2017) Backlobe and sidelobe suppression of a Q-band patch antenna array by using substrate integrated coaxial line feeding technique. *IEEE Antennas Wirel Propag Lett* 16:3043–3046
661. Cüneray K, Akçam N (2019) LCP substrate based crescent shaped microstrip patch array antenna design for 5G applications. In: *Proceedings of the 2019 19th IEEE international symposium on multidisciplinary studies and innovative technologies*, Ankara
662. Jilani SF, Munoz MO, Abbasi QH, Alomainy A (2019) Millimeter-wave liquid crystal polymer based conformal antenna array for 5G applications. *IEEE Antennas Wirel Propag Lett* 18(1):84–88
663. Govardhani I, Rajkamal K, Narayana MV, Venkateswarlu S (2011) Phased array antenna for millimeter wave radar in W-band using liquid crystal substrate. *J Emerg Trends Comput Inform Sci* 2(12):691–695
664. Patterson CE, Thrivikraman TK, Yepes AM, Begley SM, Bhattacharya SK, Gressler JD, Papapolymerou J (2011) A lightweight organic X-band active receiving phased array with integrated SiGe amplifiers and phase shifters. *IEEE Trans Antennas Propag* 59(1):100–109
665. Jin D, Xiao S, Gao S, Tang M, Wang BZ (2010) Ultra wide-band slot antenna based on liquid crystal polymer material for millimeter wave application. In: *Proceedings of the 2010 IEEE international conference on ultra-wideband*, Nanjing
666. Chieh JCS, Pham AV (2013) A bidirectional microstrip X-band antenna array on liquid crystal polymer for beamforming applications. *IEEE Trans Antennas Propag* 61(6):3364–3368
667. Nguyen VN, Yoenak SH, Smith DR (2010) Multilayer W-band artificial dielectric on liquid crystal polymer. *IEEE Antennas Wirel Propag Lett* 9:974–977
668. Dalmia S, Sundaram V, White G, Swaminathan M (2004) Liquid crystalline polymer based RF/wireless components for multiband applications. In: *Proceedings of the 2004 54th electronic components and technology conference*, Las Vegas, NV, pp 1866–1873
669. Dalmia S, Sundaram V, White G, Swaminathan M (2004) Liquid crystalline polymer (LCP) based lumped element bandpass filters for multiple wireless applications. In: *Proceedings of the 2004 IEEE MTT-S international microwave symposium*, fort worth, Texas, pp 1991–1994
670. Govind V, Dalmia S, Sundaram V, White G, Swaminathan M (2004) Design of multiband baluns on liquid crystalline polymer (LCP) based substrates. In: *Proceedings of the 2004 54th electronic components and technology conference*, Las Vegas, NV, pp 1812–1818
671. Yun W, Sundaram V, Swaminathan M (2007) High-Q embedded passives on large panel multilayer liquid crystalline polymer-based substrate. *IEEE Trans Adv Pack* 30(3):580–591

672. Kameni Ngassa CL, Lacroix B, Papapolymerou J (2012) Design of a low loss wideband millimeter-wave balun on a multilayer liquid crystal polymer technology. In: Proceedings of the 2012 IEEE radio and wireless symposium, Santa Clara, CA, pp 175–178
673. Ta HH, Pham AV (2013) A compact broadband balun on multilayer organic substrate. *Microw Opt Technol Lett* 55(8):1957–1959
674. Pham CV, Pham AV (2019) Novel stacked-defected ground structures for ultra-wideband low loss balun designs. *Microw Opt Technol Lett* 61(8):2008–2012
675. Jou WS, Wu TL, Chiu SK, Cheng WH (2002) The influence of fiber orientation on electromagnetic shielding in liquid-crystal polymers. *J Electr Mater* 31(3):178–184
676. Davis MF, Yoon SW, Pinel S, Lim K, Laskar J (2003) Liquid crystal polymer-based integrated passive development for RF applications. In: Proceedings of the 2003 IEEE MTT-S international microwave symposium, Philadelphia, PA, pp 1155–1158
677. Mukherjee S, Dalmia S, Mutnury B, Swaminathan M (2004) Layout-level synthesis of RF bandpass filter on organic substrates for Wi-Fi applications. In: Proceedings of the 2004 34th European microwave conference, Amsterdam
678. Mukherj S, Mutnury B, Dalmia S, Swaminathan M (2005) Layout-level synthesis of RF inductors and filters in LCP substrates for Wi-Fi applications. *IEEE Trans Microw Theory Techn* 53(6):2196–2210
679. Yun W, Bavisi A, Sundaram V, Swaminathan M, Engin E (2005) 3-D Integration and characterization of high Q passives on multi-layer liquid crystalline polymer (M-LCP) based substrate. In: Proceedings of the 2005 Asia-Pacific microwave conference, Suzhou
680. White G, Swaminathan M, Sundaram V, Dalmia S (2005) Integrated passive devices fabricated utilizing multi-layer organic laminates. Patent No. US6900708, Georgia Tech Research Corp
681. Yang K, Pinel S, Kim K, Laskar J (2006) Low-loss integrated-waveguide passive circuits using liquid-crystal polymer system-on-package (SOP) technology for millimeter-wave applications. *IEEE Trans Microw Theory Techn* 54(12):4572–4579
682. Hao ZC, Hong JS (2008) Ultra wideband bandpass filter using embedded stepped impedance resonators on multilayer liquid crystal polymer substrate. *IEEE Microw Wirel Comp Lett* 18(9):581–583
683. Hao ZC, Hong JS (2008) Ultra-wideband bandpass filter using multilayer liquid-crystal-polymer technology. *IEEE Trans Microw Theory Techn* 56(9):2095–2100
684. Hao ZC, Hong JS (2009) Compact wide stopband ultra wideband bandpass filter using multilayer liquid crystal polymer technology. *IEEE Microw Wirel Comp Lett* 19(5):290–292
685. Hao ZC, Hong JS (2009) UWB bandpass filter with a multilayer non-uniform periodical structure on LCP substrates. In: Proceedings of the 2009 IEEE MTT-S international microwave symposium, Boston, MA, pp 853–856
686. Hao ZC, Hong JS, Parry JP, Hand DP (2009) Ultra-wideband bandpass filter with multiple notch bands using nonuniform periodical slotted ground structure. *IEEE Trans Microw Theory Techn* 57(12):3080–3088
687. Zhang X, Liu J, Cai P, Kärnfelt C, Wang X, Ma S, Morris J, Zirath H (2008) Millimeter-wave ultra-wideband bandpass filter based on liquid crystal polymer substrates for automotive radar systems. *Microw Opt Technol Lett* 50(9):2276–2280
688. Hao ZC, Hong JS (2010) UWB bandpass filter using cascaded miniature high-pass and low-pass filters with multilayer liquid crystal polymer technology. *IEEE Trans Microw Theory Techn* 58(4):941–948
689. Hao ZC, Hong JS (2010) Quasi-elliptic UWB bandpass filter using multilayer liquid crystal polymer technology. *IEEE Microw Wirel Compon Lett* 20(4):202–204
690. Miller A, Hong J (2012) Cascaded coupled line filter with reconfigurable bandwidths using LCP multilayer circuit technology. *IEEE Trans Microw Theory Techn* 60(6):1577–1586
691. Qian S, Hong J (2012) Miniature quasi-lumped-element wideband bandpass filter at 0.5–2-GHz band using multilayer liquid crystal polymer technology. *IEEE Trans Microw Theory Techn* 60(9):2799–2807
692. Kao HL, Cho CL, Chang LC (2013) Inkjet-printed interdigital coupled line filter on liquid crystal polymer substrate. *IEEE Electr Dev Lett* 34(12):1584–1586

693. Cho CL, Kao HL, Chang LC, Wu YH, Chiu HC (2016) Inkjet-printed multilayer bandpass filter using liquid crystal polymer system-on-package technology. *IEEE Trans Comp Pack Manuf Technol* 6(4):622–629
694. Cervera F, Hong J (2014) Compact self-packaged dual-band filter using multilayer liquid crystal polymer technology. *IEEE Trans Microw Theory Techn* 62(11):2618–2625
695. Chlieh OL, Khan WT, Papapolymerou J (2014) L-band tunable microstrip bandpass filter on multilayer organic substrate with integrated microfluidic channel. In: *Proceedings of the 2014 IEEE MTT-S international microwave symposium*, Tampa, FL
696. Palomo T, Mumcu G (2014) Highly reconfigurable bandpass filters using microfluidically controlled metallized glass plates. In: *Proceedings of the 2014 IEEE MTT-S international microwave symposium*, Tampa, FL
697. Senior DE, Rahimi A, Yoon YK (2015) Millimeter-wave bandpass filter on LCP using CSRR-loaded triangular-shape quarter-mode substrate integrated waveguide. *Microw Opt Technol Lett* 57(8):1782–1784
698. Shen M, Shao Z, You CJ, Ban F (2015) Ku-band compact bandpass filter with wide upper stopband using multilayer liquid crystal polymer technology. *Microw Opt Technol Lett* 57(5):1121–1125
699. Zhang Y, Shi S, Martin RD, Prather DW (2015) Substrate integrated waveguide filter on LCP substrate at 94 GHz. *Microw Opt Technol Lett* 57(3):577–580
700. Zhao M, Zhang Y (2017) Compact wearable 5-GHz flexible filter. *Electr Lett* 53(10):661–663
701. Aliqab K, Hong J (2019) UWB balanced BPF using a low-cost LCP bonded multilayer PCB technology. *IEEE Trans Microw Theory Techn* 67(3):1023–1029
702. Huang F, Wang J, Aliqab K, Hong J, Wu W (2019) Analysis and design of a new self-packaged wideband balun bandpass filter with the functionality of impedance transformation. *IEEE Trans Microw Theory Techn* 67(6):2322–2330
703. Zhao M, Zhang Y, Liu S, Jia Y (2019) UWB flexible filter with low loss and excellent stopband performance. *Microw Opt Technol Lett* 61(1):194–197
704. Gu X, Liu D, Hasegawa Y, Masuko K, Baks C, Suto Y, Fujisaku Y, Sadhu B, Paidimarri A, Guan N, Valdes-Garcia A (2021) Antenna-in-package integration for a wideband scalable 5G millimeter-wave phased-array module. *IEEE Microw Wirel Compon Lett* 31(6):682–684
705. Oh Y, Lee J, Choi S (2021) Comparison of band pass filter performance using liquid crystal polymer substrate in millimeter-wave band. *J Microelectr Pack Soc* 28(2):39–44
706. Zhang Y, Shi S, Martin RD, Prather DW (2017) Slot-coupled directional filters in multilayer LCP substrates at 95 GHz. *IEEE Trans Microw Theory Techn* 65(3):476–483
707. Palazzari V, Pinel S, Laskar J, Roselli L, Tentzeris MM (2005) Design of an asymmetrical dual-band WLAN filter in liquid crystal polymer (LCP) system-on-package technology. *IEEE Microw Wirel Compon Lett* 15(3):165–167
708. Cervera F, Hong J (2015) High rejection, self-packaged low-pass filter using multilayer liquid crystal polymer technology. *IEEE Trans Microw Theory Techn* 63(12):3920–3928
709. Kampling MJ, Christie Crowe W, Looney WW (2000) Polymer compositions suitable for microwave cooking applications. CA2389078A1, Solvay specialty polymers USA LLC
710. Dalmia S, Bavisi A, Mukherjee S, Govind V, White G, Swaminathan M, Sundaram V (2004) A multiple frequency signal generator for 802.11a/b/g VoWLAN type applications using organic packaging technology. In: *Proceedings of the 2004 54th electronic components and technology conference*, Las Vegas, NV, pp 1664–1670
711. Chung DJ, Polcawich RG, Pulskamp JS, Papapolymerou J (2012) Reduced-size low-voltage RF MEMS X-band phase shifter integrated on multilayer organic package. *IEEE Trans Compon Pack Manuf Technol* 2(10):1617–1622
712. Rahimian A, Abbasi QH, Alomainy A, Alfadhil Y (2019) A low-profile 28-GHz Rotman lens-fed array beamformer for 5G conformal subsystems. *Microw Opt Technol Lett* 61(3):671–675
713. Chieh JCS, Pham AV (2010) Development of a wide bandwidth Wilkinson power divider on multilayer organic substrates. *Microw Opt Technol Lett* 52(7):1606–1609
714. Chlieh OL, Khan WT, Papapolymerou J (2014) Integrated microfluidic cooling of high power passive and active devices on multilayer organic substrate. In: *Proceedings of the 2014 IEEE MTT-S international microwave symposium*, Tampa, FL

715. Thompson DC, Tantot O, Jallageas H, Ponchak GE, Tentzeris MM, Papapolymerou J (2004) Characterization of liquid crystal polymer (LCP) material and transmission lines on LCP substrates from 30 to 110 GHz. *IEEE Trans Microw Theory Techn* 52(4):1343–1352
716. He Y, Drew E, Chahal P, Zhang JZ, Papapolymerou J (2021) 3D printed spherical cavity resonator with fine tuning using nanomagnetic thin film. In: *Proceedings of the 2020 50th European microwave conference (EuMC)*, Utrecht
717. Kivilahti J, Liu J, Morris JE, Suga T, Wong CP (2002) Panel-size component integration (PCI) with molded liquid crystal polymer (LCP) substrates. In: *Proceedings of the 2002 52nd electronic components and technology conference*, San Diego, CA, pp 955–961
718. Zou G, Grönqvist H, Starski P, Liu J (2002) High frequency characteristics of liquid crystal polymer for system in a package application. In: *Proceedings of the 2002 8th international advanced packaging materials symposium*, Stone Mountain, GA, pp 337–341
719. Zou G, Grönqvist H, Staski JP, Liu J (2002) Characterization of liquid crystal polymer for high frequency system-in-a-package applications. *IEEE Trans Adv Pack* 25(4):503–508
720. Thompson DC, Papapolymerou J, Tentzeris MM (2005) High temperature dielectric stability of liquid crystal polymer at mm-wave frequencies. *IEEE Microw Wirel Compon Lett* 15(9):561–563
721. Khan WT, Morcillo C, Ulusoy AC, Papapolymerou J (2014) Characterization of liquid crystal polymer from 110 to 170 GHz. In: *Proceedings of the 2014 IEEE radio and wireless symposium*, Newport Beach, CA, pp 157–159
722. Wang G, Thompson D, Tentzeris M, Papapolymerou J (2004) Low cost RF MEMS switches using LCP substrate. In: *Proceedings of the 2004 34th European microwave conference*, Amsterdam
723. Han L, Gao X (2016) Modeling of bending characteristics on micromachined RF MEMS switch based on LCP substrate. *IEEE Trans Electr Dev* 63(9):3707–3712
724. Gonzalez E, Mumcu G (2019) Integrated actuation of microfluidically reconfigurable mm-Wave SPST switches. *IEEE Microw Wirel Compon Lett* 29(8):541–544
725. Zhang Y, Shi S, Martin RD, Prather DW (2015) Ultrawide band CBCPW to stripline vertical transition in multilayer LCP substrates. *Microw Opt Technol Lett* 57(6):1481–1484
726. Zhang Y, Wang F, Shi S, Martin RD, Yao P, Prather DW (2017) Ultra-wideband microstrip line-to-microstrip line transition in multilayer LCP substrate at millimeter-wave frequencies. *IEEE Microw Wirel Compon Lett* 27(10):873–875
727. Zhang Y, Shi S, Martin RD, Yao P, Wang F, Prather DW (2017) Ultra-wideband vialess microstrip line-to-stripline transition in multilayer LCP substrate for E- and W-band applications. *IEEE Microw Wirel Compon Lett* 27(12):1101–1103
728. Uemichi Y, Hosono R, Guan N, Hirokawa J, Ando M (2014) A simple through-hole based transformer between microstrip line and post-wall waveguide for millimeter-wave applications. *IEICE Trans Electr* 97(10):941–947
729. Uemichi Y, Kojima A, Nakatani Y, Hosono R, Guan N, Hirokawa J, Ando M (2014) Low-loss post-wall waveguide and broadband transition to microstrip line realized in 0.6 mm-thick liquid crystal polymer-substrate for millimeter-wave application. In: *Proceedings of the 2014 Asia-Pacific microwave conference*, Sendai, pp 1067–1036
730. Hassona A, Perez-Ortega A, He ZS, Zirath H (2018) Low-cost D-band waveguide transition on LCP substrate. In: *Proceedings of the 2018 48th European microwave conference*, Madrid, pp 1049–1052
731. Rida A, Margomenos A, Wu T, Tentzeris MM (2009) Novel wideband 3D transitions on liquid crystal polymer for millimeter-wave applications up to 100 GHz. In: *Proceedings of the 2009 IEEE MTT-S international microwave symposium*, Boston, MA, pp 953–956
732. Zhang Y, Shi S, Martin RD, Prather DW (2017) Broadband SIW-to-waveguide transition in multilayer LCP substrates at W-band. *IEEE Microw Wirel Compon Lett* 27(3):224–226
733. Tentzeris MM, Laskar J, Papapolymerou J, Pinel S, Palazzari V, Li R, DeJean G, Papageorgiou N, Thompson D, Bairavasubramanian R, Sarkar S, Lee JH (2004) 3-D-Integrated RF and millimeter-wave functions and modules using liquid crystal polymer (LCP) system-on-package technology. *IEEE Trans Adv Packag* 27(2):332–340

734. Aihara K, Pham A, Zeeb D, Flack T, Stoneham E (2007) Development of multi-layer liquid crystal polymer Ka-band receiver modules. In: Proceedings of the 2007 Asia-Pacific microwave conference, Bangkok
735. Aihara K, Zhang Z, Pham AV, Zeeb D, Flack T, Stoneham E (2009) Development of multilayer liquid crystal polymer Ka-band downconverter modules. *Microw Opt Technol Lett* 51(2):364–367
736. Aihara K, Chen MJ, Pham AV (2008) Development of thin-film liquid-crystal-polymer surface-mount packages for Ka-band applications. *IEEE Trans Microw Theory Techn* 56(9):2111–2117
737. Khan WT, Lopez AL, Ulusoy AC, Papapolymerou J (2014) Packaging a W-band integrated module with an optimized flip-chip interconnect on an organic substrate. *IEEE Trans Microw Theory Techn* 62(1):64–72
738. Khan WT, Ulusoy AC, Schmid RL, Papapolymerou J (2014) Characterization of a low-loss and wide-band (DC to 170 GHz) flip-chip interconnect on an organic substrate. In: Proceedings of the 2014 IEEE MTT-S international microwave symposium, Tampa, FL
739. Zhang Y, Shi S, Martin R, Martin RD, Peng Y, Prather DW (2014) Multilayer liquid crystal polymer based RF frontend module for millimeter wave imaging. In: Proceedings of the 2014 USNC-URSI radio science meeting/2014 IEEE antennas and propagation society international symposium, Memphis, TN, pp 1700–1701
740. Zhang Y, Martin RD, Shi S, Wright AA, Yao P, Shreve K, Mackrides D, Harrity C, Prather DW (2018) 95-GHz front-end receiving multichip module on multilayer LCP substrate for passive millimeter-wave imaging. *IEEE Trans Compon Pack Manuf Technol* 8(12):2180–2189
741. Thompson D, Kirby P, Papapolymerou J, Tentzeris MM (2003) W-band characterization of finite ground coplanar transmission lines on liquid crystal polymer (LCP) substrates. In: Proceedings of the 2003 IEEE electronic components and technology conference, New Orleans, LA, pp 1652–1655
742. Wei Z, Pham A (2003) Liquid crystal polymer (LCP) for microwave/millimeter wave multilayer packaging. In: Proceedings of the 2003 IEEE MTT-S international microwave symposium, Philadelphia, PA, pp 2273–2276
743. Khan WT, Ulusoy A, Papapolymerou J (2013) D-band characterization of co-planar wave guide and microstrip transmission lines on liquid crystal polymer. In: Proceedings of the 2013 63rd IEEE electronic components and technology conference, Las Vegas, NV, pp 2304–2309
744. Cai F, Chang YH, Wang K, Khan WT, Pavlidis S, Papapolymerou J (2014) High resolution aerosol jet printing of D- band printed transmission lines on flexible LCP substrate. In: Proceedings of the 2014 IEEE MTT-S international microwave symposium, Tampa, FL
745. Liu W, Song W (2020) Broadband dielectric measurement of LCP substrate materials by differential phase length method. In: Proceedings of the 2020 IEEE MTT-S international microwave workshop series on advanced materials and processes for RF and THz applications (IMWS-AMP), Suzhou
746. Yang K, Pinel S, Kim K, Laskar J (2006) Millimeter-wave low-loss integrated waveguide on liquid crystal polymer substrate. In: Proceedings of the 2006 IEEE MTT-S international microwave symposium, San Francisco, CA, pp 965–968
747. Gao J, Kasamatsu A, Kojima F, Li K (2015) Performance of transmission line on liquid crystal polymer (LCP) from 220 to 330 GHz. In: Proceedings of the 2015 8th UK, Europe, China millimeter waves and THz technology workshop, Cardiff
748. Alhendi M, Umar A, Abbata EM, Umar A, Cadwell R, Weerawarne DL, Borgesen P, Iannotti J, Stoffel N, Poliks MD (2020) A comparative study of aerosol jet printing on polyimide and liquid crystal polymer substrates for RF applications. In: Proceedings of the 2020 70th IEEE electronic components and technology conference (ECTC), Orlando, FL, pp 1579–1585
749. Kanno H, Ogura H, Takahashi K (2003) Surface mountable liquid crystal polymer package with vertical via transition compensating wire inductance up to V-band. In: Proceedings of the 2003 IEEE MTT-S international microwave symposium, Philadelphia, PA, pp 1159–1162
750. Aihara K, Chen AC, Pham AV, Roman JW (2005) Development of molded liquid crystal polymer surface mount packages for millimeter wave applications. In: Proceedings of the

- 2005 14th IEEE topical meeting on electrical performance of electronic packaging, Austin, TX, pp 167–170
751. Roman JW (2005) Liquid crystal polymer air cavity plastic packaging for RF and power applications. In: Proceedings of the 2005 international microelectronics assembly and packaging society (iMAPS) NE
752. Thompson D, Kingsley N, Wang G, Papapolymerou J, Tentzeris MM (2005) RF characteristics of thin film liquid crystal polymer (LCP) packages for RF MEMS and MMIC integration. In: Proceedings of the 2005 IEEE MTT-S international microwave symposium, Long Beach, CA, pp 857–860
753. Aihara K, Pham AV (2006) Development of thin-film liquid crystal polymer surface mount packages for Ka-band applications. In: Proceedings of the 2006 IEEE MTT-S international microwave symposium, San Francisco, CA, pp 956–959
754. Chen MJ, Pham AV, Evers NA, Kapusta C, Iannotti J, Kornrumpf W, Maciel J, Karabudak N (2006) Design and development of a package using LCP for RF/Microwave MEMS switches. *IEEE Trans Microw Theory Techn* 54(11):4009–4015
755. Chen M, Pham A, Kapusta C, Iannotti J, Kornrumpf W, Evers N, Maciel J, Karabudak N (2006) Development of multilayer organic modules for hermetic packaging of RF MEMS circuits. In: Proceedings of the 2006 IEEE MTT-S international microwave symposium, San Francisco, CA, pp 271–274
756. Thompson DC, Tentzeris MM, Papapolymerou J (2006) Packaging of MMICs in multilayer LCP substrates. *IEEE Microw Wirel Comp Lett* 16(7):410–412
757. Yazdani F (2006) Signal integrity characterization of microwave XFP ASIC BGA package realized on Low-K liquid crystal polymer (LCP) substrate. *IEEE Trans Adv Pack* 29(2):359–363
758. Chen M, Evers N, Kapusta C, Iannotti J, Kornrumpf W, Pham AV, Maciel J, Karabudak N (2007) Reliability of a hermetic LCP package for RF MEMS switches. In: Proceedings of the 2007 GOMACTech, Lake Buena Vista, FL
759. Ha D, Kim BG, Lin TY, Ouyang Y, Irazoqui PP, Chappell WJ (2010) 3D packaging technique on liquid crystal polymer (LCP) for miniature wireless biomedical sensor. In: Proceedings of the 2010 IEEE MTT-S international microwave symposium, Anaheim, CA, pp 612–615
760. Kuang K, Kim F, Cahill SS (eds) (2010) RF and microwave microelectronics packaging. Springer, Berlin
761. Pham A (2010) Liquid crystal polymer for microwave and millimeter-wave multi-layer packages and modules. In: Proceedings of the 2010 40th European microwave conference, Amsterdam
762. Pham AV (2011) Packaging with liquid crystal polymer. *IEEE Microw Mag* 12(5):83–91
763. Pham AVH, Chen MJ, Aihara K (2012) LCP for microwave packages and modules, series: the Cambridge RF and microwave engineering series. Cambridge University Press, Cambridge
764. Chlieh OL, Morcillo C, Pavlidis S, Khan WT, Papapolymerou J (2013) Integrated microfluidic cooling for GaN devices on multilayer organic LCP substrate. In: Proceedings of the 2013 IEEE MTT-S international microwave symposium, Seattle, WA
765. Elliott A, McDearmon J (2016) Liquid crystal polymer air cavity plastic packaging in RF applications. *Chip Scale Rev* 12:1–2
766. Pillans B, Coryell L, Malczewski A, Moody C, Morris F, Brown A (2012) Advances in RF MEMS phase shifters from 15 to 35 GHz. In: Proceedings of the 2012 IEEE MTT-S international microwave symposium, Montreal, QC
767. Xin J, Wang C, Wei L (2015) A laser-assisted bonding method using a liquid crystal polymer film for MEMS and sensor packaging. *IEEE Trans Compon Pack Manuf Technol* 5(5):583–591

Chapter 4

Preparation of Advanced Microwave Nematic Liquid Crystal Materials



Synthesis of novel nematic liquid crystal mixtures with high dielectric anisotropy, low dielectric loss, and low melting point for K-band application is presented in this chapter. The effect of molecular structure on dielectric properties is studied first, followed by a study on the temperature dependence of dielectric property and viscosity of liquid crystal. 45 intermediate liquid crystal compounds in 5 series with high dielectric anisotropy, and low melting point are then synthesized. Ultimately, 7 new microwave nematic liquid crystal mixtures with different dielectric anisotropy are developed. The dielectric constants of M1, M3, and M6 are larger than those of Merck's liquid crystal samples and $\Delta\epsilon_r$ are all greater than 1.12. The $\Delta\epsilon_r$ of M2, M3, M6, M7 is about 0.2–0.4 higher than that of Merck's samples. The maximum dielectric loss or dielectric loss tangent ($\tan\delta_{\perp\max}$) of our microwave nematic liquid crystal mixtures is generally lower than that of Merck's liquid crystal samples.

4.1 Initial Screening and Pooling

We do not reinvent the wheel for our synthesis of K-band liquid crystal. Hence, 65 types of existing liquid crystal materials are examined. These liquid crystal materials are.

- (1) including alkyl (fluorine-containing) biphenyl cyanide compounds (5 types)
- (2) alkyl (fluorine-containing) biphenyl cyanide compounds (3 types)
- (3) ester liquid crystal compounds (2 types)
- (4) dialkyl biphenyl acetylene compounds (8 types)
- (5) isothiocyano-fluorinated diphenylacetylenes (6 types)
- (6) isothiocyano-fluorinated biphenylacetylenes (7 types)
- (7) alkyl fluorine-containing polyphenyl isothiocyanates (3 types)
- (8) isothiocyano fluorine-containing phenylacetylenes (4 types)
- (9) alkylcyclohexyl fluorine-containing biphenyls (4 types)

- (10) alkylcyclohexyl diphenylacetylene alkoxy compounds (4 types)
- (11) dialkyl fluorine-containing Triphenyldiynes (5 types)
- (12) dialkyl pendant methyl or ethyl fluorine-containing triphenyldiyne (4 types)
- (13) alkyl fluorine-containing biphenyl acetylene difluorovinyl liquid crystal compounds (5 types)
- (14) fluorine-containing polybiphenyls (5 types).

Dielectric properties of the above liquid crystal materials are measured. The measurement setup will be detailed in the following chapter and the measurement data will be posted to the companion website.

4.1.1 Molecular Structure

It is well known that the molecular structural properties, or more precisely, the polar end group, the ring, and the bridging bond, play a critical role in liquid crystal. It is therefore insightful to correlate dielectric properties of liquid crystal materials with their molecular structures. Different molecular structures will exhibit different stability and polarity, resulting in different dielectric loss. Generally, highly polar and/or less stable liquid crystal materials are more lossy with higher dielectric constant.

The dielectric properties of liquid crystal are more sensitive with the ester group and the cyano group. Additionally, the stronger the polarity of the polar end group in the molecule is, the higher the low frequency dielectric constant is. In general, the dielectric loss decreases in the order of $-\text{CO}_2\text{R} > -\text{CN} > -\text{NCS} > -\text{OCH}_3 \geq -\text{F} > -\text{Alkyl}$.

As shown in Fig. 4.1, the dielectric loss of liquid crystal compounds with different polar molecular structures is different, even if they have the same flexible end group. Besides the largest molecular polarity, the ethyl biphenyl cyanide 2CB is thermally the most unstable. Unsurprisingly, it is the most lossy liquid material and its loss increases even more as frequency increases. Meanwhile, the diphenyldiyne 2PTTP2 is thermally more stable than 2CB and its dielectric loss is lower than that of 2CB. Furthermore, the difluorovinyltrifluorobiphenylacetylene 2PUTGV is even more stable than 2PTTP2 and exhibits the lowest dielectric loss. This builds up a positive correlation between dielectric loss and the molecular stability.

The molecular stability depends not only on the bridging bond but also the molecular substituents. For high birefringence liquid crystal molecules, a single bond connecting two aromatic rings is the most stable and lower dielectric loss is thus more likely. Generally, the stability of bridging bonds takes the order as $-\text{CO}_2 \rightarrow -\text{CH}=\text{CH} \rightarrow -\text{OCH}_2 \rightarrow -\text{C}\equiv\text{C} \rightarrow -\text{OCF}_2 \rightarrow \text{single bond}$.

The benzene ring is more stable in the aromatic ring system than the nitrogen-containing heterocyclic ring. The correspond dielectric loss is relatively small.

Measurement results show that the dielectric properties of many series of liquid crystal compounds correlate with their optical properties. The higher the molecule's optical anisotropy (Δn), the lower the dielectric loss. A closer look at the optical

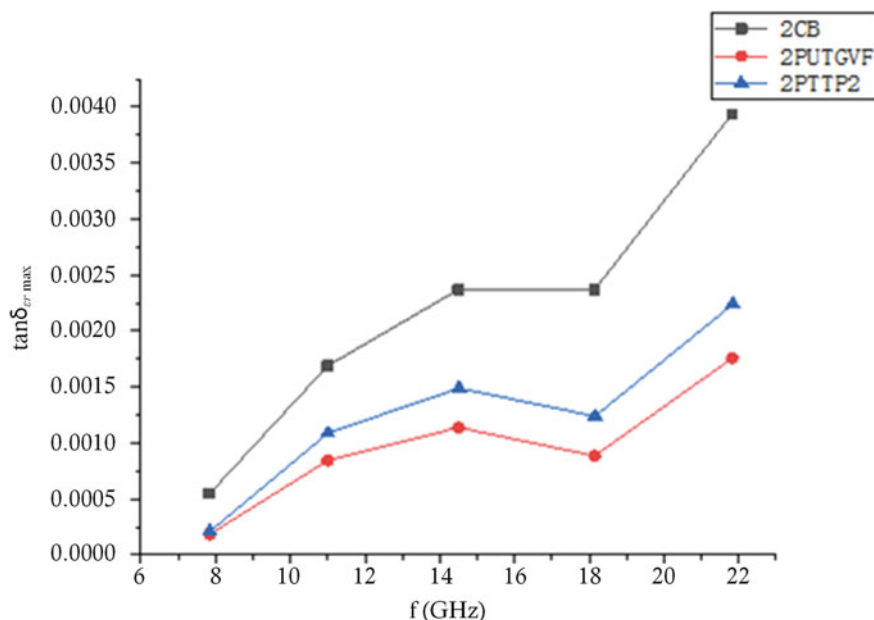


Fig. 4.1 Relationship between substituent polarity and dielectric loss of liquid crystal compounds

anisotropy shows that the length of the carbon chain plays a role. As the carbon chain of the liquid crystal compound with the same host structure gets longer, the Δn value and the $\Delta\epsilon$ value continuously decrease and the dielectric loss becomes greater. Both alkyldiphenylacetylene isothiocyanates and alkyldiphenyldiynes follow this law as shown in Fig. 4.2.

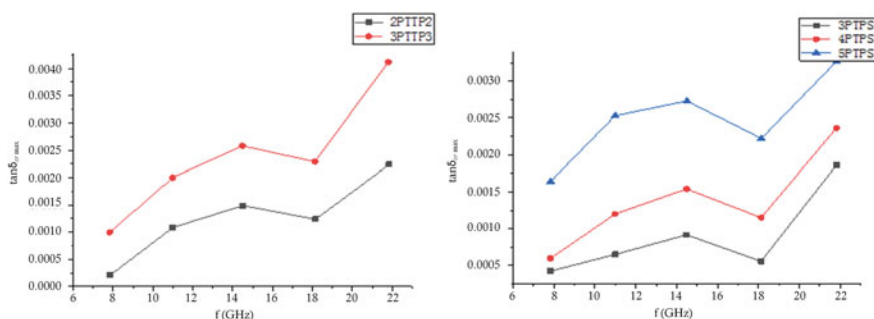


Fig. 4.2 Dielectric loss of compounds nPTTPm and nPTPS with different alkyl groups

4.1.2 Temperature Dependence of Dielectric and Viscosity Properties of Liquid Crystals

The dielectric loss in solid state is smaller while the dielectric loss in liquid state is generally higher. This may be related to the molecular arrangement and the corresponding viscosity at different temperature. The temperature dependence of viscosity properties of liquid crystal compounds and compositions with different structures at different temperatures is therefore of important interest. Lower melting point and weaker temperature dependence generally are more favorable.

Intermolecular forces corresponding to different molecular structures greatly affect the viscosity of liquid crystals, as evidenced in Figs. 4.3, 4.4 and 4.5. For example, the viscosity of the composition 5PTPP3-3PCF2OP5 system changes little with temperature with the lowest melting point. On the contrary, the melting point of 2PTTP2-3PEP5 system is higher and the viscosity at about 18 °C changes abruptly. The intermolecular force of difluorovinyl 5UTPVF is weak, resulting in relatively low melting point and viscosity and weak temperature. Additionally, even though both 5PTPVF and 5UTPVF are difluorovinyl compounds, their viscosity properties are noticeably different due to the different fluorine content on the benzene ring. The effect is even much stronger for the alkoxy compound (5PTPO2). The larger intermolecular force brings a higher melting point and a higher viscosity. Meanwhile, compound nPUTGVF and compound nPTGS behave similarly but their temperature dependence is apparently different with that of amylphenol propyl benzoate (3PEP5).

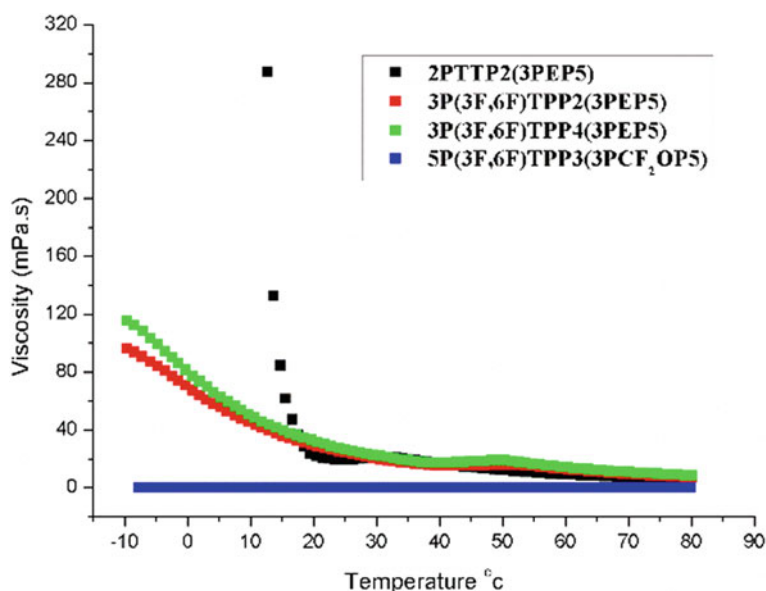


Fig. 4.3 Measured viscosity of ether series

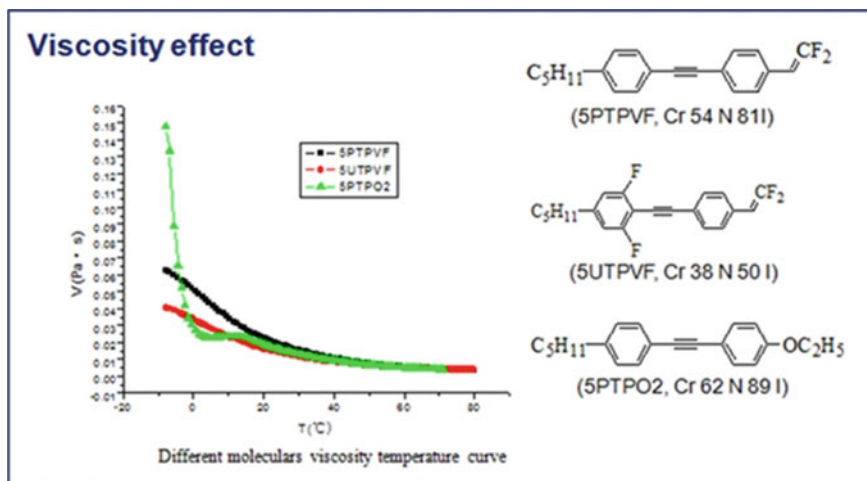


Fig. 4.4 Viscosity of difluorovinyl liquid crystal compounds

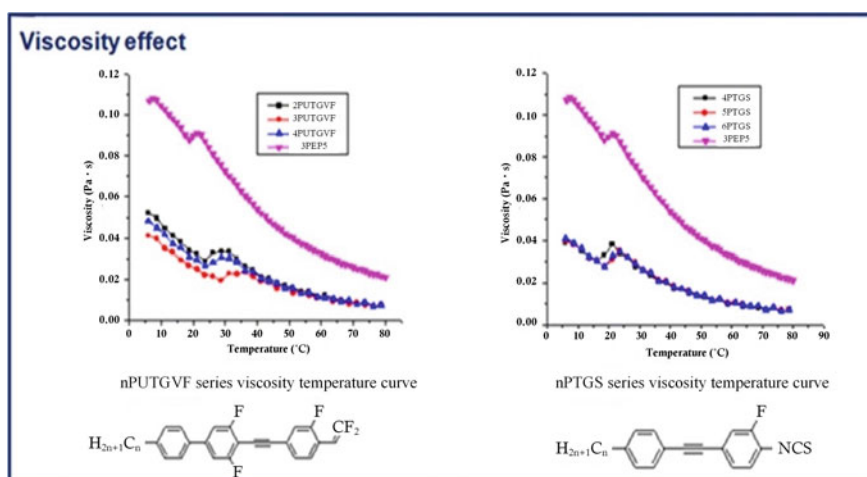


Fig. 4.5 Viscosity of nPUTGVF and nPTGS

The dielectric properties of liquid crystal solvent and its mutual solubility at low temperature also affect the low temperature properties of mixed liquid crystal. More importantly, the influence is usually substantial since the liquid crystal solvent component accounts for a relatively large proportion of the mixed liquid crystal. As shown in Fig. 4.6, when the temperature is higher than 33 °C, the viscosity of 5PTP(2)TP2 (m.p.28 °C), 4PUTGVF, and 4PTP(2)GS changes are almost the same because they all were mixed with 80% liquid crystal solvent 3PEP5.

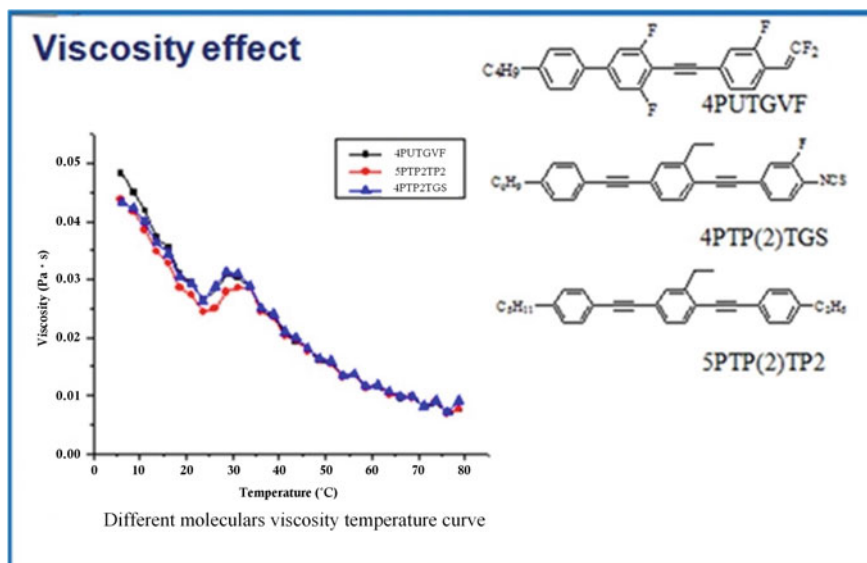


Fig. 4.6 Viscosity of liquid crystals with 80% solvent 3PEP5

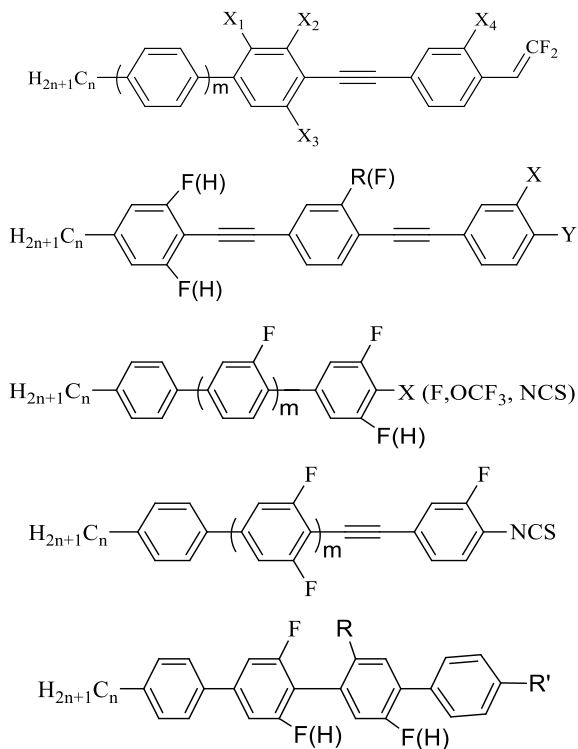
In conclusion, the low-viscosity, low-melting compounds are beneficial for improving the low-temperature performance of liquid crystal. The preferred molecular structures of liquid crystal compounds that are conducive to lowering the melting point mainly include lateral fluorine-containing polyaromatic ring systems (such as 2,3-difluorophenyl, 3,5-difluorophenyl, etc.), side-position fluorine-containing di(bi)phenylacetylene system, or side-position ethyl or methyl aromatic ring system. Meanwhile, favorable polar end groups are mainly $-NCS$, $-F$, $-OCF_3$, $-OCF=CF_2$, fluoroalkyl. In addition, unit structural components such as a flexible alkyl chain or a terminal alkenyl chain are advantageous.

4.2 Microwave Liquid Crystal Compounds

Based on the previous studies, we will now synthesize new molecular structures for K-band applications. Highly stable structures with a low melting point, low viscosity, high dielectric anisotropy ($\Delta n \geq 0.35$), and temperature insensitive are desired. Side fluorine-containing polyaromatic ring system or side alkyl fluorine-containing polyaromatic ring like (without bridging group) system and its diphenylacetylene system in nematic liquid crystal compounds, mostly with $-NCS$, $-F$, $-CF=CF_2$, and fluoroalkyl polar end groups, are investigated.

So far, 45 liquid crystal compounds in five structural series as shown in Fig. 4.7 have been synthesized. The dielectric, viscosity, and other properties at low temperatures are measured. The relationship between molecular polarity and molecular

Fig. 4.7 Synthesized structural series of 45 liquid crystal compounds



groups of liquid crystal compounds is accordingly obtained as summarized in Table 4.1.

4.2.1 Weakly Polar Side-Position Methyl

15 types of compounds in three series have been synthesized. All compounds here exhibit nematic phase over a wide temperature range with relatively low melting points and high optical anisotropy ($\Delta n \geq 0.4$).

The complete synthetic route of the compounds nPTP(2)TPm and nPTP(2)TGS is shown in Fig. 4.8.

Table 4.1 Molecular group and molecular polarity of some liquid crystal compounds and compositions

Compound name	Molecular polarity	
	Main group	Polarity
7CB	–CN	Strong
5CB	–CN	Strong
3PEP5	–CO ₂ –	Medium
2CEGF	–CO ₂ –, C–F	Medium
4PTGS	–C≡C–, –NCS	Strong
6PTGS	–C≡C–, –NCS	Strong
4PGUS	–C–F, –NCS	Strong
5PGUS	–C–F, –NCS	Strong
3PGUS	–C–F, –NCS	Strong
3PTP(2)TGS	C≡C, NCS, C–F	Strong
5PTP(2)TGS	C≡C, NCS, C–F	Strong
5PUTGS	C≡C, NCS, C–F	Strong
4UTP2	–C≡C–, C–F	Nonpolar
5PTPO1	–C≡C–, –OR	Weak
3UTPP4	–C≡C–, C–F	Weak
3UTPP2	–C≡C–, C–F	Weak
4UTPP3	–C≡C–, C–F	Weak
2UTPP3	–C≡C–, C–F	Weak
3UTGTP4	–C≡C–, C–F	Weak
4UTGTP3	–C≡C–, C–F	Weak
3UTP(1)TP2	–C≡C–, C–F	Weak
4UTP(1)TP3	–C≡C–, C–F	Weak
5PTP(2)TP2	2–C≡C–	Nonpolar
4PTP(2)TP3	2–C≡C–	Nonpolar
6PTP(2)TP3	2–C≡C–	Nonpolar
5PP(2)GP4	Terphenyl, C–F	Weak
5PP(2)GP5	Terphenyl, C–F	Weak
3CGPC3	C–F	Weak
3PGF	3C–F	Weak
3PGUF	2C–F	Weak
5PPUF	2C–F	Weak

4.2.2 Ethyltriphenyldiyn Liquid Crystal Compounds

As shown in Fig. 4.9 and Tables 4.2 and 4.3, the melting point of nPTP(2)TPm is only about 14–40 °C, making it a good candidate for microwave liquid crystal solvent component.



Fig. 4.8 Synthetic route of compounds nPTP(2)TPm and nPTP(2)TGS

Mesomorphic properties

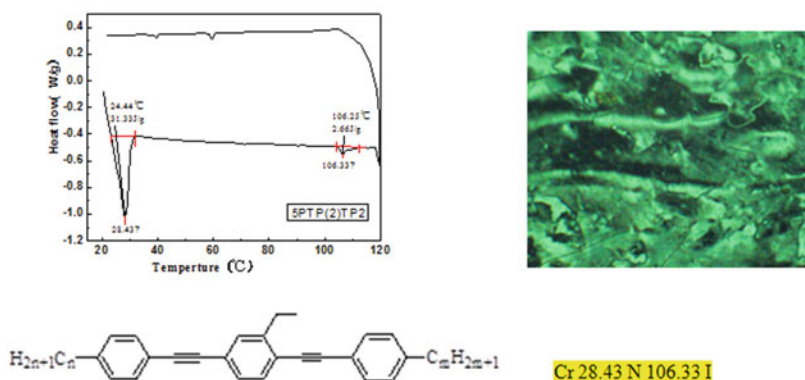


Fig. 4.9 DSC spectrum of 5PTP(2)TP2

Table 4.2 Phase transition temperature, birefringence, and dielectric loss of series I compound (nPTP(2)TPm)

Target compound	Phase transition temperature T (°C)	ΔT_N (°C)	Δn	$\tan\delta_{\text{ave}}$ (18.1 G)
4PTP(2)TP3	Cr 42 N 126.7 I _{so}	84.7	0.414	Untested
4PTP(2)TP4	Cr 32.0N 119.2 I _{so}	87.2	0.402	2.15E-03
5PTP(2)TP2	Cr 28.4 N 128.0 I _{so}	100.4	0.405	5.35E-03
6PTP(2)TP3	Cr 14.5 N 107.8 I _{so}	93.3	0.409	1.37E-03

Note **a** Cr stands for anisotropic crystal, S stands for smectic phase, N stands for nematic phase, and Iso stands for isotropic liquid; **b** The previous test method is not accurate enough to measure the anisotropy, but it can be used to analyze the variation law; **c** Tested at 598.2 nm, 2 °C

Table 4.3 Measured high frequency dielectric properties of (5PTP(2)TP2)

f (GHz)	Q-factor	ϵ_r	ϵ'_r	$\tan\delta_{\epsilon_r \text{ ave}}$
7.834	2035	3.17	2.89E-02	1.01E-02
10.992	2314	3.21	1.60E-02	1.08E-02
14.491	2517	3.28	1.80E-02	1.03E-02
18.129	2806	3.39	1.85E-02	8.61E-03
21.805	2674	3.71	1.67E-02	1.19E-02

The synthetic route of compounds in series II (nUTGTPm) and III (nUTP(1)TPm) is shown in Fig. 4.10. The phase transition temperature and dielectric properties are shown in Table 4.4.

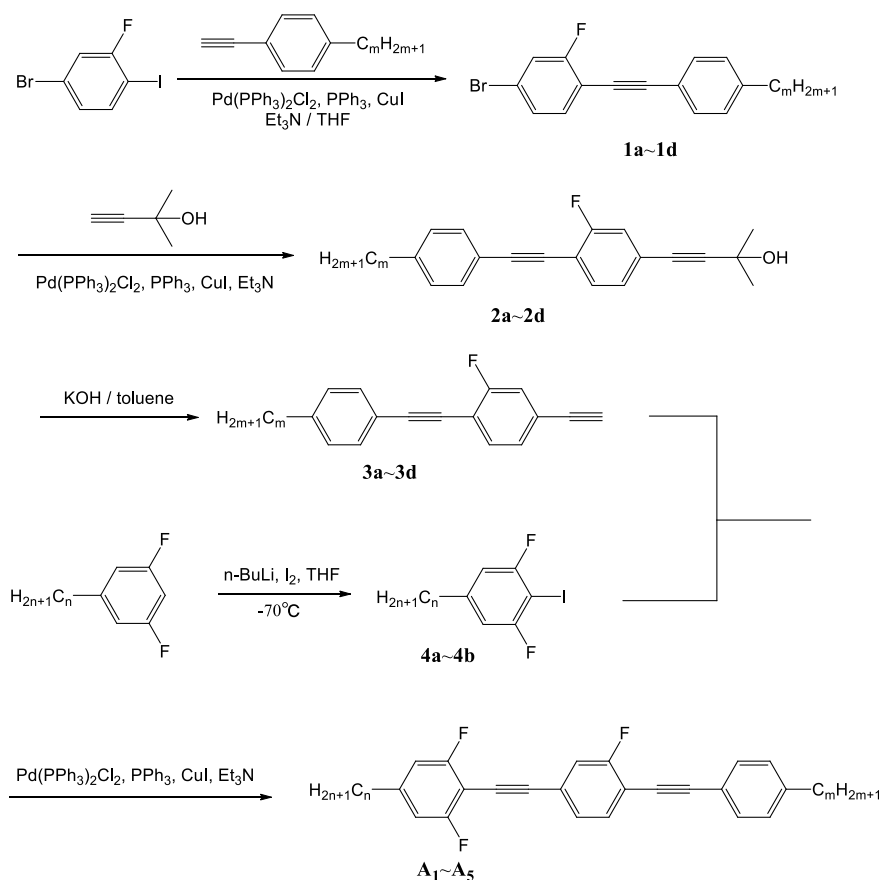
**Fig. 4.10** Synthetic route of series II compounds mUTGTPn ($A_1 \sim A_5$)

Table 4.4 Phase transition temperature birefringence and dielectric loss of (nUTGTPm)

Target compound	Phase transition temperature T (°C)	ΔT_N (°C)	Δn	$\tan\delta_{\text{er ave}}$ (18.1G)
3UTGTP2	Cr 98.63 S 107.25 N 184.75 I _{so}	77.5	0.418	2.62E-03
3UTGTP3	Cr 110.92 N 199.40 I _{so}	88.48	0.424	1.13E-03
3UTGTP4	Cr 87.99 N 180.07	92.08	0.408	1.85E-03
3UTGTP5	Cr 77.97 N 184.75 I _{so}	106.78	0.405	2.54E-03
4UTGTP5	Cr 72.12 N 172.81 I _{so}	100.69	0.409	Untested

Note **a** Cr represents anisotropic crystal, S represents smectic phase, N represents nematic phase, and Iso represents isotropic liquid; **b** The previous test method is not accurate enough to measure the anisotropy, but it can be used to analyze the variation law; **c** Tested at 598.2 nm, 20 °C

Table 4.5 Phase transition temperature and dielectric properties of (mUTP(1)TPn)

Target compound	Phase transition temperature T (°C)	ΔT_N (°C)	Δn	$\tan\delta_{\text{er ave}}$ (18.1 G)
3UTP(1)TP2	Cr 72.16 N169.09 I _{so}	96.93	0.426	2.12E-03
4UTP(1)TP2	Cr 83.16 N 160.75 I _{so}	77.60	0.412	3.42E-03
4UTP(1)TP3	Cr 80.27 N 152.65 I _{so}	71.73	0.408	2.04E-03
4UTP(1)TP5	Cr 79.06 N 142.66 I _{so}	63.60	0.417	3.02E-03

Note **a** Cr represents anisotropic crystal, S represents smectic phase, N represents nematic phase, and Iso represents isotropic liquid; **b** The previous test method is not accurate enough to measure the anisotropy, but it can be used to analyze the variation law; **c** Tested at 598.2 nm, 20 °C

The phase transition temperature and dielectric properties of compounds in series III (nUTP(1)TPm) are shown in Table 4.5.

4.2.3 Polar Isothiocyanate Compounds

A total of 17 compounds in three series were synthesized. The dielectric properties of these compounds are relatively good, and their Δn and $\Delta\epsilon$ values are large.

4.2.3.1 NPTGS

The phase state and optical properties of double-ring fluorine-containing diphenylacetylene isothiocyanate compounds (NPTGS) are given in Table 4.6. Their melting point and viscosity are relatively low. Therefore, they may be good component to reduce the freezing point of mixture albeit its narrow phase state.

Table 4.6 Properties of diphenylacetylene (nPTGS)

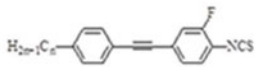
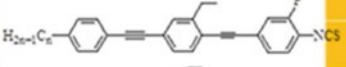
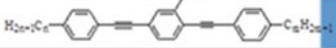
Compounds	Abbreviation	Phase transition temperature T (°C)	Δn
	4PTGS	Cr 31.73 (53.52) I	0.412
	5PTGS	Cr 50.59N 90.59 I	0.419
	6PTGS	Cr 32.62 N 35.27 I	0.395
	4PTP(2)TGS	Cr 90.99 N 143.84 I	0.622
	5PTP(2)TGS	Cr 96.47 N 144.05 I	0.594
	5PTP(2)TP2	Cr 28.43 N 106.33 I	0.425

Table 4.7 Measured high frequency dielectric properties of 4PTGS and 6PTGS

f (GHz)	6PTGS			4PTGS		
	ϵ_r	ϵ'_r	$\tan\delta_{\text{er ave}}$	ϵ_r	ϵ'_r	$\tan\delta_{\text{er ave}}$
5.62	4.214	0.0263	6.25E−03	3.394	5.80E−03	1.71E−03
7.83	4.048	0.016	3.94E−03	3.266	5.81E−03	1.78E−03
10.99	4.007	0.0141	3.52E−03	3.261	6.49E−03	1.99E−03
14.49	3.888	0.0194	5.00E−03	3.221	1.53E−02	4.75E−03
18.13	3.996	0.0200	5.00E−03	3.328	1.90E−02	5.71E−03
21.80	5.063	0.0484	9.55E−03	4.285	1.35E−02	3.16E−03

Note The previous test method is not accurate enough to measure the anisotropy, but it can be used to analyze the variation law

Dielectric properties of two representative nPTGS, i.e., 4PTGS and 6PTGS, are measured and given in Table 4.7. Their melting points are only 31.7 °C and 32.6 °C, respectively.

4.2.3.2 Tricyclic Diacetylenic Series IV Compounds

The nematic liquid crystal state of tricyclic diacetylenic series IV compounds have a wide temperature range and high birefringence. In particular, the birefringence of 4PTP(2)TGS is $\Delta n = 0.622$, making it an effective component of microwave liquid crystal materials. Although the melting point is high, it is 35–60 °C lower than that of the pendant ethyl counterparts.

The measured high frequency dielectric properties of 4PTP(2)TGS and 5PTP(2)TGS are shown in Tables 4.8 and 4.9.

Table 4.8 High frequency dielectric properties of (4PTP(2)TGS)

f (GHz)	Q-factor	ε_r	ε'_r	$\tan\delta$
7.836	2206	2.945	1.47E-02	5.00E-03
10.996	2527	2.931	1.47E-02	5.00E-03
14.497	2108	2.889	6.65E-02	2.30E-03
18.139	3157	2.955	1.48E-02	5.00E-03
21.824	3143	3.517	2.61E-02	7.42E-03

Note The previous test method is not accurate enough to measure the anisotropy, but it can be used to analyze the variation law

Table 4.9 High frequency dielectric properties of (5PTP(2)TGS)

f (GHz)	Q-factor	ε_r	ε'_r	$\tan\delta$
7.83	2245	4.113	2.06E-03	5.00E-03
10.99	2555	4.028	8.50E-03	2.11E-03
14.49	2798	3.846	2.57E-03	6.69E-03
18.13	3109	3.859	2.20E-03	5.70E-03
21.81	3141	4.13	1.08E-02	2.61E-03

Note The previous test method is not accurate enough to measure the anisotropy, but it can be used to analyze the variation law

4.2.3.3 Fluorine-Containing Biphenylacetylene Series V Compounds

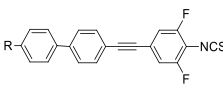
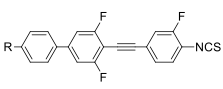
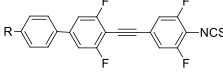
All fluorine-containing biphenylacetylene series V liquid crystal compounds (nPPTUS, nPUTGS, nPUTUS) have a wide temperature range and a birefringence above 0.45. Although the melting point is high, they are also important components of liquid crystal mixtures. The phase state and optical properties are shown in Table 4.10.

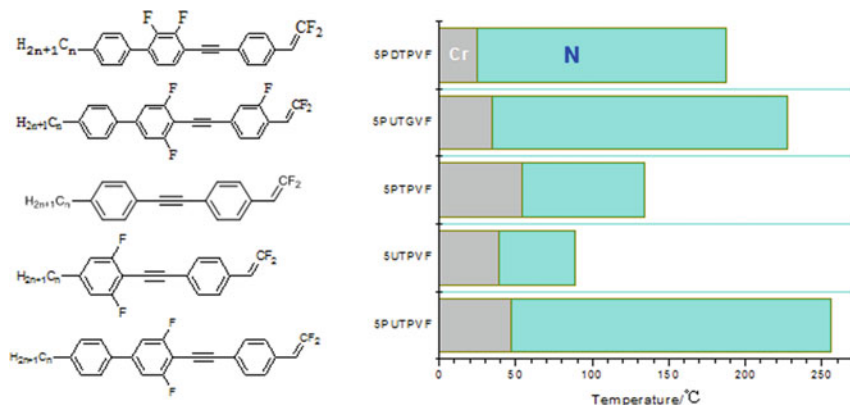
4.2.4 Difluorovinyl Fluorine-Containing Polyphenylacetylene Liquid Crystal VI Compounds (nPUTGVF, nPUTPVF, nPDTPVF, nPTPVF)

The liquid crystal phase states of the 12 liquid crystal compounds synthesized are shown in Fig. 4.11 and Table 4.11. Most of the compounds have a melting point, a wide temperature phase, high birefringence, and low-temperature viscosity.

However, the measured dielectric loss given in Tables 4.12 and 4.13 is not as good as that of isothiocyanate compounds. In addition, the dielectric loss generally increases with frequency. Apparently, it is unfavorable as evidenced by the dielectric loss given in Fig. 4.12.

Table 4.10 Phase transition temperature and optical properties of fluorine-containing biphenylacetylene isothiocyanate series compounds

Molecular structure	Abbreviation	Phase transition temperature T (°C)	ΔT_{N-I}	Δn
	2PPTUS	Cr114.1N204.1Iso	90.0	0.527
	3PPTUS	Cr122.4N234.3Iso	111.9	0.511
	4PPTUS	Cr63.2S98N212.4Iso	114.4	0.514
	5PPTUS	Cr84.2N201.5Iso	117.3	0.505
	3PUTGS	Cr122N226.7Iso	104.7	0.503
	4PUTGS	Cr106N211Iso	95.0	0.481
	5PUTGS	Cr96N218Iso	122.0	0.475
	4PUTUS	Cr126.7N197.1Iso	70.4	0.481
	5PUTUS	Cr128.1N196.0Iso	67.9	0.457



These compounds all have lower melting points, higher isotropic point and wider liquid crystal phase

Fig. 4.11 Nematic phase states of difluorovinyl fluorine-containing diphenylacetylene compounds

4.2.5 Fluorinated Terphenyl (mPGUS) and Tetraphenyl (mPP(2)GPn) Series Liquid Crystal Compounds

All the compounds here have low dielectric loss and broad nematic liquid crystal state. Although the birefringence is low, mostly around 0.30–0.39, and the melting point is higher than room temperature, the measured dielectric properties show that they can be a promising component for high-dielectric and low-loss nematic phase liquid crystal mixtures. The synthetic design routes of fluorinated terphenyl (mPGUS) and fluorinated tetraphenyl (mPP(2)GPn) series are shown in Figs. 4.13

Table 4.11 Properties of difluorovinyl fluorine-containing polyphenylacetylene compounds (nPUTGVF, nPUTPVF, nPDTPVF)

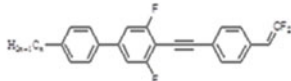
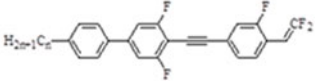
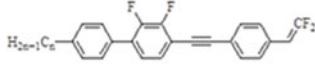
Compounds	Abbreviation	Heating(T/°C)	Δn
	3PUTPVF	Cr 70.0 N 213.7 I	0.425
	4PUTPVF	Cr 63.3 N 213.4 I	0.403
	5PUTPVF	Cr 47.2 N 209.0 I	0.430
	3PUTGVF	Cr 79.4 N 205.3 I	0.364
	4PUTGVF	Cr 50.3 N 187.1 I	0.418
	5PUTGVF	Cr 38.4 N 179.8 I	0.416
	3PDTPVF	Cr 34.4 N 192.8 I	0.432
	4PDTPVF	Cr 26.2 N 173.8 I	0.445
	5PDTPVF	Cr 24.6 N 162.9 I	0.456

Table 4.12 Test results of dielectric properties of liquid crystal compounds 4PUTGVF and 5PPTGVF at high frequency

<i>f</i> (GHz)	4PUTGVF			5PPTGVF		
	ε _r	ε' _r	tanδ	ε _r	ε' _r	tanδ
5.62	3.534	0.0122	3.45E−03	3.955	0.0178	4.49E−03
7.83	3.383	0.00989	2.92E−03	3.776	0.0153	4.04E−03
10.99	3.362	0.0102	3.03E−03	3.738	0.0150	4.01E−03
14.49	3.294	0.00449	1.36E−03	3.634	0.0093	2.56E−03
18.13	3.387	0.00251	7.40E−04	3.737	0.00618	1.65E−03
21.80	4.326	0.0138	3.18E−03	4.737	0.0177	3.73E−03

Table 4.13 Test results of dielectric properties of liquid crystal compound (7PTPVF) at high frequency

<i>f</i> (GHz)	Q-factor	ε _r	ε' _r	tanδ
7.834	2209	4.837	2.76E−03	5.71E−04
10.992	2513	4.708	5.37E−03	1.14E−03
14.491	2750	4.462	6.31E−03	1.41E−03
18.129	3124	4.552	4.46E−03	9.79E−04
21.805	3059	5.784	1.23E−02	2.13E−03

Note The previous test method is not accurate enough to measure the anisotropy, but it can be used to analyze the variation law

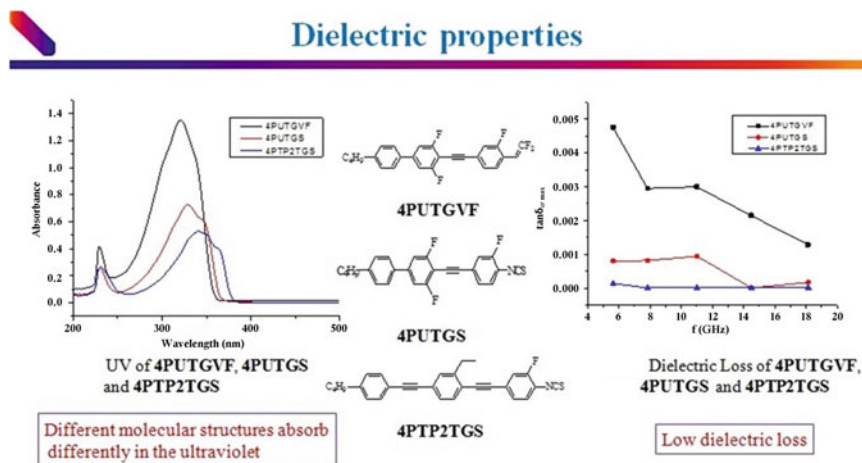


Fig. 4.12 Comparison of UV light absorption and dielectric loss of difluorovinyl liquid crystal compounds

and 4.14, respectively. The liquid crystal phase and dielectric properties are shown in Table 4.14.

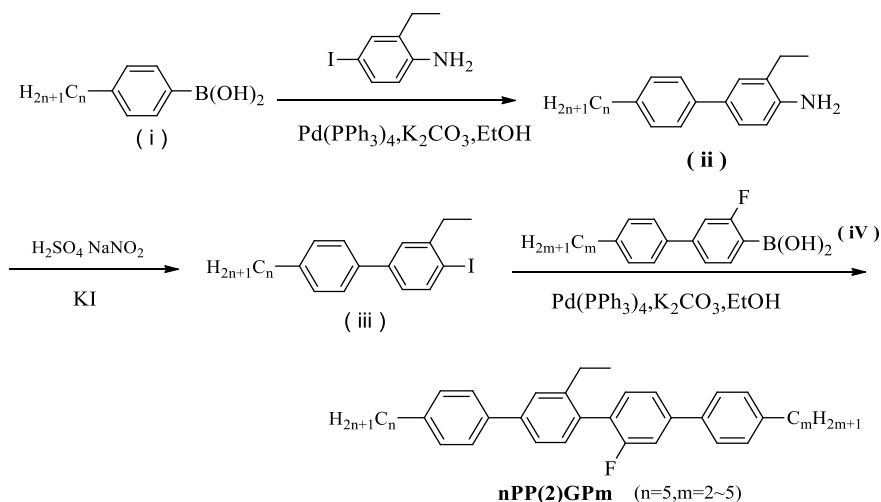


Fig. 4.13 The complete synthesis route of the series of compounds nPP(2)GPn

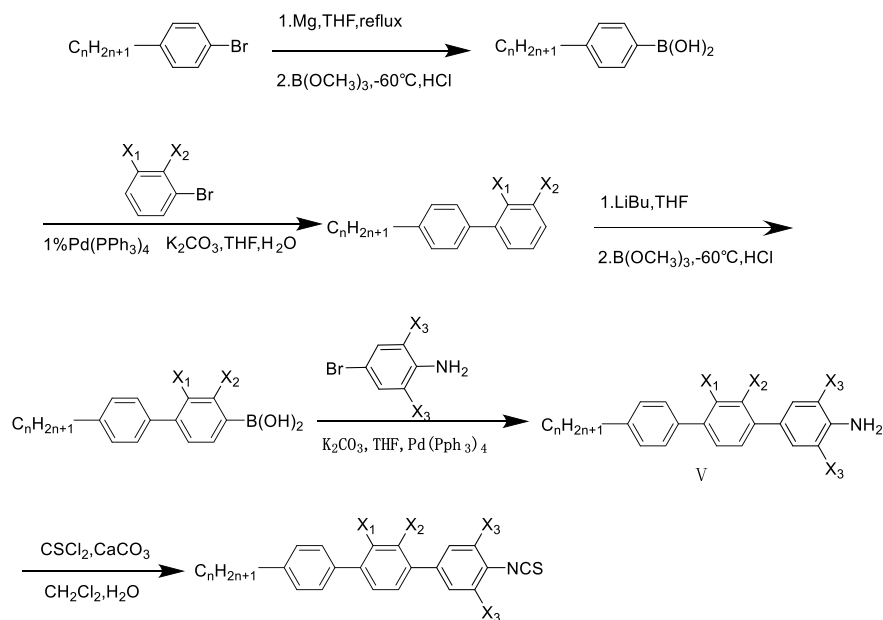


Fig. 4.14 The Complete synthesis route of the series of compounds mPGUs ($n = 2-5$; $\text{X}_1-\text{X}_3 = \text{F}, \text{H}$)

Table 4.14 Liquid crystal phase transition temperature and dielectric properties of fluorinated polybiphenyl compounds

Molecular structure	Abbreviation	Phase transition temperature (T/°C)	ΔT_{N-1}	Δn
	2PGUS	Cr71N154.1Iso	83.1	0.397
	3PGUS	Cr69.0N169.3Iso	100.3	0.395
	4PGUS	Cr66.7N157.4Iso	91.7	0.392
	5PGUS	Cr56.2N159.6Iso	103.4	0.395
	5PP(2)GP2	Cr82.6N120.7Iso	38.1	0.305
	5PP(2)GP3	Cr98.8N126.9Iso	28.1	0.298
	5PP(2)GP4	Cr56.3Sm73.8N110.3Iso	54.0	0.295
	5PP(2)GP5	Cr75.8N112.5Iso	36.7	0.291

4.3 Composite Microwave Nematic Liquid Crystal Materials

No single liquid crystal compound can meet the requirements of high anisotropy and low loss from practical microwave devices. Composite material is therefore the only feasible choice. It is necessary to reasonably mix several to dozens of

liquid crystal compound monomers with different properties according to a certain proportion to form a composition. In general, optimal matching can be realized if the principles of thermodynamics and “like dissolves like” are followed. Usually, the dielectric anisotropy of the composite material is a linear superposition of that of each component

$$\Delta\varepsilon = \sum_{i=1}^m x_i \Delta\varepsilon_i \quad (4.1)$$

Obviously, the liquid crystal compounds with high Δn values are the choice of our first priority. In our practice, liquid crystal compounds with high Δn values and low melting points with different structural properties are selected as solvent components, while those with wide temperature nematic phases and different polarities are selected as main components. More than 10 microwave nematic liquid crystal compositions with different dielectric properties have been formulated and measured by using a new setup which will be described in Chap. 5.

4.3.1 Microwave Nematic Liquid Crystal Materials with Medium Polarity and High Birefringence

According to the performance requirements of the microwave phase shifter, we prepared a polar mixed liquid crystal material (MLC-F) by formulating the synthesized difluorovinyl liquid crystal compound and the fluorine-containing isothiocyanate polar liquid crystal compound. Its liquid crystal components and properties are shown in Table 4.15.

The measured high frequency dielectric properties are shown in Table 4.16. It can be seen that the high frequency dielectric loss and dielectric loss tangent of MLC-F are relatively large. Further improvement is necessary to meet the requirements from high-frequency devices for liquid crystal materials.

The viscosity of MLC-F and liquid crystal propyl phenol benzoate (3PEP5) between 0 and 80 °C is shown in Fig. 4.15. It can be seen that the viscosity of both

Table 4.15 MLC-F composition

No	Compounds	Wt (%)	Property
1	nPTGS (n = 4, 5, 6)	34.0	$\Delta n = 0.4011$; m.p. = -18.6 °C; Iso. = 94.7 °C; $\Delta\varepsilon = 8.5(1 \text{ kHz})$; $\rho = 8.5 \times 10^9 \text{ } \Omega \text{ cm}$ $\mu = 85 \text{ cps (25 } ^\circ\text{C)}$
2	nPTP(2)TGS (n = 3, 5)	11.0	
3	nPTP(2)TPm (m, n = 2–5)	20.0	
4	nPUTG-VF (n = 3, 5)	20.0	
5	nPUTGS (n = 4, 5)	8.0	
6	nUTPPm (m, n = 2–5)	7.0	

Table 4.16 High frequency dielectric properties of MLC-F

f (GHz)	Permittivity ε	Dielectric loss ε'	Loss tangent $\tan\delta$
9.857	3.807	3.75E-02	9.85E-03
14.857	3.886	4.50E-02	1.16E-02
25.564	3.887	4.56E-02	1.17E-02

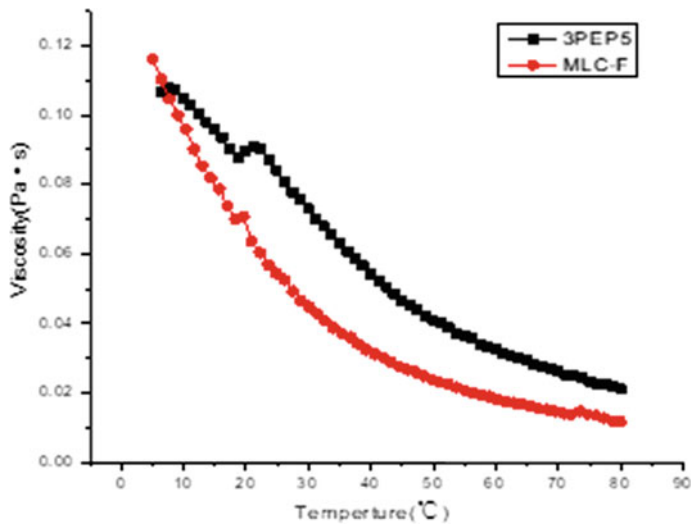


Fig. 4.15 Comparison of viscosity variation curves of mixed liquid crystal MLC-F and liquid crystal 3PEP5 with temperature

MLC-F and 3PEP5 is low and decreases as temperature increases. It is also observed that the viscosity of MLC-F is generally smaller than that of general-purpose liquid crystal solvent 3PEP5.

4.3.2 High Birefringence Microwave Nematic Liquid Crystal Materials

The non-polar and weak polar fluorine-containing liquid crystal compounds are mixed to make polar liquid crystal mixture (MLC-C-3). Its composition and properties are shown in Table 4.17.

The high frequency dielectric properties at low-temperature viscosity were also measured and shown in Table 4.18.

Table 4.17 MLC-C-3 composition

No	Compounds	Wt(%)	Property
1	nUTP(1)TPm (n, m = 2, 3, 4, 5)	38.5	$\Delta n = 0.37$; m. p. = 10 °C; Iso. = 105 °C; $\Delta \epsilon = 3.5$ (1 kHz); $\rho = 1.5 \times 10^{10} \Omega \text{ cm}$ $\mu = 65 \text{ cps}$ (25 °C)
2	nUTGTPm (n, m = 3, 4, 5)	30.0	
3	5PPUF	5.0	
4	3PGUF	3.5	
5	nUTPP3(n = 4, 5)	23.0	

Table 4.18 Measured high frequency dielectric properties of MLC-C-3

f (GHz)	Permittivity ϵ	Dielectric loss ϵ'	Loss tangent $\tan \delta_{\epsilon r \text{ average}}$
7.829	4.63	5.72E-02	1.24E-02
10.986	4.535	5.88E-02	1.30E-02
14.483	4.358	5.28E-02	1.21E-02
18.119	4.492	4.49E-02	9.99E-03
21.791	5.756	8.00E-02	1.39E-02

It can be seen from Table 4.19 that the high frequency dielectric loss of MLC-C-3 is relatively large. Moreover, the dielectric constant and dielectric loss of MLC-C-3 are larger than those of Merck's high birefringence ($\Delta n = 0.2892$) liquid crystal given in Table 4.19. Hence, MLC-C-3 still cannot meet the requirements of high-frequency devices. Its dielectric loss has to be further reduced.

The dielectric loss of Merck's high birefringence liquid crystal we measured is slightly larger than Merck's original data ($\epsilon_{r\parallel} = 3.2$, $\epsilon_{r\perp} = 2.63$, $\tan \delta_{\parallel} = 0.0035$, $\tan \delta_{\perp} = 0.0128$, 20 GHz). It hints that our use, storage and transportation might have to be improved. Trace ions or impurities and moisture in the liquid crystal material greatly influence the dielectric loss of liquid crystal, especially formulated nematic liquid

Table 4.19 Dielectric properties of Merck's liquid crystal samples

f (GHz)	$\epsilon_{r\parallel}'$	$\epsilon_{r\perp}'$	$\Delta \epsilon_r'$	$\tan \delta_{\parallel}'$	$\tan \delta_{\perp}'$	$\Delta \tan \delta$
7.823	3.286	2.63	0.656	3.08E-03	1.92E-02	-1.61E-02
10.977	3.346	2.658	0.688	3.97E-03	2.05E-02	-1.65E-02
14.470	3.43	2.721	0.709	4.25E-03	1.87E-02	-1.45E-02
18.103	3.549	2.812	0.737	3.80E-03	1.51E-02	-1.13E-02
21.764	3.665	2.839	0.826	3.08E-03	1.92E-02	-1.61E-02
25.577	3.584	2.814	0.77	3.97E-03	2.05E-02	-1.65E-02
29.359	3.635	2.863	0.772	4.25E-03	1.87E-02	-1.45E-02

Note The improved dielectric loss test method is stable, and the data is accurate and available for use

crystal mixture. Therefore, we improved the material of packaging container, the packaging conditions, and the mixing preparation method. Moreover, we upgraded the experimental environment for preparing mixed crystals at the optoelectronic clean laboratory in the University of Electronic Science and Technology of China.

4.3.3 Novel Microwave Nematic Liquid Crystal Mixtures

According to the measured dielectric loss of the liquid crystal compounds with different structures, we turned our attention to the refining and purifying high-birefringence liquid crystal compounds and design and synthesis of new high-birefringence terphenyl or quaterphenyl liquid crystals. We refined the liquid crystal compound to increase its resistivity. Meanwhile, we designed and synthesized some new structures of fluorine-containing biphenyl liquid crystal compounds. Ultimately, seven kinds of microwave nematic liquid crystal mixtures with different dielectric properties were developed. Some formulations and performance parameters of these 7 kinds of mixtures are shown in Tables 4.20, 4.21, 4.22, 4.23, 4.24, 4.25 and 4.26.

Table 4.20 Composition and dielectric properties of novel microwave nematic liquid crystal mixture (M1)

No.	Components	Wt(%)	Dielectric properties
1	nPTGS (n = 4–7)	55.0	$\Delta n = 0.406$ (598 nm) m.p. = -10.0 °C, Iso. = 105.0 °C $\rho = 2.87 \times 10^{10}$ Ω cm $\Delta \varepsilon = 18.5$ (1 kHz); $\mu = 185$ cps (25 °C) $\Delta \varepsilon'_r = 1.20$ (18.1 GHz); $\tau = 0.286$; $\eta = 15.05$ (18.1 GHz) $\tan \delta_{\varepsilon r \perp}' = 0.0190$ (18.1 GHz)
2	nPTP(2)TGS (n = 3, 5)	5.0	
3	nPGUS (n = 3–5)	10.0	
4	nPUTGS (n = 4, 5)	5.0	
5	nPPTUS (n = 4, 5)	12.0	
6	nUTGTPm (m, n = 2–5)	5.0	
7	nPTP(2)TPm (m, n = 2–5)	8.0	

Table 4.21 Composition and dielectric properties of novel microwave nematic liquid crystal mixture (M2)

No.	Components	Wt (%)	Dielectric properties
1	nPTP(2)TPm (m, n = 2–5)	62.0	$\Delta n = 0.386$ (598 nm); m.p. = -10.0 °C; Iso. = 125.0 °C $\rho = 7.87 \times 10^{10}$ Ω cm $\Delta \varepsilon = 5.0$ (1 kHz); $\mu = 85$ cps (25 °C) $\Delta \varepsilon'_r = 1.04$ (18.1 GHz); $\tau = 0.264$; $\eta = 25.38$ (18.1 GHz) $\tan \delta_{\varepsilon r \perp}' = 0.0104$ (18.1 GHz)
2	nUTP(1)TPm (m, n = 2–5)	19.0	
3	nUTGTPm (m, n = 2–5)	12.0	
4	nUTPPm (m, n = 2–5)	4.0	
5	nPGP(2)Pm (m, n = 2–5)	2.0	
6	nPPUF (n = 3–5)	1.0	

Table 4.22 Composition and dielectric properties of novel microwave nematic liquid crystal mixture (M3)

No.	Component	Wt (%)	Photoelectric properties
1	nPTP(2)TGS (n = 3–5)	8.0	$\Delta n = 0.400$ (598 nm); m.p. = -10.0 °C; Iso. = 150.0 °C; $\Delta \varepsilon = 13.0$ (1 kHz); $\mu = 205$ cps (25 °C); $\rho = 4.77 \times 10^{10}$ Ω cm
2	nPGUS (n = 3–5)	42.0	
3	nPTP(2)TPm (m,n = 2–5)	50.0	
Dielectric properties (18.1 GHz): $\Delta \varepsilon_r' = 1.12$, $\tau = 0.279$, $\eta = 27.33$; $\tan \delta_{\varepsilon r \perp}' = 0.0102$			

Table 4.23 Composition and dielectric properties of novel microwave nematic liquid crystal mixture (M4)

No.	Components	Wt (%)	Dielectric properties
1	nUTPPm (m, n = 2–5)	40.0	$\Delta n = 0.347$ (598.2 nm); m.p. = -15.0 °C Iso. = 155.0 °C $\rho = 3.7 \times 10^{11}$ Ω cm $\Delta \varepsilon = 6.5$ (1 kHz); $\mu = 85$ cps (25 °C) $\Delta \varepsilon_r' = 0.99$ (18.1 GHz); $\varepsilon_r' \perp = 2.94$ $\tau = 0.252$; $\eta = 13.54$ (18.1 GHz) $\tan \delta_{\varepsilon r \perp}' = 0.0186$ (18.1 GHz)
2	nUTP(1)TPm (m, n = 2–5)	27.5	
3	nUTGTPm (m, n = 2–5)	16.0	
4	nPTGF (m, n = 2–5)	6.5	
5	nPPUF (m, n = 2–5)	5.0	
6	nPGUF (n = 3–5)	5.0	

Table 4.24 Composition and dielectric properties of novel microwave nematic liquid crystal mixture (M5)

No.	Components	Wt (%)	Dielectric properties
1	nPTGS (n = 4–7)	33.0	$\Delta n = 0.408$ (598 nm) m.p. = -20.0 °C, Iso. = 125.0 °C $\rho = 3.70 \times 10^{10}$ Ω cm $\Delta \varepsilon = 16.5$ (1 kHz); $\mu = 145$ cps (25 °C) $\Delta \varepsilon_r' = 1.19$ (18.1 GHz); $\tau = 0.290$, $\eta = 16.64$ (18.1 GHz) $\tan \delta_{\varepsilon r \perp}' = 0.0174$ (18.1 GHz)
2	nPGUS (n = 3–5)	35.0	
3	nPPTUS (n = 4, 5)	13.0	
4	nPTP(2)TGS (n = 3, 5)	4.0	
5	nPTP(2)TPm (m, n = 2–5)	15.0	

Table 4.25 Composition and dielectric properties of novel microwave nematic liquid crystal mixture (M6)

No.	Components	Wt (%)	Dielectric properties
1	nPTP(2)TPm (m, n = 2–5)	35.0	$\Delta n = 0.371$ (598 nm); m.p. = -15.0 °C; Iso. = 145.0 °C $\rho = 1.89 \times 10^{11}$ Ω cm $\Delta \varepsilon = 8.0$ (1 kHz); $\mu = 105$ cps (25 °C) $\Delta \varepsilon_r' = 0.94$ (18.1 GHz); $\tau = 0.251$; $\eta = 23.71$ (18.1 GHz) $\tan \delta_{\varepsilon r \perp}' = 0.0106$ (18.1 GHz)
2	nUTP(1)TPm (m, n = 2–5)	10.0	
3	nPGUS (n = 3–5)	20.0	
4	nUTPPm (m, n = 2–5)	20.0	
5	nPGP(2)Pm (m, n = 2–5)	13.0	
6	nPGUF (n = 3–5)	2.0	

Table 4.26 Composition and dielectric properties of novel microwave nematic liquid crystal mixture (M7)

No	Components	Wt(%)	Dielectric Properties
1	nPTP(2)TPm (m,n = 2 –5)	70.0	$\Delta n = 0.405$ (598 nm); m.p. = -20.0°C ; Iso. = 155.0°C ; $\rho = 3.87 \times 10^{11} \Omega\cdot\text{cm}$; $\Delta\varepsilon = 5.0$ (1 kHz); $\mu = 95$ cps(25°C)
2	nUTP(1)TPm (m,n = 2 –5)	14.0	
3	nUTGTPm (m,n = 2 –5)	8.0	
4	nPGP(2)Pm (m,n = 2 –5)	8.0	
Dielectric Properties(18.1 GHz): $\Delta\varepsilon_r' = 1.02$, $\tau = 0.262$, $\eta = 26.81$; $\tan\delta_{\varepsilon r\perp}' = 0.00978$; $\tan\delta_{\varepsilon r\parallel}' = 0.00305$			

The developed novel mixtures are in-house characterized. The measured dielectric properties are given in Table 4.27 and Fig. 4.16.

The dielectric anisotropy ($\Delta\varepsilon_r$) and optical anisotropy (Δn) of M1, M3, M5 are larger than those of foreign sample. The maximum loss tangent value ($\tan\delta_{\perp}$) is also lower than that of the foreign and other domestic samples. The dielectric loss of M2, M3, M6, and M7 is lower than that of MM.

The measured dielectric loss shows that the prepared composite material has been greatly improved. It generally meets the requirements of microwave phase shifters.

4.3.4 Ongoing Research

The research on temperature dependence of low temperature dielectric properties of liquid crystals is still in progress. Preliminary experimental results demonstrate that the liquid crystal compound with low melting point and low viscosity is beneficial to improving the low-temperature dielectric properties of liquid crystal. Additionally, the temperature dependence of dielectric properties mainly depends on the liquid crystal solvent, the low-temperature phase temperature of the liquid crystal component, and the low-temperature viscosity change.

Table 4.27 Comparison of dielectric properties of microwave nematic mixed liquid crystal materials (18 GHz)

Mix-LC	Phase transition temperature (°C)	ϵ_r (unbiased)	$\epsilon_{r\perp}$	$\epsilon_{r\parallel}$	$\Delta\epsilon_r$	τ	$\tan\delta$ (unbiased)	$\tan\delta_{\perp}$	$\tan\delta_{\parallel}$	Δn
M1	Cr-15N105Iso	3.590	2.483	3.659	1.176	0.32	8.28E-3	1.43E-2	7.91E-3	0.34
M2	Cr-15N125Iso	3.048	2.425	3.370	0.945	0.28	4.64E-3	9.93E-3	2.69E-3	0.28
M3	Cr-15N141Iso	3.345	2.415	3.450	1.035	0.30	4.25E-3	9.71E-3	3.95E-3	0.30
M4	Cr-15N153Iso	3.265	2.454	3.354	0.90	0.27	5.45E-3	1.77E-2	4.46E-3	0.26
M5	Cr-25N125Iso	3.049	2.452	3.553	1.101	0.31	1.10E-3	1.65E-2	6.65E-3	0.32
M6	Cr-15N140Iso	3.078	2.341	3.148	0.807	0.26	3.98E-3	1.00E-2	3.02E-3	0.24
M7	Cr-20N151Iso	3.245	2.407	3.310	0.903	0.27	3.30E-3	9.28E-3	2.87E-3	0.27
MM	/	2.783	2.370	3.017	0.647	0.21	6.63E-3	1.37E-2	3.07E-3	0.20

Fig. 4.16 Dielectric properties of polytetrafluoroethylene (PTFE), Merck liquid crystal (MM), and self-developed mixed microwave nematic liquid crystals M1 ~ M7 at room temperature **a** $\epsilon_{r\perp}$; **b** $\epsilon_{r\parallel}$; **c** $\tan\delta_{\perp}$; **d** $\tan\delta_{\parallel}$

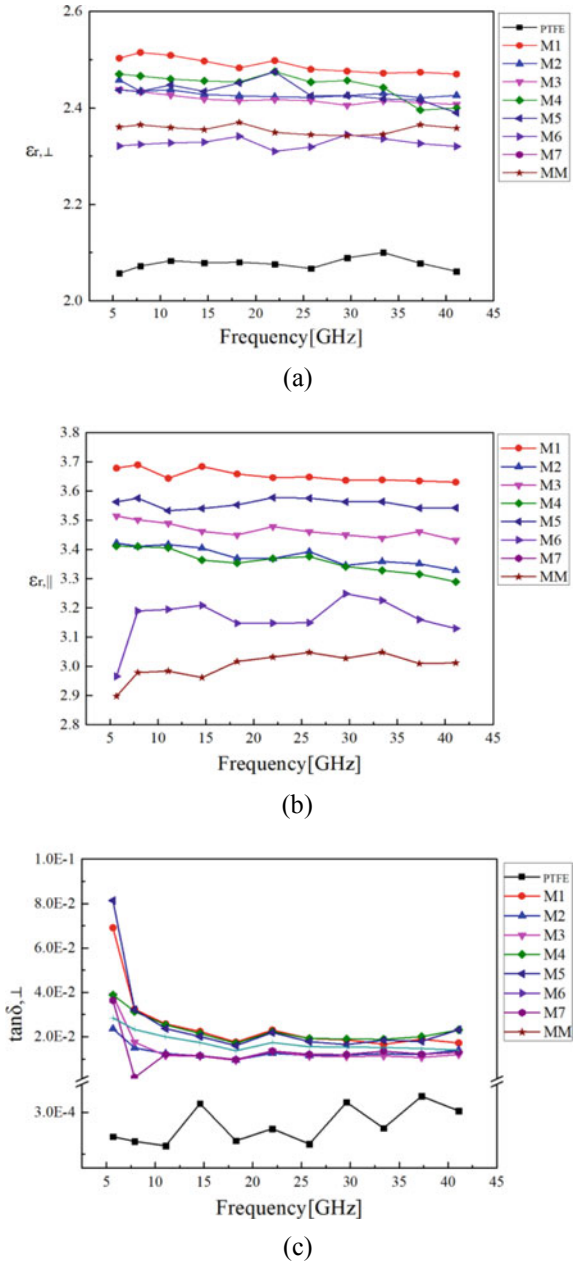
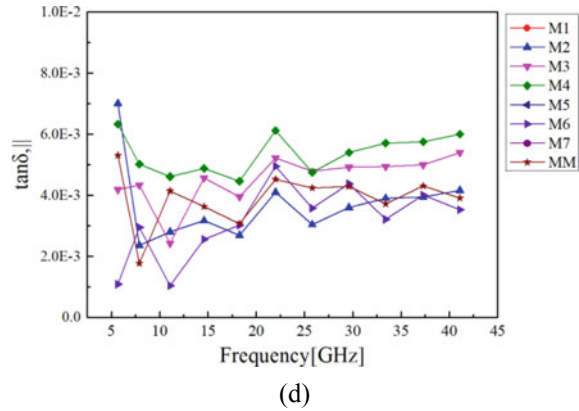


Fig. 4.16 (continued)



Chapter 5

Measurement of Electromagnetic Properties of Microwave Nematic Liquid Crystal



In this chapter, a new perturbation method of double ridge waveguide resonator is proposed for microwave characterization of liquid crystals. It meets the requirements of accurately testing the dielectric anisotropy, dielectric tuning characteristics, dielectric loss, and required working frequency band of the microwave nematic liquid crystal. This method provides valuable information for understanding microwave nematic liquid crystals and further research and development of microwave nematic liquid crystal materials.

5.1 Methods of Measuring Microwave Material Properties

In the microwave and millimeter wave bands, there are two categories of methods for testing the complex permittivity of materials: the network parameter method and the resonant cavity method. The network parameter method is suitable for measuring the complex permittivity of high-loss materials and can be conducted over a wide frequency band. On the other hand, the resonant cavity method is more appropriate for measuring the complex permittivity of low-loss dielectrics but can only be conducted at a single frequency. However, through the use of one-cavity multi-mode technology, mode recognition technology, and heterogeneous mode suppression technology, the test frequency range of resonant cavity method can be significantly extended.

5.1.1 Transmission/Reflection Method

The transmission/reflection method [1] is a popular technique used in electromagnetic testing, which involves filling the test sample in the transmission line to form

a reciprocal two-port network. By leveraging the relationship between the electromagnetic parameters and the scattering parameters of reciprocal two-port networks, which has been extensively studied and documented [2, p. 33], the method effectively reduces the electromagnetic testing problem to the measurement of scattering parameters. This method is frequently employed for room temperature testing.

5.1.2 Terminal Open/Short Circuit Method

The terminal open circuit method [1–5] measures the complex reflection coefficient of the sample under the approximate open circuit condition of the terminal. On the other hand, the terminal short circuit method measures the complex reflection coefficient under the condition that the sample terminal is short circuited. The complex dielectric constant of the material can then be calculated using the measured complex reflection coefficient.

5.1.3 Free Space Method

The free space method [6, 7] involves using antennas to radiate quasi-TEM electromagnetic waves into free space. When these waves encounter a test sample, reflection and transmission occur, and by measuring the reflection and/or transmission coefficients, one can calculate the complex dielectric constant or other electromagnetic parameters of the medium. However, this method requires the test sample to be flat with parallel sides and large enough relative area. Care should be taken during the measurement process to prevent the diffraction of electromagnetic waves and the occurrence of spatial secondary scattering.

5.1.4 Dielectric Resonator Method

The device under test in dielectric resonator method [8, 9] is resonator made of the concerned medium with a high dielectric constant and low loss. The resonant frequency and quality factor of the resonator are measured. The complex dielectric constant of the medium can then be extracted according to the corresponding resonance mode.

5.1.5 Cavity Perturbation Method

The cavity perturbation method [10] involves placing a small sample of the concerned dielectric material in the resonant cavity to slightly disturb the field inside. By measuring the resonant cavity both before and after the disturbance, one can obtain the complex permittivity of the dielectric material.

Initially, we tried the cavity perturbation method with a rectangular resonant cavity as shown in Fig. 5.1 to measure nematic liquid crystal materials. The actual experimental setup is shown in Fig. 5.2.

The cavity is formed by buckling a metal plate with a coupling hole at the top end of a standard rectangular waveguide and sealing the bottom end with a whole metal

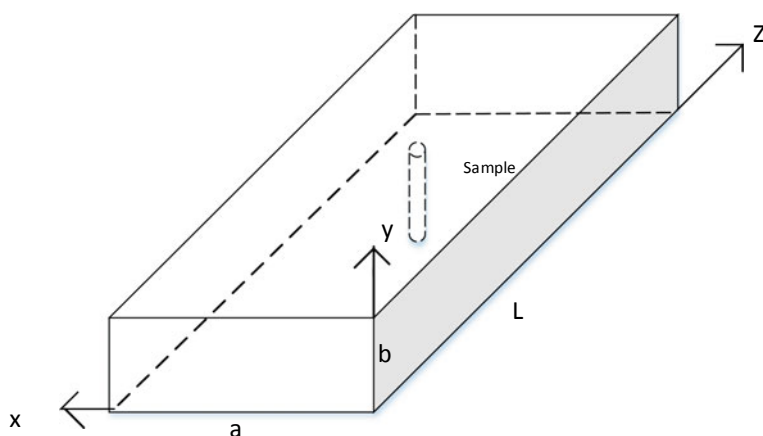


Fig. 5.1 Schematic diagram of the cavity perturbation method with a rectangular cavity

Fig. 5.2 Experimental setup for the cavity perturbation method with a rectangular cavity

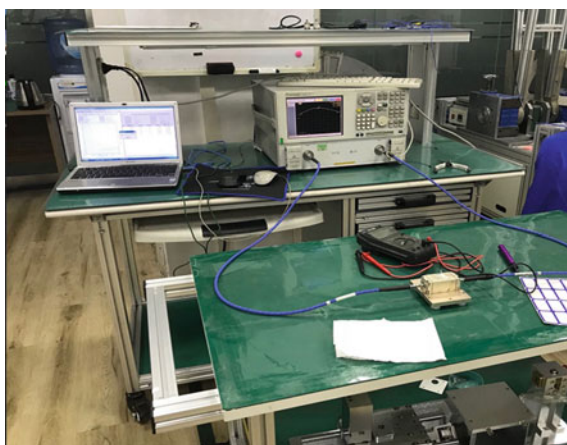


plate. Its cavity length is an integer multiple of half a wavelength. A thin-walled polytetrafluoroethylene tube containing the liquid crystal sample is inserted into the coupling hole on the rectangular resonant cavity.

The electric field in the cavity polarizes the sample, causing the quality factor and resonance frequency of the rectangular resonant cavity to change due to the energy loss of the sample during the polarization process.

$$\frac{f_{LC} - f_R}{f_R} = -2(\varepsilon' - 1) \frac{V_{LC}}{V_R} \quad (5.1)$$

$$\Delta\left(\frac{1}{Q_L}\right) = \frac{1}{Q_{LLC}} - \frac{1}{Q_{LR}} = 4\varepsilon'' \frac{V_{LC}}{V_R} \quad (5.2)$$

where f_R and f_{LC} are the resonant frequencies before and after the liquid crystal sample to be tested is put into the resonant cavity, $\varepsilon = \varepsilon' - j\varepsilon''$ is the dielectric constant of the nematic liquid crystal sample, V_{LC} is the volume of the liquid crystal sample to be tested, V_R is the cavity volume, $\Delta\left(\frac{1}{Q_L}\right)$ is the reciprocal change of the loaded quality factor of the resonator before and after putting the liquid crystal sample to be tested, Q_{LR} and Q_{LLC} are the loaded quality factors of the resonant cavity before and after the liquid crystal sample to be tested is placed, respectively.

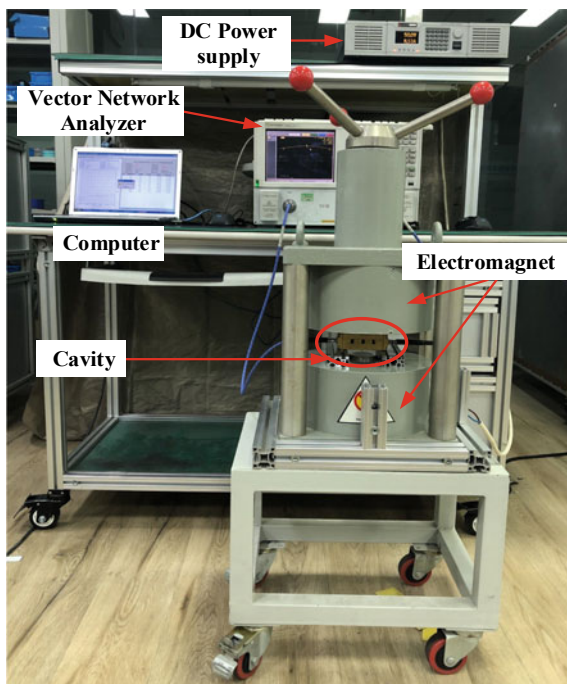
5.1.6 High- Q Cavity Method

The high- Q resonant cavity method [3] uses the TE_{01n} mode of a cylindrical cavity and involves inserting a disc-shaped dielectric sample into the cavity. The complex permittivity of the sample is determined by measuring the change in the cavity length at a fixed resonance frequency before and after loading the sample, or by measuring the change in cavity size and resonance frequency for a fixed cavity. The National Institute of Standards and Technology (NIST) of the United States has established a standardized test method for measuring the complex permittivity using the high- Q resonant cavity method, with the electric field polarization direction being on the test sample plane.

5.2 Double-Ridged Waveguide Resonator Perturbation Method

The aforementioned cavity perturbation method with a rectangular cavity cannot align and bias liquid crystals. It is therefore impossible to experimentally study the dielectric anisotropy and tuning characteristics of microwave liquid crystal materials. In this regard, the double-ridged waveguide resonator perturbation method is

Fig. 5.3 Experimental setup of the double-ridged waveguide resonator perturbation method



developed. Multi-mode technology is introduced to achieve broadband measurement of complex permittivity from 5 to 40 GHz using only one cavity. A photo of the experimental setup including DC power supply, DC electromagnet, vector network analyzer (VNA), test chamber, and programmable computer is given in Fig. 5.3.

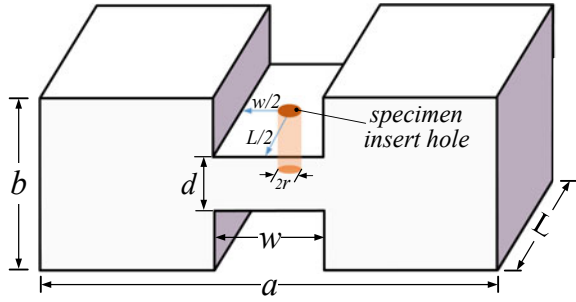
5.2.1 Double-Ridged Waveguide Resonator

The test device adopts a double-ridged waveguide segment, and the two ends are terminated with metal plates to form a resonant cavity. The geometry of a cavity with a sample insertion hole in the center is shown in Fig. 5.4.

The liquid crystal under test can be automatically absorbed into the thin-walled PTFE tube under capillary action and sealed with UV-curable glue. The liquid crystal can then be conveniently inserted into the sample hole of the cavity. The sample loading area in the double-ridged waveguide cavity is smaller, requiring a sample volume of only around 0.02 ml.

Inserting the specimen into the cavity changes its complex resonant frequency and the quality factor of the cavity

Fig. 5.4 Geometry of double-ridged waveguide resonator ($a = 18.3$ mm, $b = 8.2$ mm, $w = 4.4$ mm, $d = 2.6$ mm, $D = 2.6$ mm, $L = 77.0$ mm, $2R = 2.0$ mm)



$$\begin{aligned} \frac{\Delta \tilde{f}}{f_0} &\approx \frac{(1 - \varepsilon_r) \int_{V_s} \varepsilon_0 E_{int} E_0^* dv}{\int_{V_c} \varepsilon_0 E_0 E_0^* dv} \\ &\approx \frac{f_1 - f_0}{f_0} + j \frac{1}{2} \left(\frac{1}{Q_1} - \frac{1}{Q_0} \right) \end{aligned} \quad (5.3)$$

where f_0 is the cavity's resonant frequency,, E_{int} and E_0 are the electric field in the sample and the undisturbed cavity, respectively, V_s and V_c are the volumes of the sample and the cavity, respectively, f_1 is the resonant frequency of the cavity when the sample is added Q_1 and Q_0 are the quality factors of the cavity with or without the sample, respectively.

5.2.2 Multi-mode Technology

The operating mode of a double-ridged waveguide is TE_{10} . Accordingly, the operating modes of the double-ridged waveguide cavity are $TE_{1,0,2n-1}$, where n represents the number of half-wavelength changes of the electric field along the z direction. Specifically, $n = 11$ uniformly distributed modes are selected as working modes.

To enable a single cavity to operate over a wider frequency band, unwanted or degenerate modes need to be suppressed. Multiple non-radiative slots, as shown in Fig. 5.5 are used. Notches or cuts made in the center of the wide wall along the longitudinal direction and the narrow sides along the y -axis will handle the TM mode and some other modes, while leaving the operation mode almost intact. In addition, in order to avoid the formation of a cut-off waveguide in the depth direction of the slit, grooves were made on the sides of the slit. Furthermore, wave-absorbing material is filled in the groove further to absorb electromagnetic wave energy and reduce the quality factor of interference modes.

The simulated transmission performance of the original and slotted cavities is shown in Fig. 5.6. Obviously, after the slits are introduced, the redundant modes around the high-frequency working mode are greatly suppressed so that more modes can be obtained for testing.

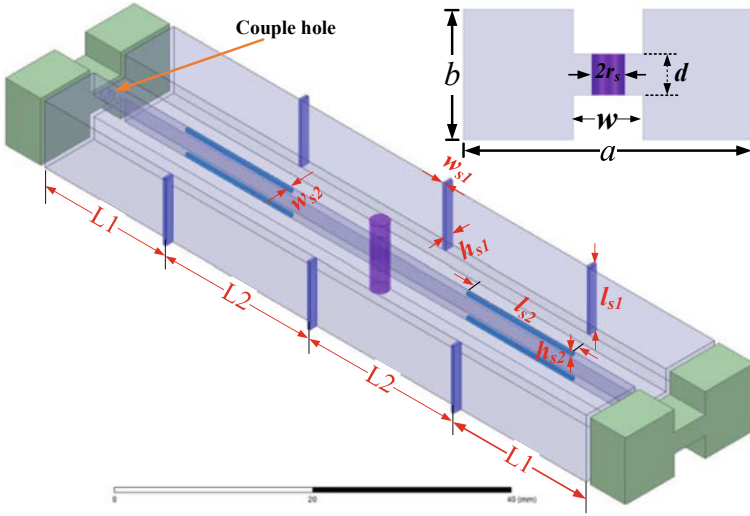


Fig. 5.5 3D Simulation model of double-ridged waveguide cavity ($L_1 = 18.0$ mm, $L_2 = 20.5$ mm, $w_{S1} = w_{S2} = 0.3$ mm, $l_{S1} = 8.2$ mm, $l_{S2} = 15.0$ mm, $h_{S1} = 1.0$ mm, $h_{S2} = 0.5$ mm, $2r_C = 2.0$ mm)

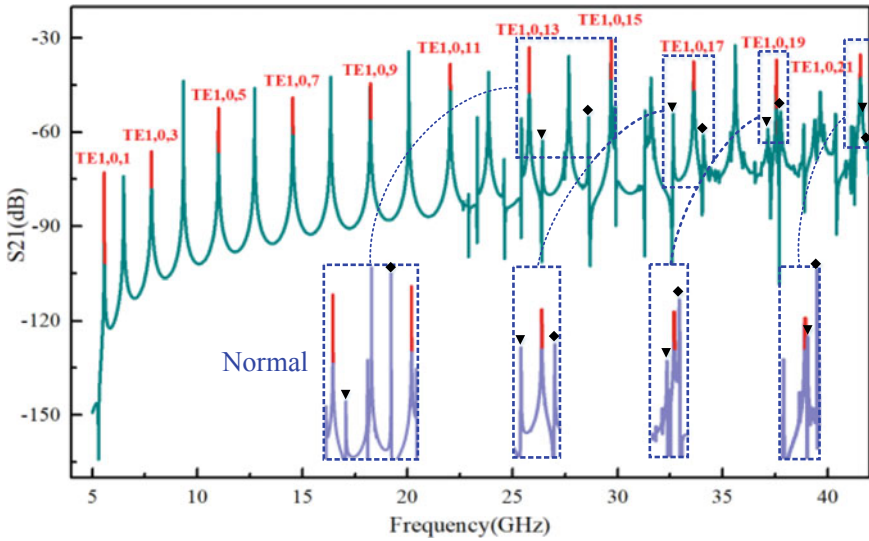


Fig. 5.6 Transmission performance of original and slotted resonators

The measured resonance parameters are shown in Table 5.1. Theoretical, numerical, and experimental results are consistent.

Table 5.1 Measured cavity resonance parameters

Resonant modes	Frequency (MHz)	Unloaded Q-factors
TE _{1,0,1}	5698	3441
TE _{1,0,3}	7932	2964
TE _{1,0,5}	11,130	3016
TE _{1,0,7}	14,674	3246
TE _{1,0,9}	18,364	3422
TE _{1,0,11}	22,127	3683
TE _{1,0,13}	25,932	3805
TE _{1,0,15}	29,761	3919
TE _{1,0,17}	33,604	4217
TE _{1,0,19}	37,457	4026
TE _{1,0,21}	41,330	4537

5.2.3 Alignment

The sample under test is assumed to be isotropic in the perturbation theory. Thus, it is necessary to ensure the orderly arrangement of the microwave nematic liquid crystal in the tube. A strong static magnetic field (0.5–1.0T) perpendicular and parallel to the electric field of TE_{1,0,2n-1} mode using a fixed static magnetic field device is applied to align liquid crystal molecules. A schematic description of the vertical and parallel alignment is depicted in Fig. 5.7. Measurements in different directions can be realized by rotating the cavity without moving the sample.

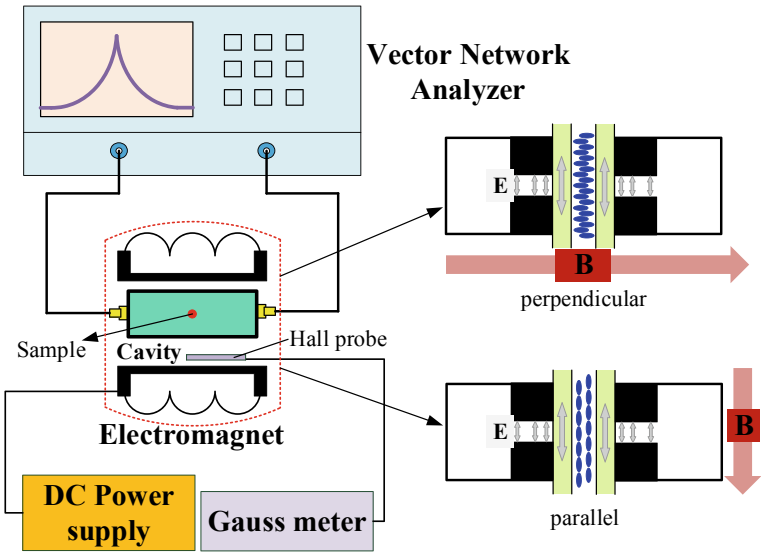


Fig. 5.7 Schematic diagram of vertical and parallel alignment of liquid crystal molecules

References

1. Baker-Jarvis J (1990) Transmission/reflection and short-circuit line permittivity measurements, series: NIST technical note, vol 1341. NIST
2. Weir WB (1974) Automatic measurement of complex dielectric constant and permeability at microwave frequencies. *Proc IEEE* 62(1):33–36
3. Baker-Jarvis J, Janezic MD, Riddle B, Holloway CL, Paulter NG, Blendell JE (2001) Dielectric and conductor loss characterization and measurements on electronic packaging materials, series: NIST technical note, vol 1520. NIST
4. Gershon DL, Calame JP, Carmel Y, Antonsen TM, Hutcheon RM (1999) Open ended coaxial probe for high temperature and broadband dielectric measurements. *IEEE Trans Microw Theory Tech* 47(9):1640–1648
5. Bringham S, Iskander MF (1996) Open-ended metallized ceramic coaxial probe for high-temperature dielectric properties measurements. *IEEE Trans Microw Theory Tech* 44(6):926–935
6. Varadan VV, Hollinger RD, Ghodgaonkar DK, Varadan VK (1991) Free-space, broadband measurements of high-temperature, complex dielectric properties at microwave frequencies. *IEEE Trans Instrum Meas* 40(5):842–846
7. Bretenoux A, Marzat C, Sardos R (1993) Turnstile reflecto-polarimeter using the principal incidence method: determination of permittivities up to 1200 °C and industrial applications. *IEEE Trans Microw Theory Tech* 41(11):1945–1949
8. Krupka J, Derzakowski K, Abramowicz A, Tobar ME, Geyer RG (1999) Use of whispering gallery modes for complex permittivity determinations of ultra-low loss dielectric materials. *IEEE Trans Microw Theory Tech* 47(6):752–759
9. Geyer RG, Kabos P, Baker J (2002) Dielectric sleeve resonator techniques for microwave complex permittivity evaluation. *IEEE Trans Instrum Meas* 51(2):383–392
10. Hutcheon R, De Jong M, Adams F (1992) A system for rapid measurements of RF and microwave properties up to 1400 °C. Part I: theoretical development of the cavity frequency-shift data analysis equations. *J Microw Power Electromagn Energy* 27(2):87–92

Chapter 6

Fabrication of Liquid Crystal Cells for Reconfigurable Microwave, Millimeter Wave and Terahertz Functional Devices



6.1 Introduction

Liquid crystal has been one of the promising solutions for reconfigurable microwave, millimeter wave and terahertz functional devices. On the other hand, many bottleneck issues unseen in liquid crystal display have emerged while developing liquid crystal-based reconfigurable microwave, millimeter wave and terahertz functional devices.

Loosely speaking, these challenging issues are spread over the full spectrum of liquid crystal synthesis, measurement of electromagnetic properties of liquid crystal, and design, fabrication and test of functional devices. Synthesis of high dielectric anisotropy and low loss nematic liquid crystal materials for reconfigurable microwave, millimeter wave and terahertz functional devices has been discussed in Chap. 4 of this book. An improved experimental setup to measure electromagnetic properties of microwave, millimeter wave and terahertz liquid crystal is described in Chap. 5 of this book. Additionally, representative novel reconfigurable microwave, millimeter wave and terahertz functional devices will shortly be presented in Chaps. 7 and 8 of this book.

In this chapter, we will be talking about fabrication of reconfigurable microwave, millimeter wave and terahertz functional devices. In particular, attention is focused on a process to fabricate liquid crystal cell in reconfigurable microwave, millimeter wave and terahertz functional devices.

Liquid crystal cell plays a core role in liquid crystal-based reconfigurable microwave, millimeter wave and terahertz functional devices. At present, in the liquid crystal display and the 3D lens industries, the thickness of liquid crystal cell is between only 2.5 and 50 μm . However, as operation frequency lowers from visible light to terahertz, millimeter wave or even microwave, the liquid crystal cell might be as thick as hundreds of microns. The extra stress accumulation caused by the curing of the frame might seriously and randomly deteriorate the uniformity of the cell thickness. Furthermore, the anchoring force of the popular rubbing alignment becomes weaker with the increase of cell thickness, especially in the middle of

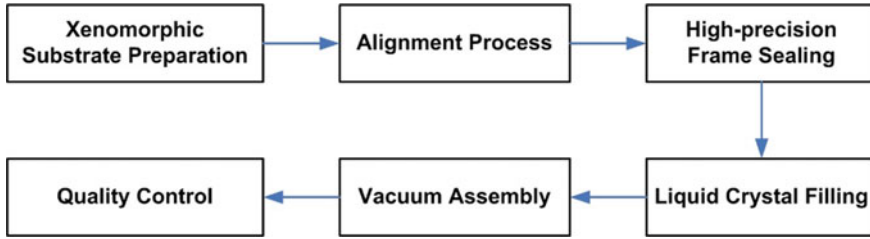


Fig. 6.1 Overall process of liquid crystal-based devices fabrication

the liquid crystal layer. Accordingly, the effective electromagnetic properties of the liquid crystal cell might be significantly more inhomogeneous. Such random non-uniformity and inhomogeneity will result in significant performance deterioration and inconsistency of reconfigurable microwave, millimeter wave and terahertz functional devices. The device may even fail in the worst scenario. What is worse, the well-established LCD photoresist and microsphere support technologies may not be applicable any more.

On account of the above unique challenges, a special fabrication technology dedicated to fabrication of liquid crystal-based reconfigurable microwave, millimeter wave and terahertz functional devices is developed. The overall process is depicted in Fig. 6.1.

6.2 Process of Fabricating Liquid Crystal Cells

6.2.1 *Xenomorphic Substrate Preparation Technology*

Xenomorphic substrate is essentially three-dimensional material with complex structure. Standardized photolithography processes can reduce its inconsistency to less than 0.5%.

The block diagram of the process is shown in Fig. 6.2. It includes cleaning & preparation, photoresist coating, exposure and developing, etching, photoresist removal, and polishing. Modern cleanrooms use automated, robotic wafer track systems to coordinate the process.

6.2.1.1 Cleaning and Preparation

Organic or inorganic contaminations may be present on the flat fused quartz substrate surface and must be removed. Usually, wet chemical treatment such as the RCA clean procedure are used. Cleaning solutions can be made with hydrogen peroxide, trichloroethylene, acetone or methanol.

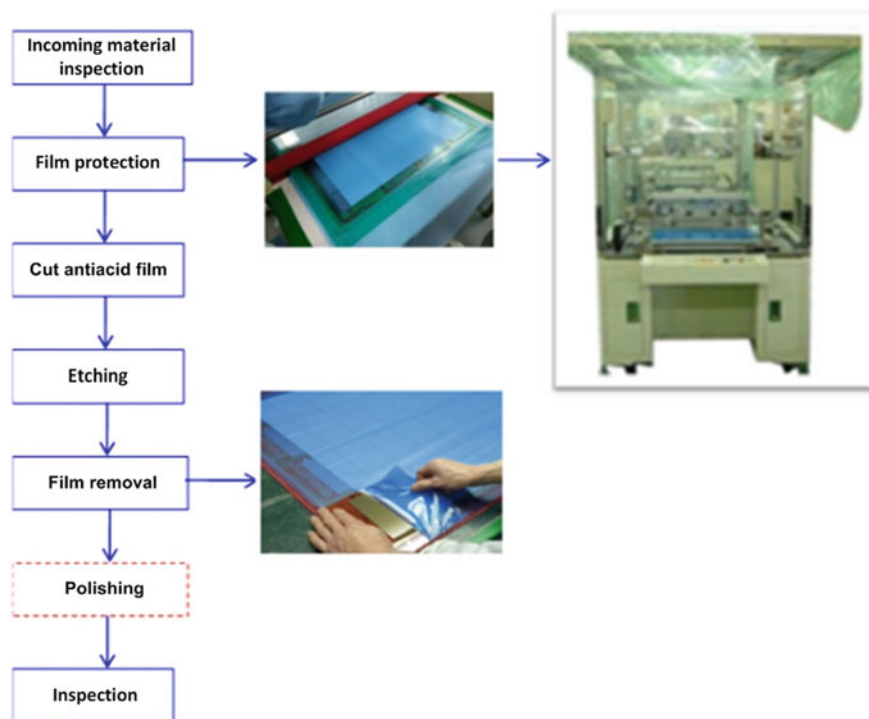


Fig. 6.2 Xenomorphic substrate photolithography process

The substrate is next heated to a temperature sufficient to drive off any moisture that may be present on the surface. A liquid or gaseous “adhesion promoter”, such as Bis(trimethylsilyl)amine (“hexa-methyl-disilazane”, HMDS), is then applied to promote adhesion of the photoresist to the substrate.

6.2.1.2 Photoresist Coating

The cleaned flat fused quartz substrate is covered with a uniform photoresist thin film by spin coating. Prebaked is then applied to drive off excess photoresist solvent, typically at 90–100 °C for 30–60 s on a hotplate.

6.2.1.3 Exposure and Developing

The photoresist-coated substrate is exposed to a pattern of intense light. The exposure to light causes a chemical change that allows some of the photoresist to be removed by a special solution, i.e., developer by analogy with photographic developer. Metal-ion-free developers such as tetramethylammonium hydroxide (TMAH) are now

commonly used. The resulting substrate is then hard-baked if a non-chemically amplified resist was used, typically at 120–180 °C for 20–30 min. The hard bake solidifies the remaining photoresist, to make a more durable protecting layer in future wet chemical etching or plasma etching.

6.2.1.4 Etching

A three-dimensional pattern on the prefabricated board is formed through etching. At present, the etching process is mainly realized by chemical etching. A liquid (“wet”) or plasma (“dry”) chemical agent removes the uppermost layer of the substrate in the areas that are not protected by photoresist. For example, hydrogen fluoride (HF) reacts with SiO_2 and dissolve it $6\text{HF} + \text{SiO}_2 \rightarrow \text{H}_2\text{SiF}_6 + \text{H}_2\text{O}$.

6.2.1.5 Photoresist Removal

After a photoresist is no longer needed, it must be removed from the substrate. This usually requires a liquid resist stripper. Alternatively, the photoresist may be removed by a plasma containing oxygen or 1-Methyl-2-pyrrolidone (NMP) solvent.

6.2.1.6 Polishing

To reduce surface scratches and optimize the quality of the xenomorphic substrate surface, a pressured polishing liquid made of polishing powder and pure water flows between the xenomorphic substrate and the panel of the polishing machine. The thickness of the xenomorphic substrate will be cut by hard abrasive grains in direct contact with the xenomorphic substrate surface.

6.2.2 Liquid Crystal Alignment Technology

The performance consistency and tunability of reconfigurable microwave, millimeter wave and terahertz functional devices is strongly dependent on the pointing consistency of liquid crystal molecules. As the thickness of the liquid crystal cell increases, the general rubbing alignment process popular in liquid crystal display industry can no longer meet the demand because the anchoring force of the rubbing alignment layer will become weaker, especially in the middle of the liquid crystal layer. Optimized rubbing alignment process and/or high-polarity polyimide (PI) material can enhance the anchoring effect of polyimide on liquid crystal molecules but the improvement is limited.

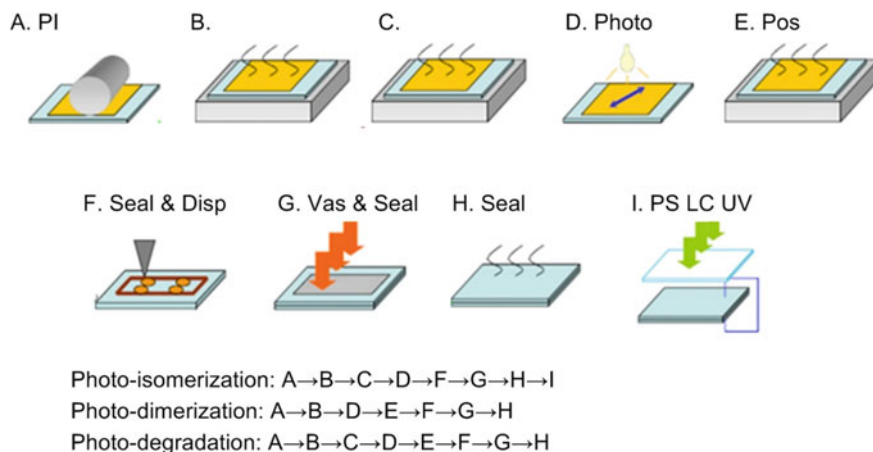


Fig. 6.3 Photo-alignment flow chart

Among many alternatives such as ion beam alignment [1], Langmuir–Blodgett (LB) film [2], oblique evaporating [3], the more mature non-contact photo alignment [4–10] is feasible for microwave, millimeter wave and terahertz liquid crystal. It reversibly orients liquid crystal molecules to desired alignment by exposure to polarized light and a photo reactive alignment chemical. Very small domains can be aligned which results in extremely high quality alignment. Moreover, it can be applied to various heterogeneous structures with even mechanically inaccessible areas.

During the photo-alignment process, the alignment material ('command surface') is exposed to polarized light with desired orientation which then aligns the liquid crystal cells or domains to the exposed orientation. The alignment material is a thin polyimide film layer uniformly printed on the substrate through standardized process. Currently, the alignment materials can be photo-isomerizable, photo-dimerizable, or photo-degradable. It has to be carefully selected according to the specific substrate for optimal alignment effect.

For the above three different materials, the complete process of photo-alignment technology is shown in Fig. 6.3.

6.2.2.1 Photo-Isomerization

Some cis–trans isomer materials exhibit reversible deformation or isomerization when irradiated by ultraviolet light. For example, a rod-like photoswitchable compound is transformed into a V-shaped isomer. This is the basic principle behind photoisomerization alignment of liquid crystal molecules. The isomerized material will induce a molecular reorientation in the liquid crystal bulk.

6.2.2.2 Photo-Dimerization

When photosensitive polyethylene cinnamate (PVCi) is irradiated with linearly polarized ultraviolet light, the branched-chain parallel to the polarization direction of the polarized ultraviolet light will undergo a dimerization reaction [6]. This photodimerization process [11, 12] induces anisotropy perpendicular to the polarized direction, which is along with the mono-unit cinnamate side chain.

6.2.2.3 Photo-Degradation

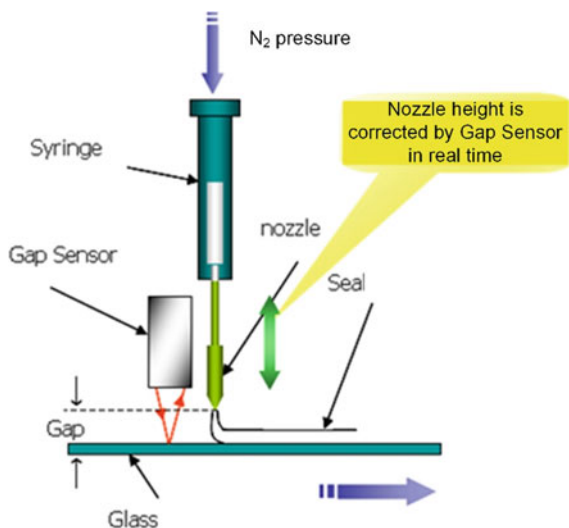
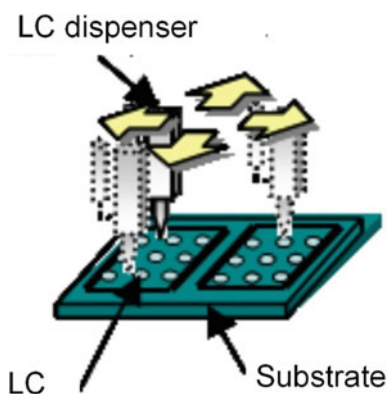
Photo-degradation, also known as photodissociation, photolysis, or photofragmentation, is the chemical reaction in which target molecules of a chemical compound are destructed by photons following the absorption of light energy. Polyimide selectively decomposes along the linearly polarized ultraviolet light direction and causes the liquid crystal alignment to be perpendicular to the linearly polarized ultraviolet light direction [10, 13].

6.2.3 High-Precision Frame Sealing

High-precision frame sealing is one of the most important processes for consistency of liquid crystal layer thickness. As shown in Fig. 6.4, the vacuum degassed mixture of sealant and spacer in the syringe is dispensed to the substrate through the guide nozzle under the pressure of nitrogen. The control of dispensing pressure and the position of dispensing nozzle are very important to obtain a uniform seal line width, especially at the corners. The real time height of the nozzle above the xenomorphic substrate is sensed and adjusted to ensure that the frame is evenly glued.

6.2.4 Liquid Crystal Filling

There are two main filling methods for liquid crystal display [14], namely the vacuum filling method and the one drop filling (ODF) method. Due to larger cell in liquid crystal-based reconfigurable microwave, millimeter wave, and terahertz functional devices, the more efficient and less wasteful ODF technique as shown in Fig. 6.5 is implemented. An automatic liquid crystal dispenser will fill the cell with the exact amount of liquid crystal.

Fig. 6.4 Frame sealing**Fig. 6.5** One drop filling of liquid crystal

6.2.5 Vacuum Assembly

The substrate with arrays of dispensed liquid crystal droplets and the substrate with printed sealant are aligned in a vacuum chamber and bonded together. The lower substrate with liquid crystal droplets is placed on the stage of the vacuum assembly system (VAS) chamber as shown in Fig. 6.6. The upper substrate with printed sealant is handled without touching the lower substrate and aligned using alignment marks on each corner with high accuracy. The upper substrate is then pressed down for bonding to the lower substrate.

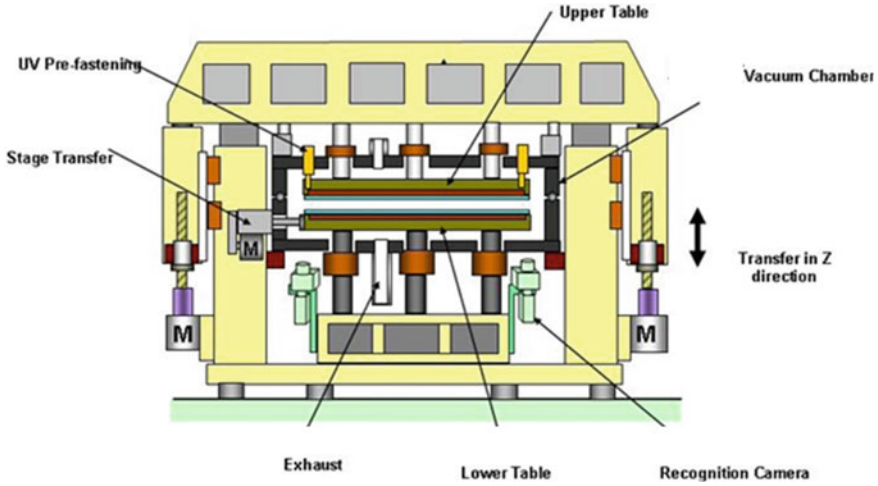


Fig. 6.6 Vacuum assembly system chamber

6.3 Quality Control

The fabricated liquid crystal cells and the ultimate liquid–crystal based reconfigurable microwave, millimeter wave, and terahertz functional devices are subject to quality inspection.

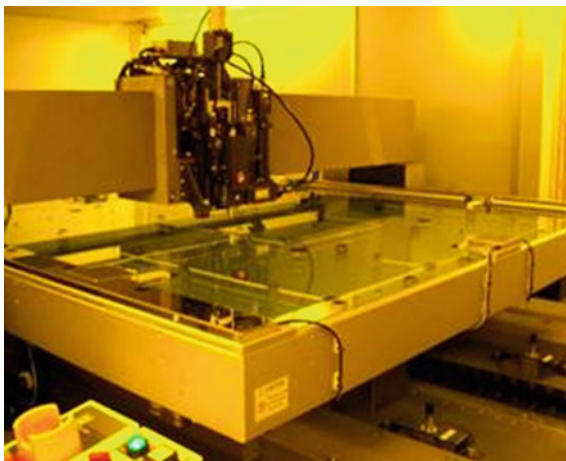
6.3.1 Leak Rate

The leak rate is an essential indicator for evaluating the sealing quality of electronic components. The device under test will go through high pressure and high temperature aging test in a pressure cooker test chamber. In liquid crystal display industry, the panel after PCT test will be inspected whether there are poor sealing-related displays such as liquid crystal leakage and uneven borders. However, such optical characterization does not fit non-display applications effects cannot confirm the application in microwave devices. Instead, deterioration of electromagnetic signatures of liquid–crystal based reconfigurable microwave, millimeter wave, and terahertz functional devices are more appropriate metrics.

6.3.2 Critical Dimensions

The electromagnetic signatures of liquid–crystal based reconfigurable microwave, millimeter wave, and terahertz functional devices may be more or less sensitive with

Fig. 6.7 Critical dimension measurement



some geometrical parameters. Critical dimension measurement as shown in Fig. 6.7 has to be carried out.

References

1. Doyle JP, Chaudhari P, Lacey JL, Galligan EA, Lien SC, Callegari AC, Lang ND, Lu M, Nakagawa Y, Nakano H, Okazaki N, Odahara S, Katoh Y, Saitoh Y, Sakai K, Satoh H, Shiota Y (2003) Ion beam alignment for liquid crystal display fabrication. *Nucl Inst Methods Phys Res B* 206:467–471
2. Zasadzinski JA, Viswanathan R, Madsen L, Garnaes J, Schwartz DK (1994) Langmuir-Blodgett films. *Science* 263(5154):1726–1733
3. Janning L (1972) Thin film surface orientation for liquid crystals. *Appl Phys Lett* 21(4):173–174
4. Ichimura K, Suzuki Y, Seki T, Hosoki A, Aoki K (1988) Reversible change in alignment mode of nematic liquid crystals regulated photochemically by command surfaces modified with an azobenzene monolayer. *Langmuir* 4(5):1214–1216
5. Gibbons WM, Shannon PJ, Sun ST, Swetlin BJ (1991) Surface-mediated alignment of nematic liquid crystals with polarized laser light. *Nature* 351(6321):49–50
6. Schadt M, Schmitt K, Kozinkov V, Chigrinov V (1992) Surface-induced parallel alignment of liquid crystals by linearly polymerized photopolymers. *Japanese J Appl Phys Part 1: Regular Pap Short Notes* 31(7R):2155–384
7. Li W, Gao ZQ, Mi BX, Huang W (2009) Progress in the liquid crystal alignment. *J Nanjing Univ Posts Telecommun (Nat Sci)* 29(4):90–96
8. Wang XQ, Shen D, Zheng ZG, Guo HC (2015) Review of liquid crystal photoalignment technologies. *Chin J Liquid Cryst Displays* 30(5):737–751
9. Zou PF, Wei BY, Yang SL, Liang X, Chen GF, Chen K, Lu YQ, Hu W (2017) Some progresses of photoalignment technique applied in liquid crystal nondisplay field. *Chin J Liquid Cryst Displays* 32(6):411–423
10. Sugiyama H, Sato S, Nagai K (2022) Photo-isomerization, photodimerization, and photodegradation polyimides for a liquid crystal alignment layer. *Polymer Adv Technol* 33(7):2113–2122
11. Liang ZY, Yan S, Xuan L, Ma K, Huang XM, Xie JL, Zhang YJ, Tian YQ, Zhao YY, Zhang JB (2000) The effect of photochemical reaction of cinnamate material 2-(Cinnamoyloxy)Ethyl methacrylate on liquid crystal molecules alignment. *Acta Physica Sinica* 49(6):1114–1119

12. Schadt M (2017) Liquid crystal displays, LC-materials and LPP photo-alignment. *Mol Cryst Liq Cryst* 647(1):253–268
13. Hasegawa M, Taira Y (1995) Nematic homogeneous photo alignment by polyimide exposure to linearly polarized UV. *J Photopolym Sci Technol* 8(2):241–248
14. Souk J, Morozumi S, Luo FC, Bita I (eds) (2018) Flat panel display manufacturing, series: Wiley—SID series in display technology. Wiley, New York

Chapter 7

Nematic Liquid Crystal Microwave Phase Shifters



Microwave phase shifters are one of the core components in electronic information systems and phased array radar systems. In this chapter, a miniature K-band microwave nematic liquid crystal-based phase shifter that can realize 360° phase shift in K-band is proposed.

7.1 Introduction

In electronic information systems and phased array radar systems, the phase difference $\Delta\phi$ of adjacent antennas can be changed by a phase shifter. As a result, the array antenna beam can be electronically scanned in space, thereby replacing the mechanical scanning system, so the scanning speed of the antenna beam is more accurate and faster, and the flexibility is greater. At present, phased array radar systems generally use diode or ferrite for phase control. However, with the increasing complexity of phased array radar system, traditional phase shifters can no longer meet the needs. Therefore, the use of new materials, technologies, processes, and methods for better performance is a significant trend in the development of future phase shifters [1].

This chapter uses nematic liquid crystal as the dielectric substrate material to realize a new type of miniaturized liquid crystal-based phase shifter. The phase shifting is realized by using the dielectric anisotropy of highly anisotropic nematic liquid crystal when a bias voltage is applied. Compared with traditional phase shifter, it has the advantages of miniaturization, low cost, large phase shift range, low working voltage, convenient manufacture, and therefore excellent potential and development prospects in practical applications.

Merck GT3-23001 is unavailable in China. Domestic E7 is therefore used in numerical simulation and prototype fabrication.

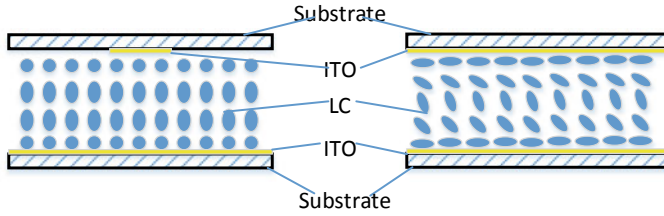


Fig. 7.1 Liquid crystal inverted microstrip line phase shifter

7.2 Theory of Liquid Crystal Phase Shifters

Inverted microstrip line as shown in Fig. 7.1 is a typical liquid crystal microwave phase shifter. Nematic liquid crystal fill the area between the conduction band and the grounding plate where guided wave TEM_{00} propagates. The conduction band serves as not only the loading line of the microwave signal to be phase-shifted but also the control driving electrode.

The transmission phase delay ϕ is given by

$$\phi = k_0 \cdot \sqrt{\varepsilon_{eff}} \cdot L \quad (7.1)$$

where k_0 is the wave number in free space, ε_{eff} is the effective dielectric constant, and L is the length of the transmission line.

The differential phase shift when the effective dielectric constant of microwave nematic liquid crystal is changed is

$$\Delta\Phi = L_p(\beta_{\parallel} - \beta_{\perp}) = L_p \frac{\omega}{c} (\sqrt{\varepsilon_{\parallel}} - \sqrt{\varepsilon_{\perp}}) \quad (7.2)$$

where L_p is the physical length of the phase shifter, $\beta_{\parallel}$ represents the phase constant when the microwave nematic liquid crystal is in saturation bias, $\beta_{\perp}$ represents the phase constant when there is no bias and alignment, ω is the angular frequency, c is the speed of light in vacuum, and $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ are the corresponding permittivity which can be calculated by using the Maier-Meier theory.

7.3 Numerical Simulation

7.3.1 Microstrip Phase Shifter

This microstrip phase shifter as shown in Fig. 7.2 is used to study the loss of microwave nematic liquid crystal materials and feeding coplanar waveguide-to-microstrip transition.



Fig. 7.2 0.05 mm Liquid crystal microstrip phase shifter

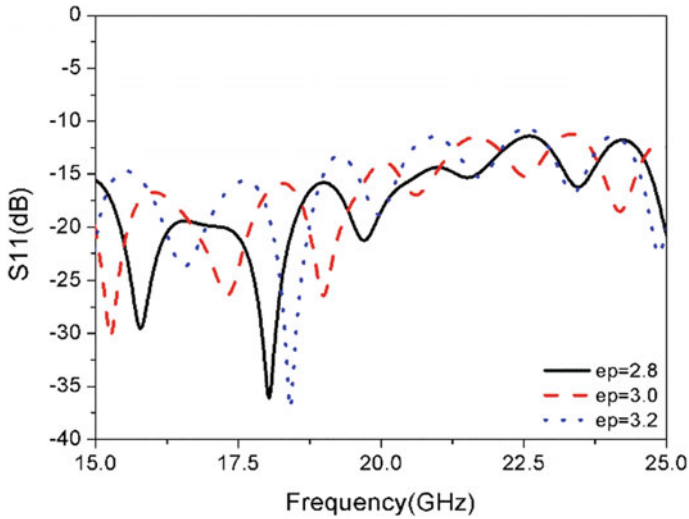


Fig. 7.3 Simulated S_{11} of 0.05 mm liquid crystal microstrip phase shifter

The simulated S_{11} is shown in Fig. 7.3. It is lower than -10 dB in the whole frequency range, and lower than -15 dB in the 15–20 GHz and 26–30 GHz frequency bands.

The phase shifting performance is shown in Fig. 7.4 while the simulated S_{21} is shown in Fig. 7.5. As frequency increases, the phase shift increases, but the overall loss increases.

7.3.2 *Inverted Microstrip Serpentine Line (IMSL) Mphase Shifter*

This phase shifter as shown in Fig. 7.6 achieves 360° phase shift in the K-band.

The simulated S_{11} is shown in Fig. 7.7. There is a more extensive frequency range below -15 dB. Moreover, S_{11} from 15 to 20 GHz is lower than -15 dB.

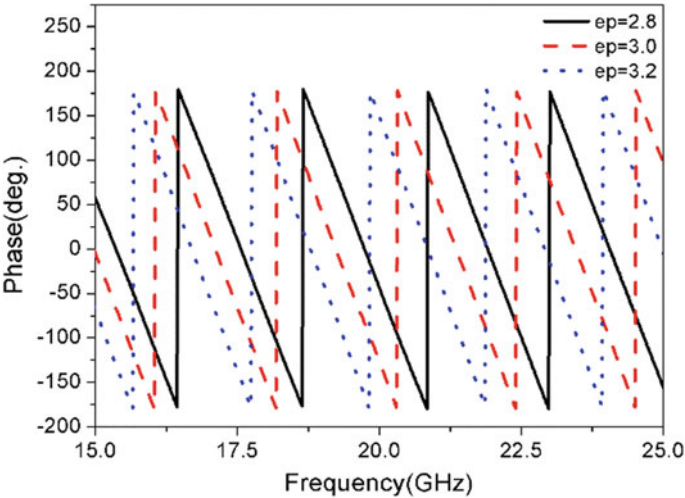


Fig. 7.4 Simulated phase shift of 0.05 mm liquid crystal microstrip phase shifter

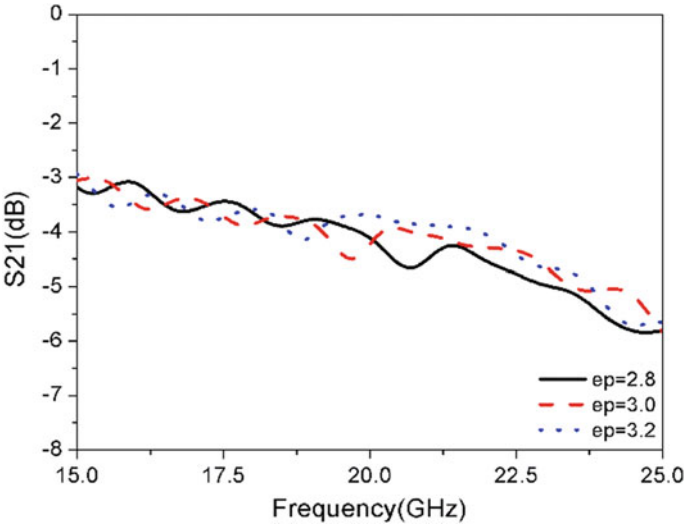


Fig. 7.5 Simulated S_{21} of 0.05 mm liquid crystal microstrip phase shifter

The phase shifting performance is shown in Fig. 7.8. The phase shift reaches 360° between 19.6 GHz and 20.9 GHz due to the use of serpentine line.

The simulated S_{21} is shown in Fig. 7.9. As frequency increases, the phase shift increases, but the overall loss increases. The increase of transmission distance leads to an increase in loss. From 19.6 to 20.9 GHz, the insertion loss is about -7 dB, which is about 3 dB larger than the microstrip phase shifter.

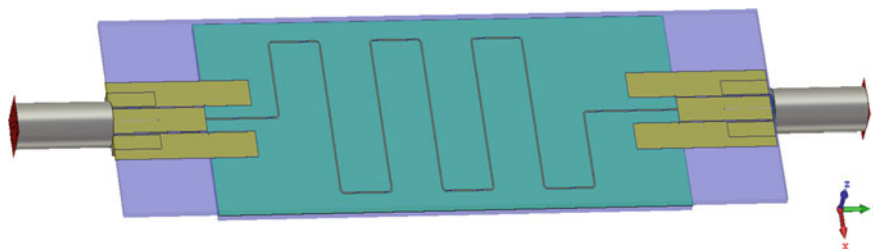


Fig. 7.6 0.05 mm Liquid crystal IMSL phase shifter

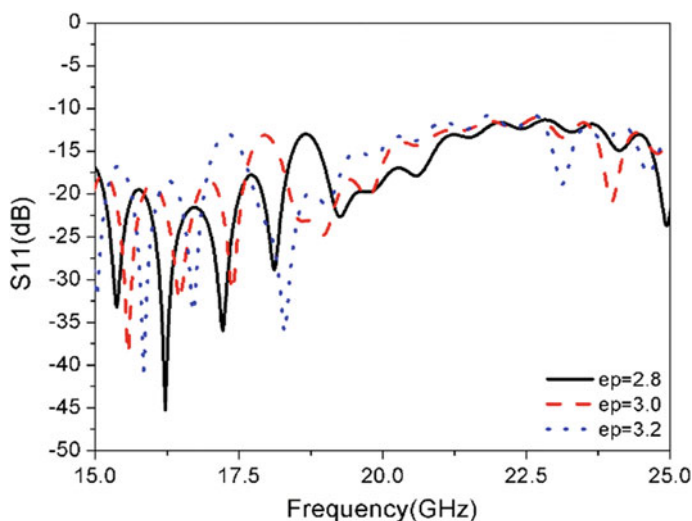


Fig. 7.7 Simulated S_{11} of 0.05 mm liquid crystal imsl phase shifter

7.4 Experimental Test

7.4.1 *Prototype Under Test*

Two prototypes corresponding to the two phase shifters numerically simulated above are fabricated. The physical samples are shown in Figs. 7.10 and 7.11.

7.4.2 *Assembly*

The nematic liquid crystal phase shifter prototype is assembled with matching network and DC bias circuit. Biasing is controlled through FPGA module. The block

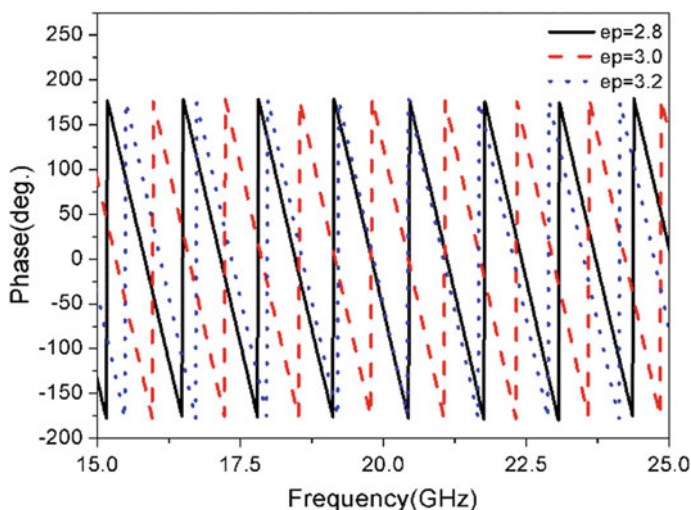


Fig. 7.8 Simulated phase shift of 0.05 mm liquid crystal IMSL phase shifter

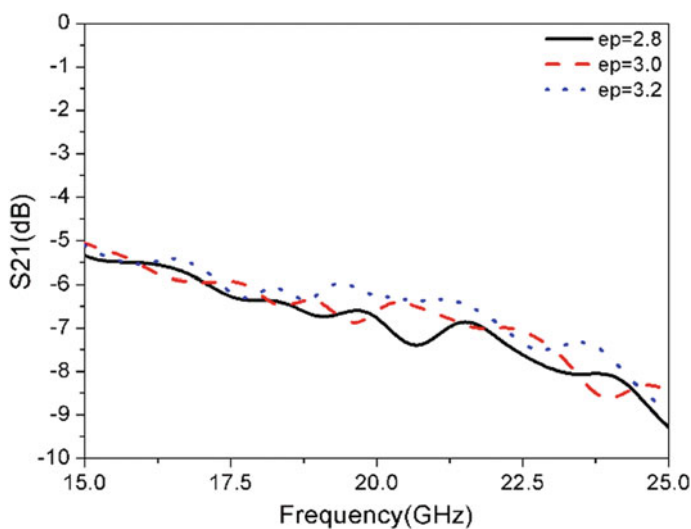


Fig. 7.9 Simulated S_{21} of 0.05 mm liquid crystal IMSL phase shifter

diagram of the assembled microwave nematic liquid crystal phase shifter device is shown in Fig. 7.12.

When the bias voltage changes, the effective dielectric constant of the microwave nematic liquid crystal will change. The characteristic impedance will also vary accordingly. Therefore, in order to achieve good matching, stub matching as shown in Fig. 7.13 is used. The phase shifter under test is connected in parallel with the stub

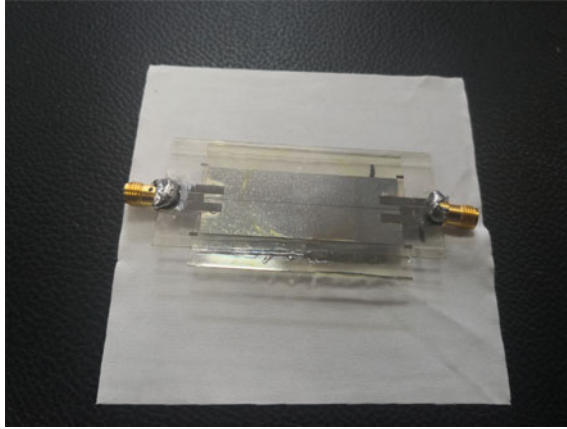


Fig. 7.10 Prototyped 0.05 mm liquid crystal microstrip phase shifter

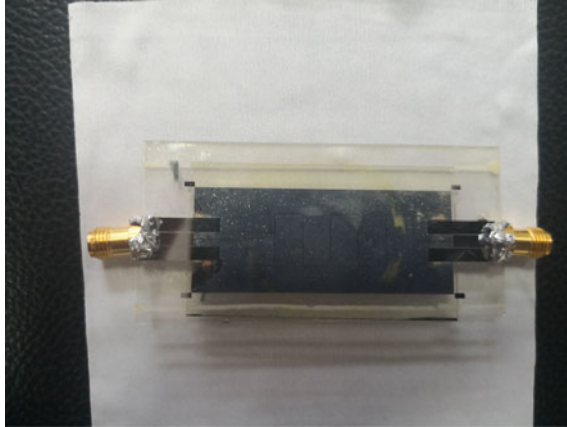


Fig. 7.11 Prototypes 0.05 mm liquid crystal IMSL phase shifter

and then connected in series with a section of the transmission line. Tuning parameters include the length L_0 and characteristic impedance Z_0 of the serial transmission line, the length L_1 and characteristic impedance Z_1 of the parallel stub. A balanced matching solution as shown in Fig. 7.14 is further developed.

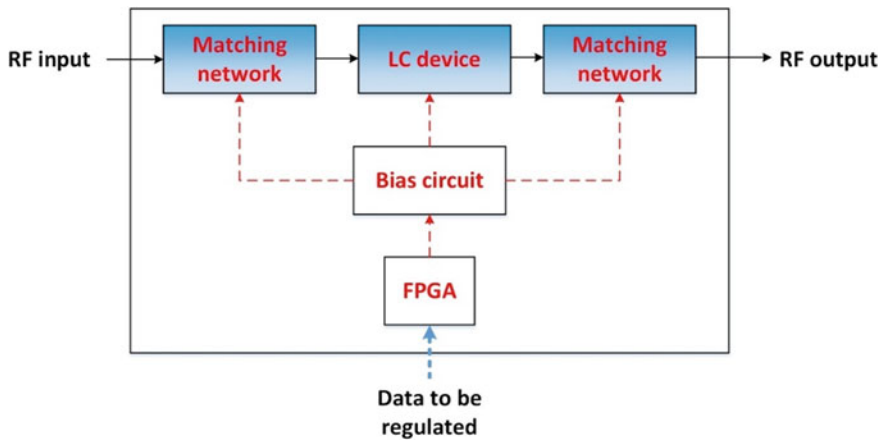


Fig. 7.12 Block diagram of assembled microwave nematic liquid crystal phase shifter under test

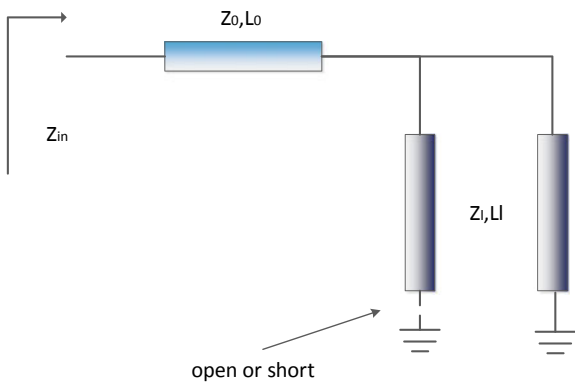


Fig. 7.13 Stub impedance matching

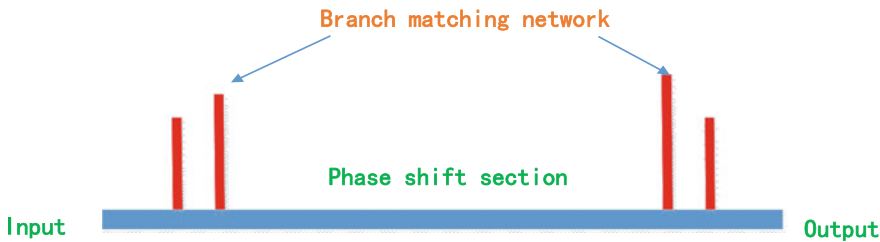


Fig. 7.14 Balanced stud impedance matching

7.4.3 Experimental Setup

The block diagram of the test platform is depicted in Fig. 7.15 and the actual experimental setup is shown in Fig. 7.16. The crucial instrument is a vector network analyzer. The whole process is controlled by a computer.

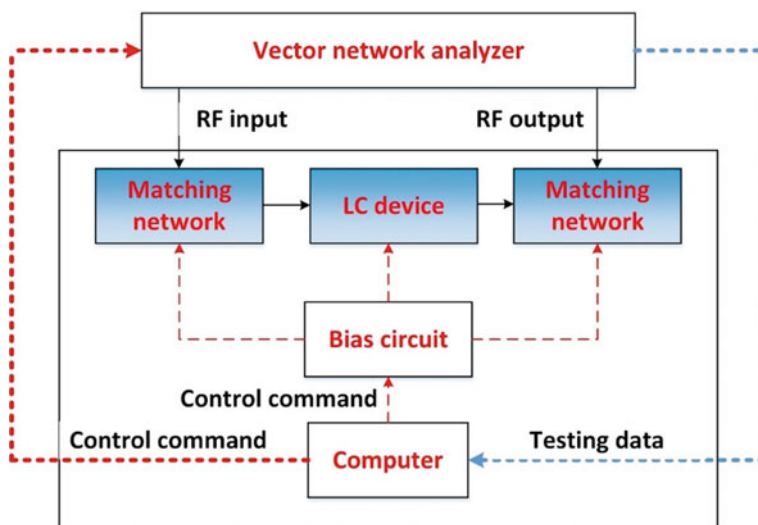


Fig. 7.15 Block diagram of test platform

Fig. 7.16 Photograph of the test platform



7.4.4 Measurement Results

The measured phase shift of the microstrip phase shifter is shown in Fig. 7.17. Good agreement with numerical simulation is observed from 15 to 25 GHz.

The measured phase shift of the IMSL phase shifter is shown in Fig. 7.18 and the measured S_{21} is shown in Fig. 7.19. Similarly, measured result agrees well with numerical result from 15 to 25 GHz.

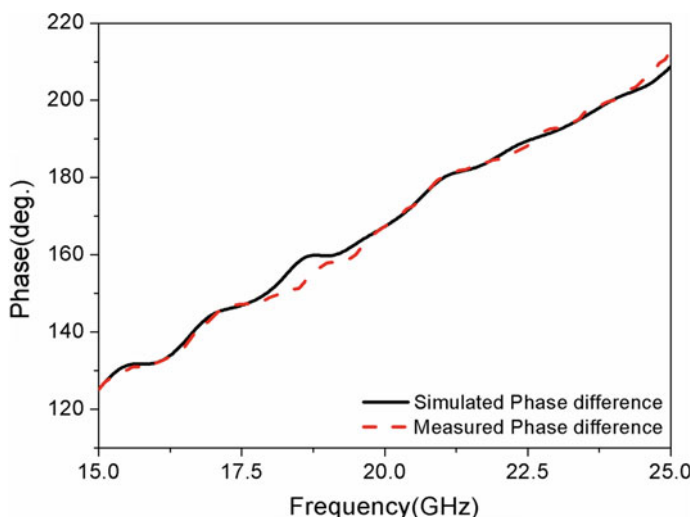


Fig. 7.17 Simulated and measured phase shift of the microstrip phase shifter

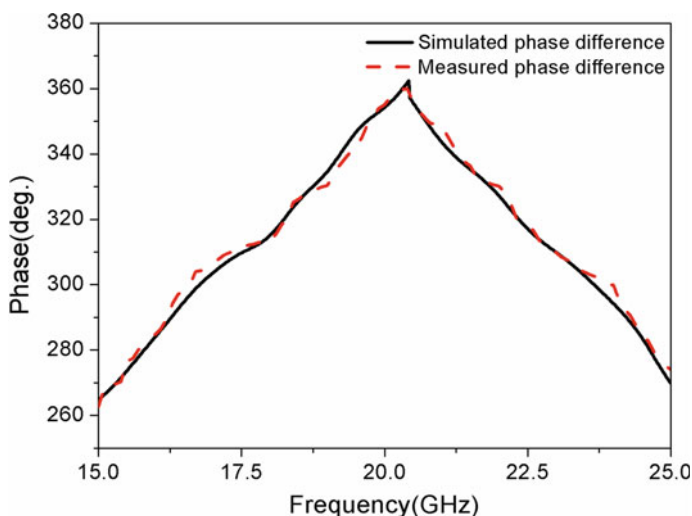


Fig. 7.18 Simulated and measured phase shift of the IMSL phase shifter

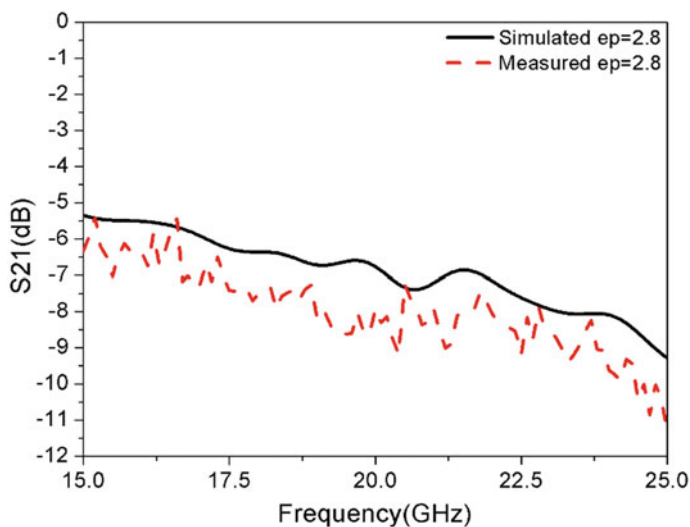


Fig. 7.19 Simulated and measured S_{21} of IMSL phase shifter

Reference

1. Konforti N, Marom E, Wu ST (1988) Phase-only modulation with twisted nematic liquid crystal spatial light modulators. Opt Lett 13(3):251–253

Chapter 8

Frequency Tunable and Pattern Reconfigurable Phased Array Antenna Based on Microwave Nematic Liquid Crystal



A frequency tunable and pattern reconfigurable 1×4 phased array antenna is designed. Numerical simulation proves that the antenna can dynamically adjust its operating frequency between 14.5 and 16.4 GHz and continuously and dynamically control the beam direction between -20° and 20° .

8.1 Introduction

With the rapid development of modern electronic technology, a great variety of applications must coexist within limited space, frequency, or time. Amid these challenges, miniaturization and/or reconfigurable technology have been intensively and extensively investigated in the antenna fields.

Low-cost and low-loss liquid crystal technology has emerged as one of the most promising solutions to achieve electromagnetic reconfigurability, continuous tunability, and low power consumption, especially in the field of communication above 10 GHz such as wireless internet, multimedia, communication, and broadcasting services from terrestrial systems and satellites to a mobile terminal. Application of liquid crystal may even simplify manufacture. For example, arrays with many elements can be fabricated with a simple and low-cost automated manufacturing technique.

In this chapter, we combine liquid crystal technology with phased array antenna technology and propose a frequency and pattern reconfigurable 1×4 phased array antenna. Each array element is composed of a strip at the center and 6 series patches in cascade. The phase shifters are the IMSL discussed in Chap. 7 of this book. The nematic liquid crystal is Merck GT3-23001 with $\varepsilon_{r\parallel} = 3.2$, $\varepsilon_{r\perp} = 2.4$, $\tan\delta_{\parallel} = 0.002$, $\tan\delta_{\perp} = 0.006$. Simulation results of a show that the operating frequency can be dynamically changed between 14.5 and 16.4 GHz, and the beam direction can also be continuously and dynamically adjusted between -20° and 20° .

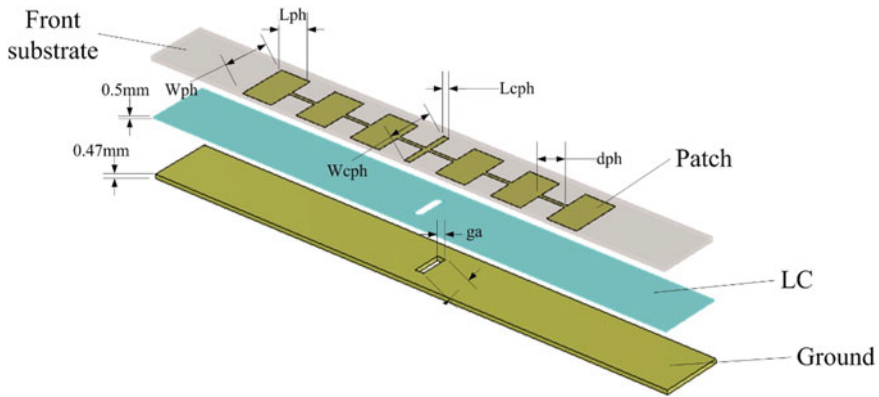


Fig. 8.1 Configuration of the liquid crystal antenna

8.2 Frequency Reconfigurable Patch Antenna

8.2.1 Configuration

Figure 8.1 shows the geometric model of the antenna using a nematic liquid crystal substrate. The radiating element etched on top of the upper Rogers RT5880 copper-clad laminate with a dielectric constant of $\epsilon_r = 2.2$ consists of a strip at the center and six rectangular patches in cascade. A ground plane with a coupling slot at the center separates the radiating element and the feeding microstrip line on the bottom of the lower RT5880 laminate with a thickness of 0.127 mm. A nematic liquid crystal layer of thickness 0.5 mm is utilized as tunable substrate to tune the operating frequency of the patch array antenna.

8.2.2 Parametric Study

Physical parameters of the antenna subject to parametric study by using CST are summarized in Table 8.1. All other physical parameters are assumed fixed in the design.

8.2.2.1 Central Strip

The effect of the physical parameters of the central strip is given in Figs. 8.2 and 8.3. It can be seen from Fig. 8.2 that as W_{cph} increases from 7.5 to 8.5 mm, the S_{11} resonance depth becomes shallower. Similarly, as L_{cph} increases from 0.5 to

Table 8.1 Physical parameters of frequency reconfigurable antenna

Symbol	Description
W_{cph}	Width of the central strip
L_{cph}	Length of the central strip
W_{ph}	Width of the rectangular patches
L_{ph}	Length of the rectangular patches
h_a	Length of the coupling slot
g_a	Width of the coupling slot
d_{ph}	Spacing between patches or strip

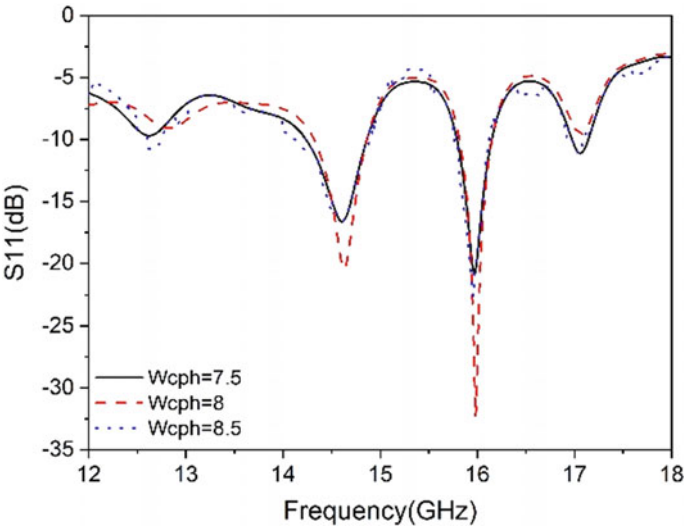


Fig. 8.2 Effect of W_{cph}

1.5 mm, the S_{11} resonance depth deepens. It is therefore concluded that the central strip mainly affects the antenna’s overall resonance depth.

8.2.2.2 Patches

The effect of the patch width is drawn in Fig. 8.4. It is observed that when the width increases from 7.5 to 8.5 mm, the resonant frequency decreases from 14.9 to 14.2 GHz and the resonant depth deepens at the same time.

The effect of the patch length is drawn in Fig. 8.5. Likewise, three representative values are investigated. As the length increases from 5 to 6 mm, the resonant frequency decreases from 15.7 to 12.9 GHz.

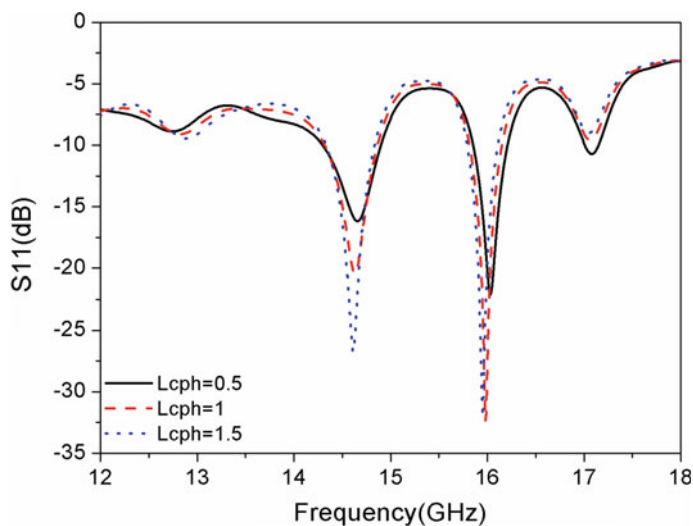


Fig. 8.3 Effect of L_{cph}

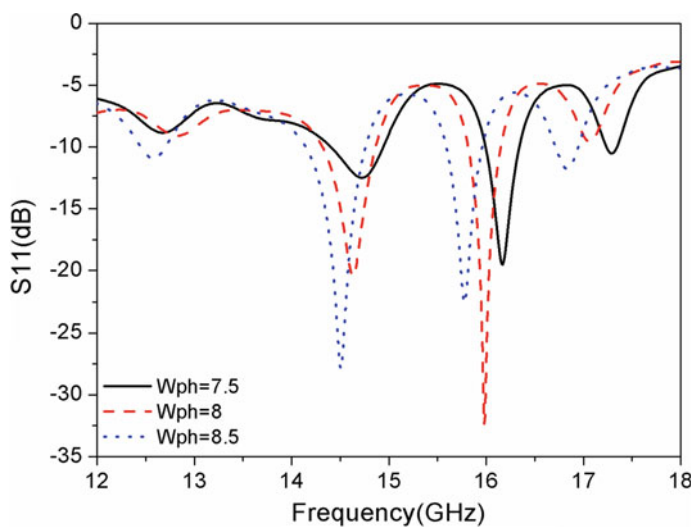


Fig. 8.4 Effect of W_{ph}

8.2.2.3 Coupling Slot

A parametric study on the coupling slot is also conducted as shown in Figs. 8.6 and 8.7. Once again, three representative values for each parameter are examined. The results show that the -10 dB working bandwidth of the antenna increases with the

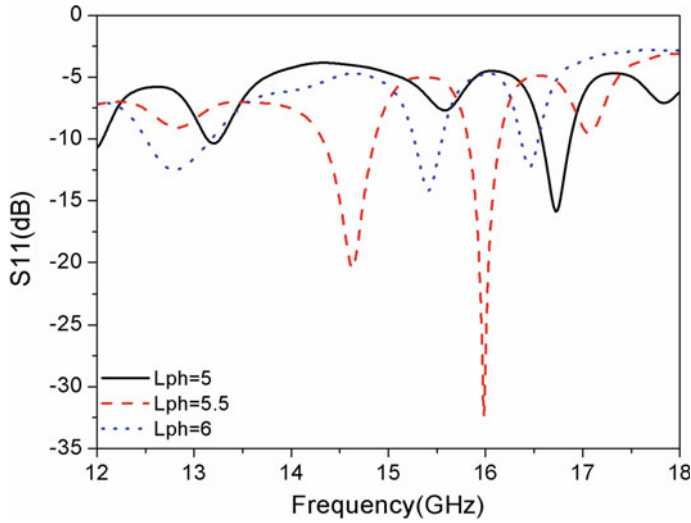


Fig. 8.5 The effect of L_{ph} on the antenna

increase of h_a and increases with the increase of g_a . The resonance depth decreases with the increase of h_a and decreases with the increase of g_a . It can therefore be concluded that the coupling slot is broadband and its size mainly affects the antenna's impedance and bandwidth.

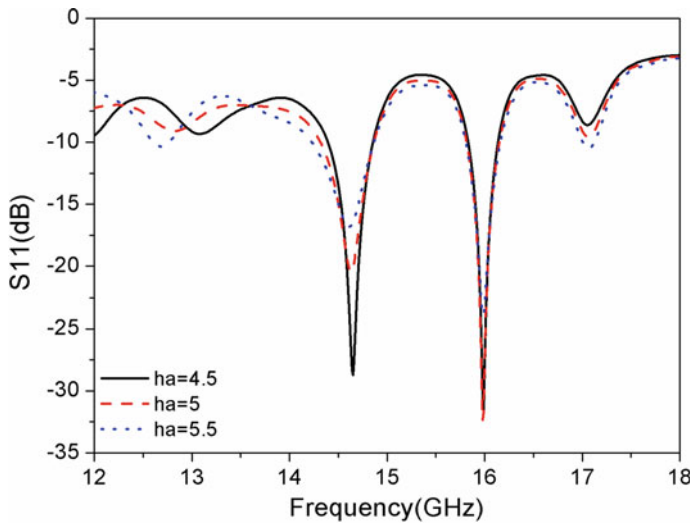


Fig. 8.6 Effect of h_a

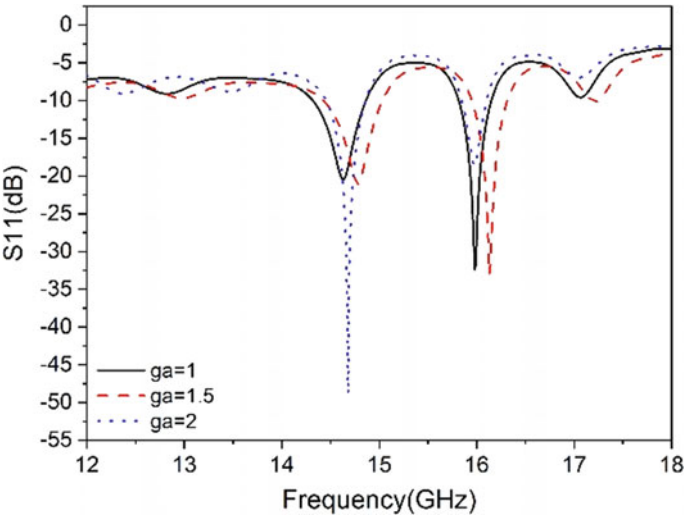


Fig. 8.7 Effect of g_a

Table 8.2 Optimal physical parameter values

Physical parameter	Optimal value (mm)
W_{cph}	8
L_{cph}	1
W_{ph}	8
L_{ph}	5.5
h_a	5
g_a	1.5
d_{ph}	5.5

8.2.2.4 Optimal Physical Parameters

Optimal values of the physical parameters found through the above parametric study are summarized in Table 8.2.

8.2.3 Tuning Characteristics

Nematic liquid crystal exhibit different effective permittivity $\epsilon_{r, \text{eff}}$ depending on how an external static electric field is applied. For the unbiased state, the effective permittivity would be the minimum $\epsilon_{r, \perp}$. A bias voltage would reorient the liquid crystal molecules, leading to a variation in the effective permittivity. When the voltage is further increased, most of the liquid crystal molecules would orient in parallel with

the static field. The effective permittivity would be the maximum $\epsilon_{r\parallel}$. Such dielectric anisotropy allows tuning of resonant frequency and phase shift.

The simulated S_{11} from 14.0 and 16.5 GHz as the effective permittivity increases from 2.4 to 3.2 is shown in Fig. 8.8. The designed antenna resonates at frequencies of 16.1 GHz, 15.3 GHz, and 14.5 GHz, respectively.

The gain of the antenna from 14 to 16.5 GHz is shown in Fig. 8.9. As the effective permittivity increases from 2.4 to 3.2, the peak gain keeps almost the same at about 12 dBi but the corresponding frequency is similarly shifted from 16.1 to 14.5 GHz.

Fig. 8.8 S_{11} of the Frequency reconfigurable antenna

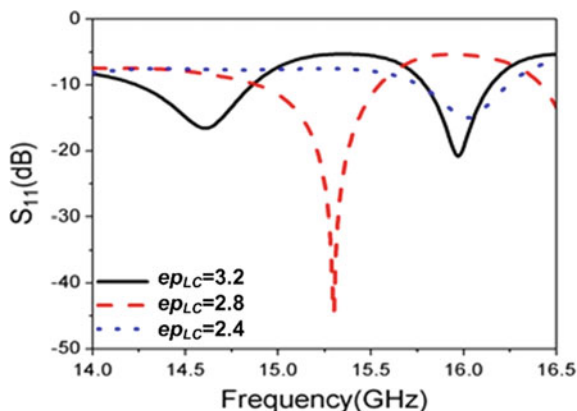
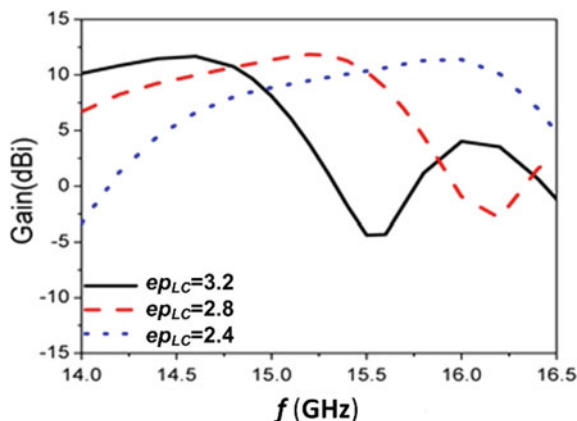


Fig. 8.9 Gain of the frequency reconfigurable antenna



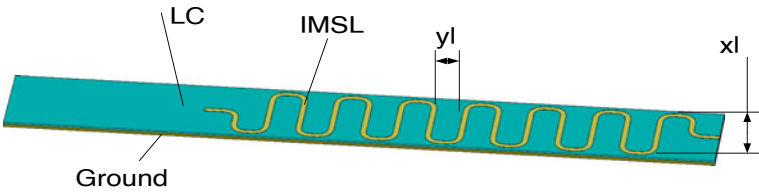


Fig. 8.10 Liquid crystal IMSL phase shifter

Table 8.3 Optimal values of the IMSL phase shifter physical parameters

Symbol	Optimal Value
x_1	9 mm
y_1	3 mm
h	

8.3 Phase Shifters

8.3.1 Configuration

Phase shifters are crucial for phased array antennas. The prospective phase shifters are the IMSL discussed in Chap. 7 of this book as shown in Fig. 8.10. The optimal physical parameters are summarized in Table 8.3.

8.3.2 Tunable Phase Shift

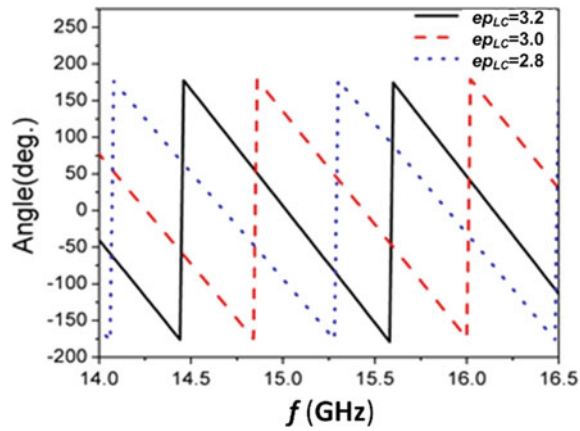
The tunable phase shift is simulated and shown in Fig. 8.11. As the effective permittivity varies from 3.2 to 2.8, a phase tuning range of 185° can be obtained between 15.3 GHz and 14.5 GHz. It is sufficient for the ultimate phased array antenna.

8.4 Integrated Phased Array Antenna

8.4.1 Configuration

The patch antennas and the liquid crystal phase shifters are integrated to develop a 1×4 phased array antenna as shown in Fig. 8.12. Each array element integrates a patch antenna and a phase shifter isolated by the ground plane with coupling slots. Two liquid crystal layers are used to independently tune the operating frequency and

Fig. 8.11 Tunable phase shift of the liquid crystal IMSL phase shifter



radiation pattern. Not only the operating frequency is tunable, the beam can also be steered.

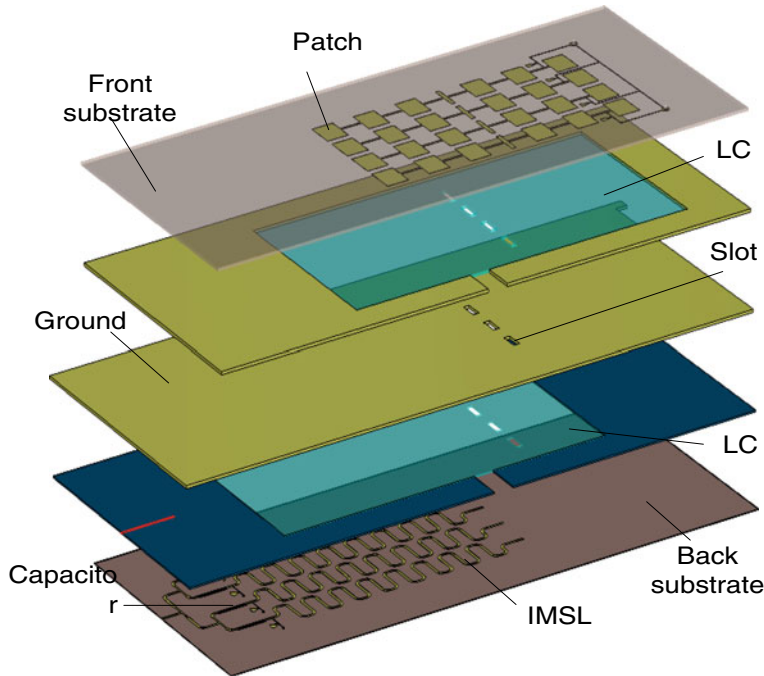


Fig. 8.12 Schematic model of the proposed reconfigurable antenna array

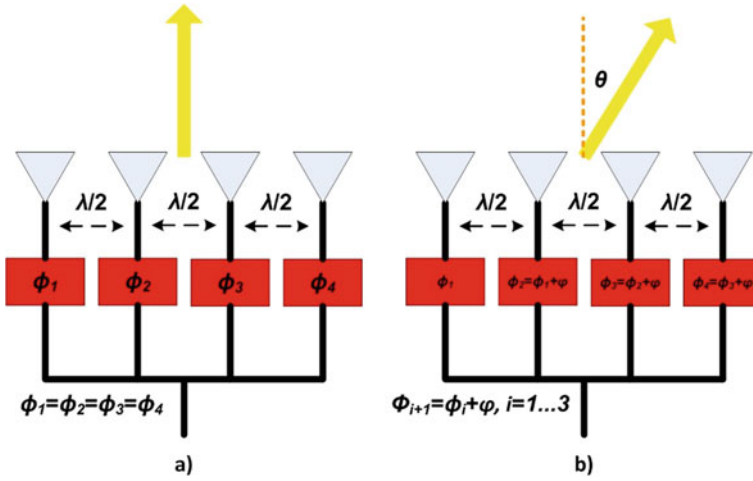


Fig. 8.13 Gradient phase distribution of phased array antenna

8.4.2 Beam Deflection

Beam deflection can be realized when microwave nematic liquid crystal phase shifter is used to generate the gradient phase distribution as shown in Fig. 8.13.

The phase difference between adjacent radiating elements can be expressed as

$$\Delta\phi = -p\beta = -kp\sqrt{\mu_r\epsilon_r LC} \quad (8.1)$$

where p is the distance between adjacent elements.

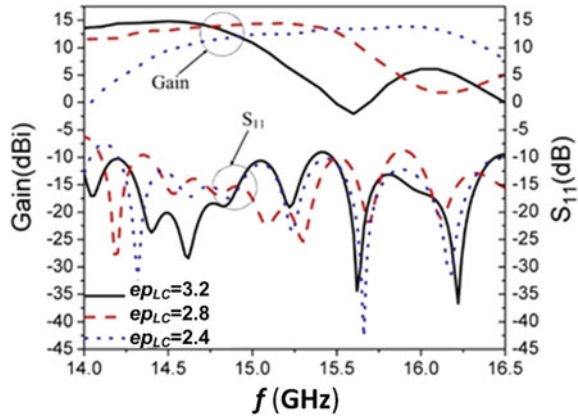
The electrically tunable effective permittivity of nematic liquid crystal would change the guide wavelength, enabling dynamically adjustment of the phase shifter's transmission phase. The maximum phase tuning range is

$$\Delta\phi_{\max} = kp\sqrt{\mu_r\epsilon_{r\parallel}} - kp\sqrt{\mu_r\epsilon_{r\perp}} \quad (8.2)$$

8.4.3 Bias

In order to produce the desired amount of phase shift between adjacent antenna elements, each phase shifter has to be controlled independently. Four thin metal wires with a fan-shaped metal structure are designed to connect the 50-ohm inverted microstrip line to the electrodes, which are used to load the bias voltage. A interdigital capacitor is used in each branch of the one-to-four power divider to separate the RF signal from the DC.

Fig. 8.14 Gain and S_{11} of the phased array antenna



Simulation shows that the insertion loss is less than 0.5 dB and the S_{11} is less than -20 dB between 14.2 and 16.1 GHz. Therefore, the use of interdigital capacitors has little effect on the transmission of radio frequency signals in the desired frequency range and can effectively isolate DC signals.

8.4.4 Numerical Results

The reflection coefficient and gain of the phased array antenna is shown in Fig. 8.14. The frequency corresponding to the peak gain can be continuously tuned from 14.5 to 16.1 GHz when the permittivity is varied from 3.2 to 2.4. The peak gain is larger than 12 dBi and the corresponding S_{11} is less than -10 dB for the above three cases.

In order to verify the beam steering performance of the reconfigurable antenna array, the radiation patterns of the phased array antenna with different phase difference are investigated at the resonant frequency of 14.5 GHz. The phased array antenna can produce different directive beams as shown in Fig. 8.15. The radiation angles of the main lobes are directed towards -20° , -10° , ..., respectively.

Table 8.4 summarizes the effective permittivity of liquid crystal for each phase shifter at the scanning angle of -20° , -10° , 0° , 10° , 20° , respectively. The corresponding transmission phase difference are about -185° , -94° , 0° , 94° , 185° , respectively.

Fig. 8.15 Beam steering of the phased array antenna at 14.5 GHz

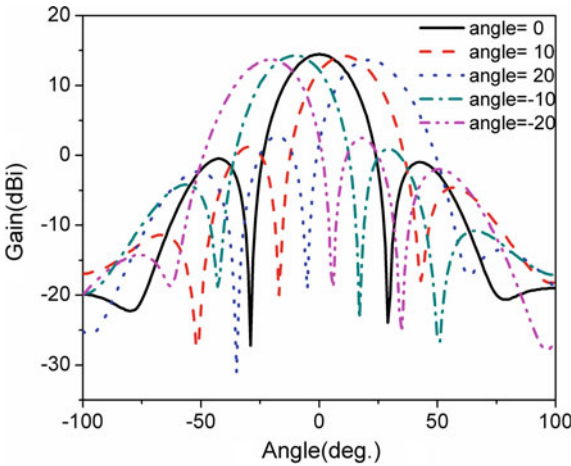


Table 8.4 Effective permittivity of liquid crystal for each phase shifter

Scanning angle	ε_1	ε_2	ε_3	ε_4
- 20°	2.8	2.93	3.07	3.2
- 10°	2.8	2.87	2.93	3.0
0°	2.8	2.8	2.8	2.8
10°	3.0	2.93	2.87	2.8
20°	3.2	3.07	2.93	2.8

Chapter 9

Digital Metamaterial of Arbitrary Base Based on Voltage Tunable Liquid Crystal



In this chapter, we introduce nematic liquid crystal (NLC) as a means to develop novel metamaterials—namely, multifunctional digital metamaterials of arbitrary base. To accomplish this, we design general coding elements or codes of specific bases by carefully selecting appropriate NLC and designing the geometrical configuration. Switching between custom applications corresponding to different coding patterns is made simple. We propose a proof-of-concept prototype consisting of a superstrate of quartz, an array of metallic patches, a substrate of NLC, and a ground. Encoding is achieved by biasing NLC to shift the phase of incoming waves. The novel coding mechanism has been proven through both numerical simulation and preliminary experiments. We present two representative applications of different bases—base-4 beam steering and base-2 RCS reduction—to demonstrate the novelty of the digital metamaterial. The coding freedom of the NLC-based digital metamaterial is clearly demonstrated.

9.1 Digital Metamaterial

Metamaterials [1] offer unique solutions due to their extraordinary electromagnetic properties that are absent in natural materials. They have been utilized to achieve remarkable functions, such as invisible cloaking [2], negative refraction [3], and perfect lenses [4]. In recent decades, numerous metamaterials have been designed specifically to control the phase of electromagnetic waves [5, 6].

Recently, a novel type of metamaterial known as coding metamaterials (CMM) [7, 8], or more generally digital metamaterials [9], have been proposed to address this purpose. CMMs are constructed using only two types of unit cells, specifically 0 and 1 elements, where the phase difference between these elements is approximately 180° . These metamaterials have been successfully utilized to achieve terahertz anomalous reflections [10] and broadband diffusions [11].

9.1.1 Theory of Coding Metamaterials

Coding metamaterials are constructed using subwavelength resonant structures and exhibit homogenous material-like responses to electric and magnetic fields. Typically, coding metamaterials take the form of a two-dimensional periodic array of subwavelength unit cells, as illustrated in Fig. 9.1.

Compared to the current analog metamaterials that rely on effective medium parameters or specific dispersion relations to regulate EM fields, coding metamaterials operate by manipulating EM waves using various coding sequences composed of 0 and 1 elements. While the physical implementation of a digital element (m, n) may not be exclusive, its influence on EM waves can be modeled as a phase modulation $\phi(m, n)$, and the behavior of the coding metamaterial is akin to that of a phased array antenna. When subjected to plane waves, the far pattern of the coding metamaterial can be described as follows:

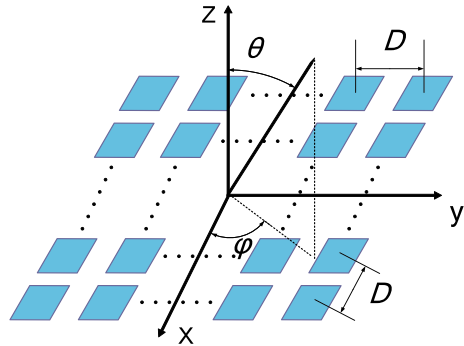
$$f(\theta, \varphi) = \sum_{m=1}^M \sum_{n=1}^N e^{j[\phi(m,n) + mkD \sin \theta \cos \varphi + nkD \sin \theta \sin \varphi]} \quad (9.1)$$

where θ and φ are the elevation and azimuth angles, D is the periodicity in x and y .

In the binary case, the maximum phase difference is π (or 180°). Hence, we design the ‘0’ element as a metamaterial particle with a 0 phase response and the ‘1’ element as a metamaterial particle with a π phase response. In this way, the phase responses of the ‘0’ and ‘1’ elements are simply defined as $\phi_b = b\pi$, ($b = 0, 1$).

Clearly, the digital state $\phi(m, n)$ of particle (m, n) is crucial in digital metamaterials. By properly adjusting $\phi(m, n)$, the digital metamaterial can be multiplexed to perform various functions and achieve diverse far-field patterns.

Fig. 9.1 The far pattern of a digital metamaterial



9.1.2 *Classification of Coding Metamaterials*

9.1.2.1 **Passive Coding Metamaterials**

The groundbreaking innovation [7] utilized a subwavelength square metallic patch printed on a dielectric substrate to implement passive binary elements. Patches of different width correspond to different binary codes. Although multi-bit CMM can be realized by applying multi-bit passive coding particles, each passive coding particle corresponding to a specific digital state has to be independently designed. The design process is therefore much more tedious, which causes bulky sizes and complex tuning mechanisms. What's worse, it is impossible to multiplex a passive CMM once finalized. Consequently, instant switching of coding patterns for different functions is a very tough challenge.

9.1.2.2 **Active Coding Metamaterials**

Tunable structures are essential in achieving dynamic performance in the fields of frequency selective surfaces, reconfigurable antennas, and metamaterials. Switches, such as PIN diodes, varactor diodes [12, 13], and microelectromechanical systems (MEMS) devices, are common tunable structures.

It is worth noting that PIN diodes have also been utilized to achieve digital control of the '0' and '1' responses, as demonstrated in [7]. Different digital states correspond to ON/OFF states of PIN diodes of active coding particles [6–8]. Regrettably, the binary characteristics of PIN diodes severely restricts the coding possibilities of CMM. Obviously, PIN diode-based active binary particles can only achieve 1-bit CMM ($B = 2$). Furthermore, the utilization of tuning switches often leads to undesirable effects such as parasitic resistances, electrostatic forces [14], losses [15], and increased cost, particularly at higher frequencies. Likewise, active CMM might be very complicated and bulky.

9.2 **NLC-Based Digital Particle of Base B**

As mentioned before, NLC is an emerging tunable dielectric material whose effective permittivity can be continuously adjusted by applying a bias voltage to align NLC molecules [16–18]. It has garnered considerable attention within the electromagnetic community due to its experimentally verified low loss, liquid state, low profile, and cost-effectiveness, especially at higher frequencies. The material properties of NLC have been extensively studied at microwave and millimeter-wave frequencies. Remarkable applications of NLC include phase shifters [19, 20], leaky-wave antennas [21, 22], and metasurface [23, 24].

In this section, NLC is introduced to develop active digital particles of base B and accordingly multifunctional base- B digital metamaterials for different applications. Ideally, for a digital particle of base B ,

$$\phi(m, n) \in \left\{ \phi_i | \phi_i = \frac{i}{B} 360^\circ, 0 \leq i \leq B - 1 \right\} \quad (9.2)$$

9.2.1 Configuration

Figure 9.2 shows the configuration of the active digital particle. It uses the upper and lower layers of quartz (relative permittivity of $\varepsilon_r = 3.75$ and loss tangent of 0.0004) plates as the base. A rectangular metal patch is plated on the lower surface of the upper quartz plate as a radiation element. The entire surface of the lower quartz plate is grounded, and a space with a certain layer thickness is left between the upper and lower quartz plates to fill the liquid crystal.

At different bias voltages, microwave NLCs will present different dielectric properties accordingly. For example, when no bias voltage is applied to the microwave NLC, the NLC molecules are parallel aligned and perpendicular to the metal patch due to the use of the polyimide alignment layer. Therefore, the dielectric constant of the microwave NLC at this time is the minimum dielectric constant $\varepsilon_{r\perp}$. Intruding the bias voltage would reorient the NLC molecules, which causes a variation in the effective permittivity of the microwave NLC. When the voltage is further increased, most of the NLC molecules would orient in parallel with the external static electric field, hence the maximum value of $\varepsilon_{r, \text{eff}}$ is obtained, which is indicated by $\varepsilon_{r\parallel}$. That means that Increasing the bias voltage causes the NLC molecules to rotate accordingly so that the effective dielectric constant of the microwave NLC continuously

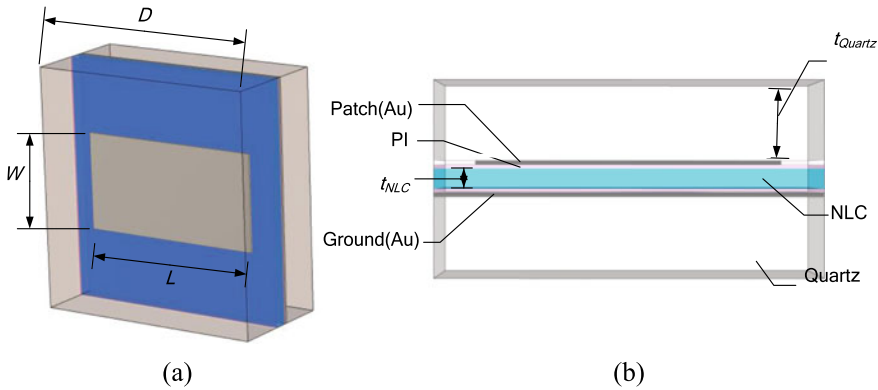


Fig. 9.2 Geometry of NLC-based coding particle **a** 3-dimensional and **b** cross section

changes from $\varepsilon_{r\perp}$ to $\varepsilon_{r\parallel}$. In accordance, ϕ or equivalently the digital state of the active digital particle depends on the applied bias voltage.

By properly selecting NLC and tuning the geometrical parameters of the digital particle, the digital particle will achieve maximum phase difference $\Delta\phi$ and B digital states if

$$\Delta\phi \geq \frac{B-1}{B} 360^\circ \quad (9.3)$$

Later in this section, we will present two representative applications, beam steering and RCS reduction, to demonstrate the concept. Beam steering requires a phase gradient of 0° , 90° , 180° , and 270° , while RCS reduction expects an alternating phase distribution of 0° and 180° . Therefore, a digital metamaterial of base 4 is sufficient for both applications.. That is, the maximum phase difference $\Delta\phi$ achieved by digital particles must satisfy $\Delta\phi \geq 270^\circ$.

This study selected GT3-23001, manufactured by Merck [25], due to its excellent tunability ($\varepsilon_{r\parallel} = 3.2$, $\varepsilon_{r\perp} = 2.4$, $\tan\delta_{\parallel} = 0.002$, and $\tan\delta_{\perp} = 0.006$, $V_{\max} = 14$ V).

To determine the five geometrical parameters (periodicity D , superstrate thickness t_{quartz} , NLC thickness t_{NLC} , patch length L and patch width W), a series of parametric studies are conducted. The optimized values are found to be $D = 3$ mm, $L = 2.5$ mm, $W = 1.5$ mm, $t_{\text{NLC}} = 0.05$ mm, $t_{\text{Quartz}} = 0.5$ mm. The corresponding maximum phase difference $\Delta\phi$ at normal incidence ($\theta = 0^\circ$, $\varphi = 0^\circ$) is shown in Fig. 9.3, where $\Delta\phi \geq 270^\circ$ from 52.1 to 53.1 GHz.

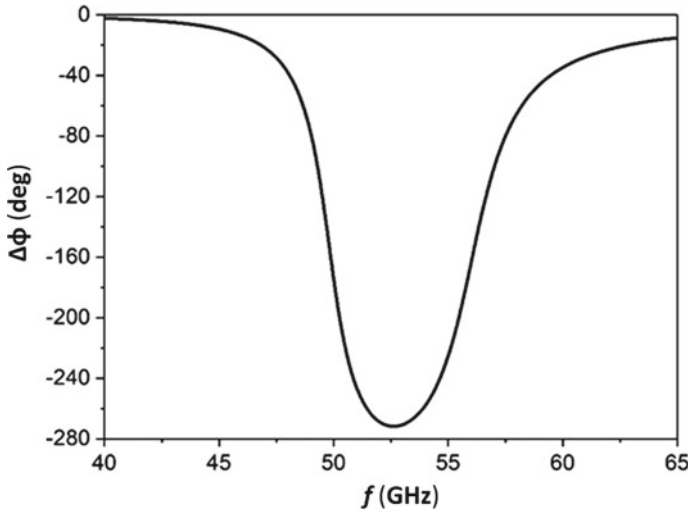
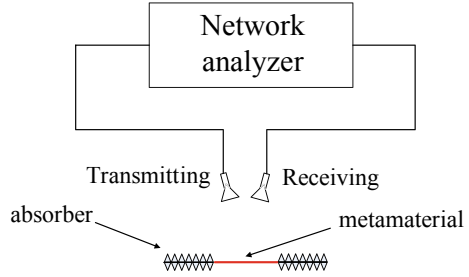


Fig. 9.3 Maximum phase difference for the coding particle at normal incidence ($\theta = 0^\circ$, $\varphi = 0^\circ$)

Fig. 9.4 Schematic diagram of the test platform for microwave NLC-based metamaterials



9.2.2 Experimental Demonstration

To demonstrate the concept, a NLC-based metamaterial is fabricated and measured. Due to availability issues with GT3-23001 manufactured by Merck, it is replaced with a commercial NLC, TIANMA9. While the tunable range of TIANMA9 ($\varepsilon_{r\parallel} = 2.815$, $\varepsilon_{r\perp} = 2.76$, $\tan\delta_{\parallel} = 0.024$, and $\tan\delta_{\perp} = 0.04$, $V_{\max} = 7$ V) falls within that of GT3-23001, it is significantly smaller. However, all optimized geometrical parameters are kept unchanged.

After the sample is processed, we first need to set up a test platform to conduct the experimental measurement of the maximum phase shift of the processed microwave NLC-based metamaterial samples. The schematic diagram of the test platform is shown in Fig. 9.4. The entire test platform includes a transmitting horn antenna, a receiving horn antenna, a vector network analyzer, absorbing materials, and positioning brackets. The processed sample is placed in the middle position between the transmitting and receiving horn antennas so that the distances between the sample and the two antennas are equal. In addition, the periphery of the sample, except for the transmission direction of the electromagnetic wave, is surrounded by a wave absorbing material, thereby removing the influence of the diffracted electromagnetic wave on the accuracy of the experimental test.

The specific test plan is as follows:

- (1) First, select two horn antennas containing the operating frequency band of the sample to be tested, and place the two horn antennas side by side with a positioning bracket. The antennas are placed at the same height and in the same polarization direction.
- (2) Hollow out the middle of the absorbing material and place it directly under the two horn antennas. The distances between the absorbing material and the two horn antennas are equal. The size of the hollow part in the middle of the absorbing material should be able to contain the sample to be tested.
- (3) Calibrate the vector network analyzer without the microwave NLC-based metamaterial sample before starting the test.
- (4) After calibration, place the microwave NLC-based metamaterial sample in the hollow area in the middle of the absorbing material. Feed the signal, and at the

same time, slowly load the bias voltage on the microwave NLC-based metamaterial, and test the phase curve of the reflected electromagnetic wave by the metamaterial loaded with different bias voltages.

Figure 9.5 presents a photograph of the fabricated metamaterial and the experimental setup, while Fig. 9.6 shows the measured and simulated maximum phase difference $\Delta\phi$. As expected, the measured phase shift is much weaker than designed but good agreement between measurement and simulation is very clear.

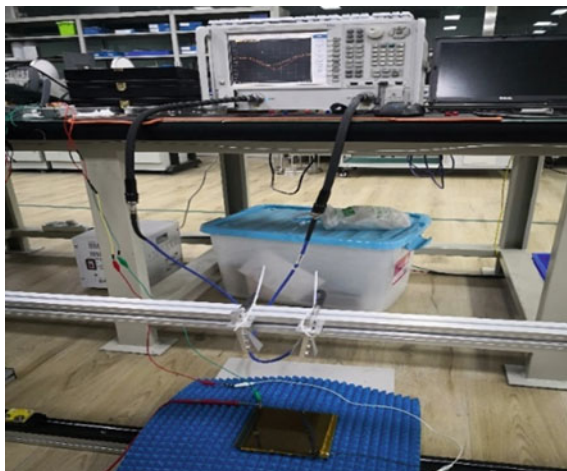


Fig. 9.5 Fabricated metamaterial and experimental setup

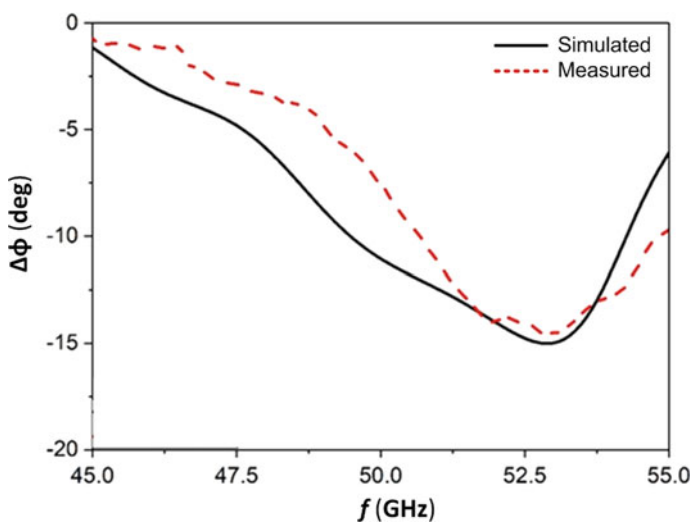


Fig. 9.6 Measured and simulated maximum phase difference of the fabricated metamaterial

9.3 Beam Steering

To demonstrate the practicality of our designed digital metamaterial based on microwave NLC, we perform a numerical study on a typical application of this digital metamaterial, namely, beam steering.

Beam steering is a prevalent application of digital metamaterials, whereby a phase gradient in the metamaterial can re-direct an outgoing beam.

According to [26], in our study, the beaming direction

$$\theta \propto \arcsin\left(-\frac{2\pi}{B\beta D}\right) \quad (9.4)$$

where B is the base for the digital particle, D is the distance between adjacent digital particles and β is the wavenumber. Therefore, θ can be tuned by changing B . Coding base $B = 3$ or larger is absolutely necessary to realize the phase gradient required in the beam steering function of digital metamaterials.

In order to multiplex our digital metamaterial, we select a coding base of $B = 4$. By biasing the digital coding particles with different voltages, we can obtain four digital states: 0, 1, 2, and 3, which correspond to phase differences of 0° , 90° , 180° , and 270° , respectively. Using a periodic coding pattern of 0123/0123... as shown in Fig. 9.7, our digital metamaterial can re-direct the outgoing beam at 54 GHz to 27° , as demonstrated in Fig. 9.8.

It is evident that by encoding the digital metamaterial differently, we can re-direct the outgoing beam to other desirable directions.

9.4 RCS Reduction

The RCS plays an essential role in understanding EM phenomena and designing radars operating in different frequency regions. RCS reduction is crucial in designing “low visibility” (stealth) weapon systems in defense technologies, such as combat aircraft and/or missiles. The RCS is calculated and/or measured from the target-scattered fields caused by an incident plane wave hitting the target from a specified direction, via

$$RCS = \lim_{R \rightarrow \infty} \left\{ 4\pi R^2 \frac{|E_s|^2}{|E_i|^2} \right\}, \quad (9.5)$$

where R is the distance between the radar transmitter and the target, and E_s , and E_i are the scattered and incident electric fields, respectively.

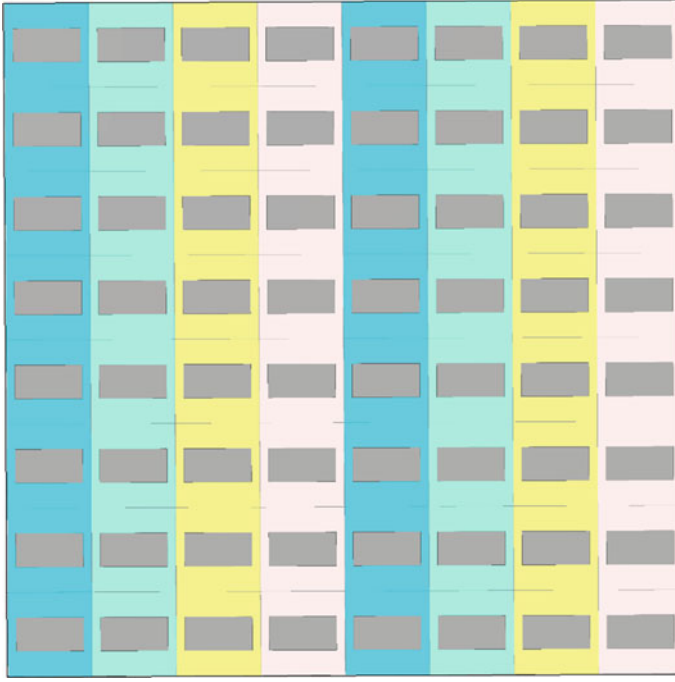


Fig. 9.7 The Periodic Coding Pattern of Metamaterials for Beam Steering, in which the Blue Region Represents “0”, the Green Region Represents “1”, the Yellow Region Represents “2”, and the Red Region Represents “3”

RCS reduction is another very important application for digital metamaterial by appropriately coding ‘0’ and ‘1’ elements. In fact, the invisible cloak is one approach to reduce RCSs by forcing EM waves to bend around the target, and the perfect absorber is another approach for reducing RCSs by absorbing all incident EM waves.

Here, we propose a new mechanism for reducing the monostatic and bistatic RCSs by redirecting EM energies to all directions through the use of a special ‘0’ and ‘1’ coding. By diversifying the incoming beam to as many outgoing beams as possible, the RCS at a specific direction can be significantly reduced, even if there is no loss in the digital metamaterials. Relative to a metallic plate with the same size, the RCS reduction caused by the coding metasurface is obtained as

$$RCS_{reduction} = \frac{\lambda^2}{4\pi N^2 D^2} \max_{\theta, \varphi} [Dir(\theta, \varphi)] \quad (9.6)$$

where λ is the wavelength in free space.

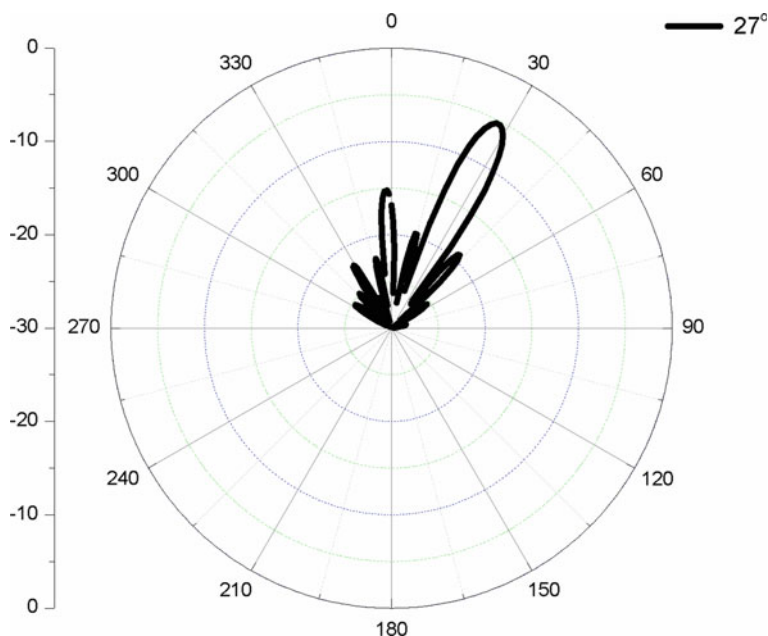


Fig. 9.8 Beam steering performance of the NLC-based metamaterial at 54 GHz

Without losing generality, we study the alternating code pattern 010101/010101... as shown in Fig. 9.9. The simulated RCS of the proposed NLC-based digital metamaterial under normal incidence is shown in Figs. 9.10 and 9.11, where a minimum of 10 dB reduction is observed.

It is very interesting to point out that the binary states of our digital coding particles can be obtained in many different biasing schemes because the maximum phase difference of our digital coding particles is much larger than 180° . From this point of view, although our digital metamaterial with a specific biasing scheme can only reduce RCS in a limited frequency band, our digital metamaterial is able to reduce RCS by at least 10dB from 51 to 56 GHz by biasing it differently in different frequency bands.

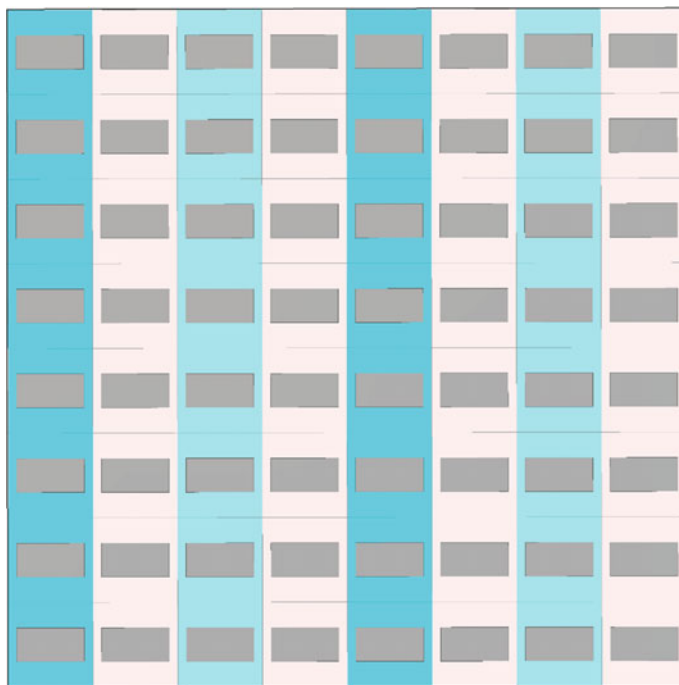


Fig. 9.9 The periodic coding pattern of metamaterials for RCS reduction, in which the Blue Region Represents “0”, and the Red Region Represents “1”

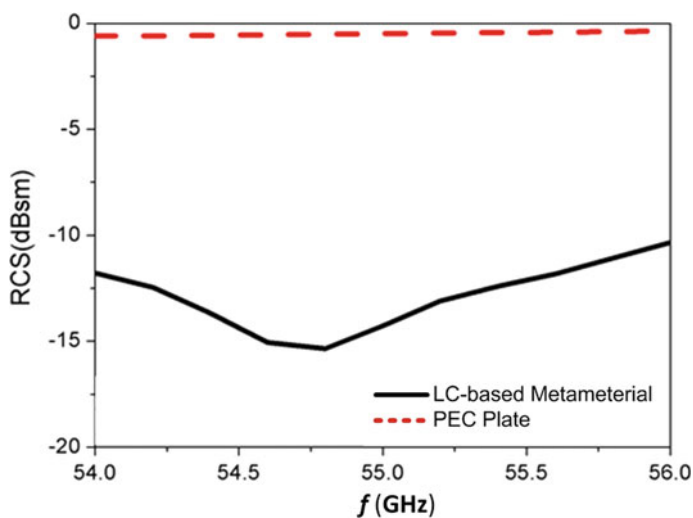


Fig. 9.10 Low-RCS property of the NLC-based metamaterial from 54 to 56 GHz under biasing scheme 1

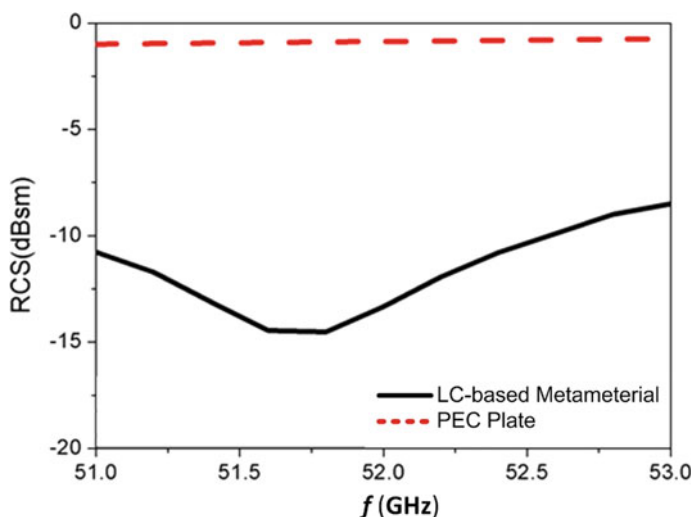


Fig. 9.11 Low-RCS property of the NLC-based metamaterial from 51 to 52.4 GHz under biasing scheme 2

References

1. Smith DR, Pendry JB, Wiltshire MCK (2004) Metamaterials and negative refractive index. *Science* 305(5685):788–792
2. Schurig D, Mock JJ, Justice BJ, Cummer SA, Pendry JB, Starr AF, Smith DR (2006) Metamaterial electromagnetic cloak at microwave frequencies. *Science* 314(5801):977–980
3. Shelby RA, Smith DR, Schultz S (2001) Experimental verification of a negative index of refraction. *Science* 292(5514):77–79
4. Pendry JB (2000) Negative refraction makes a perfect lens. *Phys Rev Lett* 85(18):3966–3969
5. Lim S, Caloz C, Itoh T (2004) Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth. *IEEE Trans Microw Theory Tech* 52(12):2678–2690
6. Liu S, Zhang L, Yang QL, Xu Q, Yang Y, Noor A, Zhang Q, Iqbal S, Wan X, Tian Z, Tang WX, Cheng Q, Han JG, Zhang WL, Cui TJ (2016) Frequency-dependent dual-functional coding metasurfaces at terahertz frequencies. *Adv Opt Mater* 4(12):1965–1973
7. Cui TJ, Qi MQ, Wan X, Zhao J, Cheng Q (2014) Coding metamaterials, digital metamaterials and programmable metamaterials. *Nat Light: Sci Appl* 3, Art. No. e218
8. Liu S, Cui TJ (2017) Concepts, working principles, and applications of coding and programmable metamaterials. *Adv Opt Mater* 5(22), Art. No. 1700624
9. Della Giovampaola C, Engheta N (2014) Digital metamaterials. *Nat Mater* 13:1115–1121, Art. No. 4082
10. Liang LJ, Qi M, Yang J, Shen X, Zhai J, Xu W, Jin B, Liu W, Feng Y, Zhang C, Lu H, Chen HT, Kang L, Xu W, Chen J, Cui TJ, Wu P, Liu S (2015) Anomalous terahertz reflection and scattering by flexible and conformal coding metamaterials. *Adv Opt Mater* 3(10):1374–1380
11. Gao LH, Cheng Q, Yang J, Ma SJ, Zhao J, Liu S, Chen HB, He Q, Jiang WX, Ma HF, Wen QY, Liang LJ, Jin BB, Liu WW, Zhou L, Yao JQ, Wu PH, Cui TJ (2015) Broadband diffusion of terahertz waves by multi-bit coding metasurfaces. *Nat Light: Sci Appl* 4, Art. No. e324
12. Ratni B, de Lustrac A, Piau GP, Burokur SN (2017) Electronic control of linear-to-circular polarization conversion using a reconfigurable metasurface. *Appl Phys Lett* 111(21), Art. No. 214101

13. Ratni B, de Lustrac A, Piau GP, Burokur SN (2018) Reconfigurable meta-mirror for wavefronts control: applications to microwave antennas. *Opt Express* 26(3):2613–2624
14. Farinelli P, Bastioli S, Chiuppesi E, Di Maggio F, Margesin B, Colpo S, Ocera A, Russo M, Pomona I (2010) Development of different K-band MEMS phase shifter designs for satellite COTM terminals. *Int J Microw Wirel Technol* 2(3–4):263–271
15. Houzet G, Burgnies L, Velu G, Carru JC, Lippens D (2008) Dispersion and loss of ferroelectric Ba_{0.5}Sr_{0.5}TiO₃ thin films up to 110 GHz. *Appl Phys Lett* 93(8), Art. No. 053507
16. Bulja S, Mirshekar-Syahkal D, James R, Day SE, Anibal Fernandez F (2010) Measurement of dielectric properties of nematic liquid crystals at millimeter wavelength. *IEEE Trans Microw Theory Tech* 58(12):3493–3501
17. Yang F, Sambles JR (2002) Resonant transmission of microwaves through a narrow metallic slit. *Phys Rev Lett* 89(6), Art. No. 063901
18. Yang F, Sambles JR (2003) Determination of the permittivity of nematic liquid crystals in the microwave region. *Liq Cryst* 30(5):599–602
19. Mueller S, Goelden F, Scheele P, Wittek M, Hock C, Jakoby R (2006) Passive phase shifter for W-band applications using liquid crystals. In: 2006 36th European microwave conference, Manchester, UK, Sept 10–15, 2006, pp 306–309
20. Moessinger A, Fritzsche C, Bildik S, Jakoby R (2010) Compact tunable Ka-band phase shifter based on liquid crystals. In: 2010 IEEE MTT-S international microwave symposium, Anaheim, CA, 23–28 May 2010, pp 1020–1023
21. Che BJ, Jin T, Erni D, Meng FY, Lyu YL, Wu Q (2017) Electrically controllable composite right/left-handed leaky-wave antenna using liquid crystals in PCB technology. *IEEE Trans Compon Packag Manuf Technol* 7(8):1331–1342
22. Ma S, Yang GH, Erni D, Meng FY, Zhu L, Wu Q, Fu JH (2017) Liquid crystal leaky-wave antennas with dispersion sensitivity enhancement. *IEEE Trans Compon Packag Manuf Technol* 7(5):792–801
23. Maasch M, Roig M, Damm C, Jakoby R (2014) Voltage-tunable artificial gradient-index lens based on a liquid crystal loaded fishnet metamaterial. *IEEE Antennas Wirel Propag Lett* 13:1581–1584
24. Couch A, Grbic A (2016) A phase-tunable, liquid crystal-based metasurface. In: 2016 10th International congress on advanced electromagnetic materials in microwaves and optics, Chania, Greece, 19–22 Sept 2016, pp 94–96
25. Bildik S, Dieter S, Fritzsche C, Menzel W, Jakoby R (2015) Reconfigurable folded reflectarray antenna based upon liquid crystal technology. *IEEE Trans Antennas Propag* 63(1):122–132
26. Pan W, Huang C, Chen P, Pu M, Ma X, Luo X (2013) A beam steering horn antenna using active frequency selective surface. *IEEE Trans Antennas Propag* 61(12):6218–6223