Liquid Crystal Materials And Tunable Devices For Optical Communications

Fang Du
University of Central Florida

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LIQUID CRYSTAL MATERIALS AND TUNABLE DEVICES FOR OPTICAL COMMUNICATIONS

by

FANG DU
B.S. Nanjing University of Science and Technology, 1994
M.S. Nanjing University of Science and Technology, 1997
M.S. University of Central Florida, 2002

A dissertation submitted in partial fulfillment of the requirements
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Major Professor: Shin-Tson Wu
ABSTRACT

In this dissertation, liquid crystal materials and devices are investigated in meeting the challenges for photonics and communications applications. The first part deals with polymer-stabilized liquid crystal (PSLC) materials and devices. Three polymer-stabilized liquid crystal systems are developed for optical communications. The second part reports the experimental investigation of a novel liquid-crystal-infiltrated photonic crystal fiber (PCF) and explores its applications in fiber-optic communications.

The curing temperature is found to have significant effects on the PSLC performance. The electro-optic properties of nematic polymer network liquid crystal (PNLC) at different curing temperatures are investigated experimentally. At high curing temperature, a high contrast, low drive voltage, and small hysteresis PNLC is obtained as a result of the formed large LC micro-domains. With the help of curing temperature effect, it is able to develop PNLC based optical devices with highly desirable performances for optical communications. Such high performance is generally considered difficult to realize for a PNLC. In fact, the poor performance of PNLC, especially at long wavelengths, has hindered it from practical applications for optical communications for a long time. Therefore, the optimal curing temperature effect discovered in this thesis would enable PSLCs for practical industrial applications. Further more, high birefringence LCs play an important role for near infrared photonic devices. The isothiocyanato tolane liquid crystals exhibit a high birefringence and low viscosity. The high birefringence LC dramatically improves the PSLC contrast ratio while keeping a low drive voltage and fast
response time. A free-space optical device by PNLC is experimentally demonstrated and its properties characterized.

Most LC devices are polarization sensitive. To overcome this drawback, we have investigated the polymer-stabilized cholesteric LC (PSCLC). Combining the curing temperature effect and high birefringence LC, a polarization independent fiber-optical device is realized with over 30 dB attenuation, $\sim12 \ V_{\text{rms}}$ drive voltage and 11/28 milliseconds (rise/decay) response times. A polymer-stabilized twisted nematic LC (PS TNLC) is also proposed as a variable optical attenuator for optical communications. By using the polarization control system, the device is polarization independent. The polymer network in a PS TNLC not only results in a fast response time (0.9/9 milliseconds for rise/decay respectively), but also removes the backflow effect of TNLC which occurs in the high voltage regime.

Another major achievement in this thesis is the first demonstration of an electrically tunable LC-infiltrated photonic crystal fiber (PCF). Two different LC PCF configurations are studied. For the first time, electrically tunable LC PCFs are demonstrated experimentally. The guiding mechanism and polarization properties are studied. Preliminary experimental results are also given for the thermo-optical properties of a LC filled air-core PCF.

In conclusion, this dissertation has solved important issues related to PSLC and enables its applications as VOAs and light shutters in optical communications. Through experimental investigations of the LC filled PCFs, a new possibility of developing tunable micro-sized fiber devices is opened for optical communications as well.
To my parents and sister
ACKNOWLEDGMENTS

I would like to thank to those who contributed and supported my efforts throughout my graduate studies at the College of Optics & Photonics/CREOL. First of all I would like to thank my advisor, Professor Shin-Tson Wu, for his guidance, and support. Thanks to him, I learned not only how to manage difficulties and accomplish challenging research projects but also how to think independently and creatively. From him, I also learned several other things aside from science. His kindness made me to realize how blessed I was to have him as my advisor.

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I would like to express my appreciations to all other colleagues in the Photonics and Display group. Special thanks to Dr. Yuhua Huang, Dr. Ladislav Jankovic, and Mr. George Sieganakis for their professional and personal advice during the very turbulent graduate program. Finally I would like to thank my family and friends for their love, understanding and support through the years. Without them, this dissertation work would have not been accomplished.
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<tr>
<td>CCD</td>
<td>charged coupled device</td>
</tr>
<tr>
<td>CMOS-IC</td>
<td>Complimentary metal oxide silicon-integrated circuit</td>
</tr>
<tr>
<td>CN</td>
<td>Cyano</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense wavelength division multiplexing</td>
</tr>
<tr>
<td>F</td>
<td>Fluoro</td>
</tr>
<tr>
<td>HTP</td>
<td>Helical twisting power</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium-tin-oxide</td>
</tr>
<tr>
<td>ITU</td>
<td>International telecommunication union</td>
</tr>
<tr>
<td>LC</td>
<td>Liquid crystal</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid crystal displays</td>
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<tr>
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<td>Isothiocyanato</td>
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<tr>
<td>PSLC</td>
<td>Polymer-stabilized liquid crystal</td>
</tr>
<tr>
<td>PS TNLC</td>
<td>Polymer-stabilized twisted nematic liquid crystal</td>
</tr>
<tr>
<td>SLM</td>
<td>Spatial light modulators</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>TIR</td>
<td>Total internal reflection</td>
</tr>
<tr>
<td>TN</td>
<td>Twisted nematic</td>
</tr>
<tr>
<td>TNLC</td>
<td>Twisted nematic liquid crystal</td>
</tr>
<tr>
<td>VOA</td>
<td>Variable optical attenuator</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength division multiplexed</td>
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<td>two-dimensional</td>
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PUBLICATION LISTS


CONFERENCE PRESENTATIONS


5. F. Du, S. Gauza and S.T. Wu, “Polymer-stabilized liquid crystal for variable optical attenuator applications”, presented at Optics in southeast 2003


CHAPTER ONE: INTRODUCTION

1.1 Motivation

With the continuously increasing data capacity requirements, optical communication has been put into the forefront of telecommunications. Compact non-mechanical optical devices, such as optical add/drop multiplexers, optical routers, and optical cross-connects etc., are in great demands, particularly for the next-generation dynamically reconfigurable networks. Liquid crystal (LC) material, with low absorption in the infrared region and large electro-optical responses, has been proven to be an important material for optical devices in optical communications. Various LC based devices have been developed, including optical switches, attenuators, filters, and spectrometers [1,2,3,4]. These devices have compact size, low cost, no moving parts and low power consumption. They provide as reliable and comparable performances as the conventional opto-mechanical devices.

Variable optical attenuator (VOA) is a key element in optical communications. It is used for power equalization in optical add/drop modules and optical cross-connects. It can be used to switch on/off channels and protect receivers. In wavelength division multiplexed (WDM) networks, amplifiers have wavelength-dependent gains; thus, VOAs are needed for gain adjustment to equalize power levels in multi-channels. In addition, VOAs are used in dense wavelength division multiplexing (DWDM) systems to control wavelength and output powers of the distributed feedback laser diodes (DFB-LDs). For that purpose several technologies have been investigated, such as microelectromechanical system (MEMS), acousto-optics and electro-
optics. The important parameters for choosing VOAs are low cost, low power consumption, and high speed. Thus LC based VOAs are particularly attractive due to their unique properties and the above-mentioned advantages.

Particular interest is in the relatively new type of LC material, so called polymer-stabilized LC (PSLC). A PSLC consists of a small percentage (<10%) of monomer in a LC mixture. The formed polymer network is anisotropic and has an aligning effect on LC. The presence of polymer network enhances the stability of a LC structure, helps liquid crystal molecules to return to the desired stable configuration and reduces the device response time, and in some cases determines and controls the size of the LC micro-domains within the network structure. Mostly it operates between two states: transparent and scattering state. Depending on the formed polymer network structure and the original LC configuration, two basic device configurations can be achieved and distinguished from the different device functionality under an applied external voltage. In a reverse-mode configuration, applied voltage transfers the initial transparent state (no voltage) to a light scattering state due to the electric-field-induced LC multi-domains. Vice versa, in a normal-mode configuration, the electric field aligns LC molecules from the initial scattering state to a transparent state. PSLCs have been developed for various applications, including displays, shutters, and VOAs [5,6,7]. The major shortcomings of PSLCs are inadequate contrast ratio, relatively high operating voltage and noticeable hysteresis. The performances displayed in optical communication wavelengths are especially poor compared to those at the visible region. It is very difficult to improve the PSLC performances due to the reduced LC birefringence at long wavelength and other conflicting effects caused by a variety of factors, including cell gap, cure conditions, and monomer concentration etc. For example, to
improve contrast ratio, one could use a thicker cell gap. The tradeoff is that both drive voltage and hysteresis would increase. A high monomer concentration helps to get fast response time but typically with a degraded contrast ratio. There is an urgent need to develop new methods for enhancing contrast ratio, reducing operating voltage, suppressing hysteresis, and improving response time of PSLCs.

Due to the birefringence properties of LC materials, most LC based devices are polarization sensitive. In order to obtain polarization independency, polarizers or other polarization control systems have to be used. In a typical case, a polarization beam splitter or a birefringent crystal beam displacer is used to separate and later recombine the ordinary and extraordinary polarization component in order to achieve polarization independency. However, such a scheme requires a precise alignment and a high uniformity LC cell. If the cell is not uniform, the ordinary wave and extraordinary wave would propagate through the cell along different paths resulting in a large polarization dependent loss (PDL). In addition, the use of a polarization control system increases the assembly cost, packaging size and makes it difficult for building arrays. An alternative way to obtain polarization independency is to use polymer-dispersed LCs (PDLCs). A PDLC consists of a large percentage of monomer (>30 wt%) in a nematic LC mixture. After polymerization of the monomer, LC droplets are formed and dispersed in an optically isotropic polymer matrix. Randomly distributed LC directors in each individual droplet cause light scattering no matter of the light polarization. However, PDLCs usually exhibit a high operating voltage (~5 V\text{rms}/\mu m). Such a high voltage is not favorable for the applications in optical communications. Therefore, further development of new configurations of LC based devices with polarization independency is of great practical interests. Especially a single LC cell
approach without any polarization control system would be highly appreciated. It would be compact, inexpensive and easy to integrate.

By applying the band-structure concepts from solid-state physics to optical systems, a novel class of optical materials consisting of multi-dimensional periodic structure, so called photonic crystal, is created. It possesses an energy band-like dispersion structure, which can be used to control electromagnetic wave propagation. Further, through defects within the photonic crystal lattice, one can control where and how electromagnetic waves propagate [8]. When combined with for instance nonlinear effects, photonic crystals provide many potential applications, including white-light supercontinuum generation [9], lasers [10], all-optical circuits [11] and waveguides [12,13].

Both planar and fiber waveguides have been developed based on the photonic crystal technology. A photonic crystal structured planar waveguide has potential to propagate light in a sharp bend fashion at low-loss and is promising to build large-scale integrated circuits or components [11,14]. A photonic crystal fiber (PCF) contains an array of air holes running down the length of the fiber [13]. The air hole lattice structure provides PCFs an additional design freedom offering various light propagation properties by choosing air-hole periodic structure pattern and structural parameters like pitch, core diameter and air holes filling. PCFs exhibit many new properties and can realize many tasks which are impossible for conventional fibers, such as high power laser delivery, supercontinuum generation, super large numerical aperture, particle and gas delivery and sensing [15,16]. It is expected that with the development of PCFs, new generation of fiber-optical systems and components will emerge and strongly affect optical communications. The
potentials of photonic crystals and PCFs have inspired the researchers worldwide to devote themselves to the new physics and applications in this area. Among these new applications, the combination LC and photonic crystals is particularly attractive due to the external-field-controllable refractive index of LC material. The concept was first proposed by Busch and John [17]. Thereafter, it is attracting increasingly more attentions [18,19,20]. Later on, the idea extends to PCF configuration. T. T. Larsen et al proposed and demonstrated for the first time a thermally tunable LC filled PCF showing a shift in the measured photonic bandgap position at small temperature changes [21]. The device demonstrated high temperature sensitivity. A 0.4 °C change in temperature produces a 60 dB attenuation. A precision temperature control module is required in such a system. In fact LC materials exhibit a large electro-optical response, which can be more useful in applications. However, the electro-optical properties of the LC infiltrated PCF are still unknown and need to be explored. That is one of the goals of this dissertation.

1.2 Thesis Overview

The research work discussed in this dissertation covers liquid crystal materials and devices with a goal of meeting challenges in liquid crystal applications for photonics systems and communications. It can be divided into two categories: 1) investigating material properties of LC and 2) developing devices for optical communications. The investigation of PSLCs has helped realizing high performance LC-based optical devices for optical communications. On the other side, the combination of LC and PCF opens possibilities of new categories of photonics systems. It is believed that these devices will find potential applications in commercial markets.
The dissertation is organized as follows. Chapter two gives a brief overview of LC materials. Starting from the history of LC, the liquid crystalline phases and basic physical properties, including birefringence, order parameter, visco-elastic coefficient, and dielectric anisotropy are defined. Following this, the relationships of these physical parameters and their influences on LC threshold voltage and switching time are given. The wavelength and temperature dependence of LC birefringence are described as well. In order to fully understand the formation of LC materials, the main building blocks of typical LC materials are introduced and followed by detailed discussions of the influences of molecular structure on LC physical properties. At the end of this chapter, the electro-optical, thermo-optical and nonlinear optical effects of LC are described.

Chapter three deals with the polymer-stabilized LC (PSLC). Curing temperature and two stage curing process were discovered to have a dramatic influence on polymer-network LC (PNLC) [22]. The influence of curing temperature on the PNLC properties was fully investigated in this chapter. At high curing temperatures, both drive voltage and hysteresis were greatly reduced. The contrast ratio was largely dependent on the operating wavelength and LC micro-domain size. The tradeoff of high curing temperature was the increased response time due to the weakened polymer network effects. Following this discovery, a reflective type PNLC with a high attenuation, low operating voltage, and fast response time was developed for applications at $\lambda=1550$ nm [23]. The isothiocyanato (NCS) tolane was used to enhance the LC birefringence. The high birefringence LC boosted the PNLC performance and was proven to be very important for LC devices in infrared applications. Such a high performance PNLC can be used as shutters,
switchable polarizers and VOAs for optical communications. The only disadvantage of PNLCs is in the fact that they are polarization sensitive.

Therefore in Chapter four a polymer-stabilized cholesteric LC (PSCLC) was proposed to obtain polarization independence [24]. The PSCLC consisted of a helical-structured cholesteric LC and a small percentage of monomer. For a reverse mode PSCLC, at the field-off state, the helical axis of the LC mixture is perpendicular to the cell substrate and the cell is transparent. When a voltage was applied, the cell switched into a focal conic structure where helical axes were randomly aligned and scattered light no matter of light polarization. Various factors, including the chiral dopant, monomer concentration, curing temperature, and LC material were studied to obtain PSCLCs with high attenuation, low drive voltage, and fast response time. At last, a simple, compact, low cost and high quality solution was provided for polarization independent optical devices in optical communications. At the last part of this chapter, an alternative polarization independent LC based system was proposed as a VOA for optical communications [25]. The system was realized by a polymer-stabilized twisted nematic LC (PS TNLC) combining with a polarization control system consisted of two beam displacers. For the first time, the polymer network is incorporated with the twisted nematic LC and their electro-optical properties were investigated. The polarization rotation effect of TNLC was utilized for optical attenuation. The polymer network introduced into the TNLC not only reduced the device response time but also suppressed the back flow effect at high drive voltages.

Chapter five is dedicated to a novel application of introducing liquid crystal into photonic crystal fiber (PCF). At first the background on photonic crystals and PCFs was given. Generally there
are two categories of PCF, the index-guiding PCF and the air-core photonic bandgap (PBG) fiber. Their working mechanisms and advantages over conventional fibers were discussed. Numerous application examples show that PCFs have opened up many new possibilities for fiber-optics and photonics applications. Following the introduction, an experimental investigation of a nematic LC filled photonic crystal fiber was presented [26]. For the first time, an electrically tunable LC PCF was proposed and demonstrated. A LC mixture was filled into an air-core PBG fiber. After filling with LC, the guiding mechanism changed from its original PBG effect to total internal reflection (TIR). With an applied voltage, the disturbance of LC molecules in the fiber demonstrated a dramatic influence on the guided light. In the field-off state, the LC-filled PCF guided light in the fiber core. When a sufficiently high voltage was applied, the guided light gradually coupled out to the cladding LC-filled holes and finally escaped from the fiber. Therefore, a miniaturized high attenuation fiber optical switch was realized. The thermo-optical properties of such a fiber system were also investigated. It was found that as the temperature approaching the clearing temperature $T_c$ of the employed LC, the guided light in the fiber core became unstable due to the strong microscopic molecular movements during phase transition. At $T_c$, the guiding effect was destroyed. Such a system is nonreversible. Experimental observations were given and analyzed. Additional measures are needed to stabilize the system. This investigation only gives a preliminary idea and should be further studied. In the last section of this chapter, a preliminary study of the electro-optical properties of a nematic LC PBG fiber was presented. A nematic LC mixture was filled into an endlessly single mode PCF. As a result of the LC filling, the core refractive index became smaller than that of the cladding. The original single mode fiber became a PBG fiber. The electro-optical properties and spectrum of such a fiber
system were measured and analyzed. The potential applications of LC PCFs were emphasized at the end of the chapter.

In Chapter six a thorough summarization of the dissertation work was given.

1.3 References


CHAPTER TWO: LIQUID CRYSTAL OPTICS

The history of LC can be dated back to around 150 years ago when Virchow, Mettenheimer and Valentin noticed that a strange behavior occurred when a polarized light was used in observation of a liquid substance formed by a nerve fiber. This is actually the first observation of LC. But at that time the observation did not draw too much attention. Even later in 1877, it was still not realized that a new phase of substance was discovered when Otto Lehmann found that a substance changed from a clear state to a cloudy state when temperature was decreased to crystalline transition temperature. The study of LC started in 1888 when Friedrich Reinitzer, an Austrian botanist, performed an experiment where he observed that cholesteryl benzoate changed from a solid state to a cloudy liquid when temperature was increased and eventually changed to a clear liquid as temperature was further increased. He was the first person who suggested that this hazy liquid was a new phase of substance and thus he is credited with discovering the LC phase. With over 100 years’ history, variety of LC materials have been studied and synthesized. They attract a lot of attentions due to the unique electro-optical and thermo-optical properties and have been used in numerous applications, such as liquid crystal displays (LCDs) for televisions, projectors, watches, cell phones, spatial light modulators (SLMs) for adaptive optics in real time optical imaging, optical switches and attenuators for telecommunications, and optical phase arrays (OPAs) for beam steering, etc. The research of LC materials and devices is of importance not only to the quality of our daily life but also to the development of the whole society.
2.1 Liquid Crystal Phase

Compare to liquid state, where molecules have no intrinsic order and are free to move in a random fashion, LC exhibits some degree of positional or orientational order. For a crystalline state, molecules are arranged in a lattice with high positional and orientational orders. LC is between solid and liquid with molecules having a tendency to point along a common axis, so called the director. The illustration of the comparison of liquid, solid and LC is shown in Figure 2-1.

![Illustration of liquid, solid, and liquid crystal](image)

(a) Solid  (b) Liquid crystal  (c) Liquid

Figure 2-1: The illustration of the arrangement of molecules of liquid, solid and liquid crystal.

Three types of LC materials have been discovered: thermotropic, lyotropic, and polymeric. Among them, thermotropic LC is the most extensively studied where phase changes from solid to LC and to isotropic liquid as temperature increases. The temperature when a thermotropic LC changes from solid to LC is called melting temperature \( T_M \) and from LC to isotropic liquid is clearing temperature \( T_c \). Several thermotropic phases exist in LCs, such as nematic, chiral nematic (cholesteric), smectic, and chiral smectic. When a LC is in the nematic phase, molecules are distributed with a degree of orientational order but without positional order as depicted in Figure 2-1 (b). The average direction of the LC molecules orientation is called the director. The
order parameter $S$ is used to quantify how much order the material has. In a liquid substance, molecules are aligned randomly thus the order parameter $S=0$. In a solid, molecules have a fixed positional and orientational order so that $S=1$. For a LC material the order parameter is usually between 0.3 and 0.9. The alignment of LC molecules can be influenced by pretreatment of alignment layer, external electric field, magnetic field, and optical field. If there is no alignment, LC appears to be cloudy due to light scattering.

Chiral nematic LC, also called cholesteric LC, consists of a nematic LC mixture with a chiral dopant. Cholesteric LC molecules possess the orientational order as in nematic LC. In addition, they have a helical structure where directors rotate through the material in a periodic manner as shown in Figure 2-2. The distance along the helical axis over which the director rotates $360^\circ$ is the pitch $p$. It is defined by the following equation:

$$p = \frac{\langle n \rangle}{c \cdot HTP}$$  \hspace{1cm} (2-1)$$

where HTP is the helical twisting power of the chiral dopant, $c$ is the relative concentration in weight percentage, and $\langle n \rangle$ is the average refractive index of the mixture.
Figure 2-2: Schematics of chiral nematic (cholesteric) phase of LC.

Due to its periodicity along the light propagation direction, the helical structure of cholesteric LCs reflects the incident light at wavelengths centered at $\lambda = n \cdot p$. However, the reflection resulted from the helical structure of cholesteric LCs is more complex than that for a usual Bragg reflector. For the light satisfying the Bragg reflection condition, only circularly polarized light with the same handedness as that of the cholesteric LC is reflected, and the other handedness circularly polarized light is transmitted. For example, a left-handed helical structure reflects the left circularly polarized incident light, and transmits the right circularly polarized light. This property makes cholesteric LCs unique bandpass reflectors/polarizers for the circularly polarized light. Another important feature of cholesteric LCs is that the pitch length changes with temperature. When the temperature is increased, pitch is decreased and vice versa, which accordingly shifts the corresponding reflected wavelength. Based on this property, cholesteric LCs can be used to develop thermometers or tunable filters.
In a smectic phase, the LC molecules exhibit not only an orientational order but also a layered structure as shown in Figure 2-3. Several smectic phases exist and are labeled in alphabet order. As an example, smectic A phase has the director normal to the layered structure and a random lateral distribution of molecules in each layer. Smectic-C is similar to smectic A except that directors are tilted with respect to the normal of the layer. When a helical structure is added in the smectic C phase, the so called ferroelectricity is presented which generally exhibits a submillisecond or even microsecond switching time and thus attracts significant attention. However, the smectic phase of LC is not related to the research work presented here and will not be covered in details in this dissertation. Detailed properties and applications of ferroelectric LC can be found in Ref. [1].

### 2.2 Physical Properties of Liquid Crystals

Birefringence, elastic constant, dielectric anisotropy, and viscosity are several key parameters affecting the performances of LC devices. The following paragraphs will give an overview of the basic physical properties of LC materials.
In order to describe the birefringence dispersion of LC, Wu proposed the single- and the three-band models [2,3]. The single-band model describes wavelength and temperature-dependent birefringence, while the three-band model considers the contributions of each electronic transition band to refractive indices and birefringence, respectively. Based on these models, a LC birefringence is mainly determined by the molecular conjugation, differential oscillator strength, and order parameter. The wavelength-dependent birefringence is given by the single-band model [2] as:

$$\Delta n(\lambda) = G \frac{\lambda^2 \lambda^*}{\lambda^2 - \lambda^*^2}$$

with $G = gN\tau S(f^*_{//} - f^*_{\perp})$. $g$ is the proportionality constant, $N$ is the molecular packing density, $Z$ is the effective number of participating electrons ($\sigma$ or $\pi$ electrons), $S$ is the order parameter, $f^*_{//} - f^*_{\perp}$ is the differential oscillator strength, and $\lambda^*$ is the mean electronic transition wavelength.

In order to visualize how LC birefringence changes with wavelength, the wavelength dispersion curve for LC BL038 is depicted in Figure 2-4. BL038 is a commercial high birefringence LC material from Merck. It has a clearing temperature $T_c=100 \, ^\circ\text{C}$, birefringence $\Delta n=0.2720$, ordinary refractive index $n_o=1.5270$, and dielectric anisotropy $\Delta \varepsilon=16.9$ ($\lambda=589\text{nm}$ and $T=20\, ^\circ\text{C}$ ).

In the figure, the purple dots are experimental data and the black solid line is the theoretical fitting curve from equation 2-2. It can be seen that both experimental data and theoretical results match very well. The fitting parameter $\lambda^* = 250 \, \text{nm}$. The birefringence decreases as the wavelength increases and saturates at infrared region where $\lambda >> \lambda^*$. 
Packing density \( N \) depends on the molecular constituents, size, shape, and intermolecular association. A LC compound with a shorter side chain may exhibit a higher birefringence due to the large packaging density, provided that the core structure remains the same. The effective number of participating electrons also represents the conjugation length, \( \sigma \) to \( \sigma^* \) and \( \pi \) to \( \pi^* \) electronic transitions are the most important ones affecting refractive indices and birefringence. The \( \sigma \) to \( \sigma^* \) transition, existing in a LC material with saturated bonds (such as cyclohexane), has a very short resonance wavelength \( \sim 125 \) nm in the vacuum UV region resulting in a small birefringence (small \( \lambda^* \)). In addition, \( \sigma \) to \( \sigma^* \) transition has a large oscillator strength but a small anisotropy, thus it has a large contribution to refractive indices rather than to birefringence. On the other side, \( \pi \) to \( \pi^* \) electronic transition, existing mostly in LCs with unsaturated bonds (such as phenyl ring), has a long resonance wavelength in UV region or even in visible region. It has a larger anisotropy compared to the \( \sigma \) to \( \sigma^* \) transition. Due to the long resonance wavelength \( \lambda^* \),
and large differential oscillator strength $f^*_{\parallel} - f^*_{\perp}$, $\pi$ to $\pi^*$ transition has dominant contributions to LC birefringence.

A long molecular conjugation length means a large $\lambda^*$ thus a high birefringence. However in order to get a long molecular conjugation length, the length of LC molecules needs to be increased resulting in a small packing density $N$, which has a negative effect on enhancing birefringence. In addition, LC with a long conjugation length tends to have high melting temperature which is unfavorable for forming LC mixtures. Thus one has to bear in mind that in order to formulate a high performance LC material, molecular constituents, shape and size have to be taken into consideration carefully. It is a state of art to optimize all physical properties of LC and a challenging task as well.

Temperature is another important factor affecting LC birefringence. Birefringence is a function of order parameter $S$. The order parameter $S$ is given by:

$$S = (1 - T / T_c)^\beta \quad (2-3)$$

where $T_c$ is the clearing temperature and $\beta$ is the material constant. The birefringence is defined by the following equation:

$$\Delta n(T) = \Delta n_0 \cdot S = \Delta n_0 \cdot (1 - T / T_c)^\beta \quad (2-4)$$

where $\Delta n_0$ is the birefringence at $T=0$ K. From above equations, it can be seen that as the temperature increases, birefringence gradually decreases. The change in birefringence becomes very steep when the temperature is approaching the clearing point $T_c$ as shown in Figure 2-5. The
solid line is theoretically fitted by equation 2-4 at $\beta=0.22$ and $\Delta n_0=0.39$. For a mixture with high $T_c$, its birefringence would be higher due to the higher order parameter.

![Temperature-dependent birefringence of LC BL038](image)

Figure 2-5: Temperature-dependent birefringence of LC BL038. Purple dots are experimental data and black solid line is theoretical fitting curve.

Dielectric anisotropy $\Delta \varepsilon$ and elastic constant $K$ are another two important LC parameters. Together they determine the LC device threshold voltage by the following formula:

$$V_{th} = \pi \sqrt{\frac{K}{\varepsilon_0 \Delta \varepsilon}}$$

(2-5)

The dielectric anisotropy $\Delta \varepsilon = \varepsilon_\parallel - \varepsilon_\perp$ can be positive or negative depending on the molecular structure and operating frequency. The frequency of the applied external voltage at which $\Delta \varepsilon$ changes sign is called the crossover frequency. For a LC with $\Delta \varepsilon >0$, when an external voltage is applied the LC directors tend to align along the field. Whereas for a LC with $\Delta \varepsilon <0$, directors tend to align perpendicular to the field.
There are three basic types of LC molecular alignments: homogeneous, homeotropic, and twisted alignments. Several technologies have been developed to introduce alignment in LC cell. For example, a mechanically buffed polyimide film can be used to provide anti-parallel alignment for homogenous cells, whereas a dipping method (surfactant) [4] or SiO₂ evaporation technique [5] is used to obtain a homeotropic alignment. The molecular alignment of LC in these three basic cell configurations is depicted in Figure 2-6. A homogeneous LC cell has an anti-parallel aligning arrangement on the top and bottom substrates thus LC directors are aligned parallel to cell substrates. A homeotropic LC cell has vertical alignment treatments on both substrates and LC molecules are aligned normal to the substrates. Generally, in order to utilize such an alignment, a negative $\Delta \varepsilon$ LC material is needed. A positive $\Delta \varepsilon$ LC can be used in a homeotropic cell if the cell operates in an in-plane switching (IPS) mode [6]. In a twisted LC cell, the molecular alignment in the top and bottom substrates is twisted by an angle $\theta$. The angle $\theta$ can be any value. However the most commonly used ones are 45°, 90°, 180° and 240° (super twisted). For a 90° twisted cell, the LC directors rotate 90° from the top to the bottom substrate as depicted in Figure 2-6.

![Diagram of LC alignments](image)

Figure 2-6: Demonstrations of three basic surface alignments of LC.
These three surface alignments correspond to three different elastic constants: splay elastic constant $K_{11}$ for homogeneous cells, twist elastic constant $K_{22}$ for twisted nematic cells, and bend elastic constant $K_{33}$ for homeotropic cells. $K_{11}$, $K_{22}$, and $K_{33}$ have the following relationship:

$$K_{33} > K_{11} > K_{22}$$  \hspace{1cm} (2-6)

A small elastic constant is favorable to achieve a low operation voltage according to equation 2-5. However the response time of a LC mixture is proportional to $1/K$, as defined in equation 2-7. A small elastic constant leads to a slow response time. Therefore, a homeotropic cell may exhibit the fastest response time among its counterpart homogeneous and twisted cell, provided that the cell gap and rotational viscosity are the same. However the threshold $V_{th}$ is increased.

$$\tau_{on} = \frac{\gamma_1 d^2}{K \pi^2} \frac{1}{(V/V_{th})^2 - 1}$$

$$\tau_{off} = \frac{\gamma_1 d^2}{K \pi^2}$$  \hspace{1cm} (2-7)

From equation 2-7, both “field-on time” $\tau_{on}$ and “field-off time” $\tau_{off}$ are proportional to $\gamma_1 / K$, where $\gamma_1$ is the rotational viscosity and $K$ is the elastic constant. In addition, “field-on time” is dependent on the applied electric field. Due to the electric field effect, $\tau_{on}$ is usually faster than $\tau_{off}$. $\gamma_1 / K$ is also called visco-elastic coefficient which is a very important value in determining response time of LC devices. By using a low viscosity LC mixture or operating a LC mixture at an elevated temperature, a small visco-elastic coefficient can be obtained. As a consequence, response time is reduced. Both viscosity and elastic constant are found to be dependent on the order parameter $S$ and can be approximated as:
\[ \gamma_1 \sim S \cdot \exp \left( \frac{E}{kT} \right) \quad (2-8) \]

\[ K \sim S^2 \quad (2-9) \]

where \( E \) is activation energy and \( k \) is Boltzmann constant. Thus the visco-elastic coefficient is:

\[ \frac{\gamma_1}{K} \sim \frac{\exp\left(\frac{E}{kT}\right)}{(1-T/T_c)^{\beta}} \quad (2-10) \]

Figure 2-7 gives the visco-elastic coefficient of BL038. As can be seen from the figure, \( \gamma_1/K \) decreases as the temperature increases. When the temperature increases from \( T=20 \, ^\circ C \) to \( T=70 \, ^\circ C \), the visco-elastic coefficient drops from \( \gamma_1/K = 37 \) to \( 5 \). Since LC switching time is proportional to the \( \gamma_1/K \) value, as a result, a fast response time is achieved by the reduced visco-elastic coefficient at an elevated temperature. In the case of BL038, the response time is reduced \( >7 \times \) when operating at \( T=70 \, ^\circ C \) instead of the room temperature.
Figure 2-7: Temperature-dependent visco-elastic coefficient $\gamma_1/K$ of BL038. Purple dots are experimental data and black solid line is theoretical fitting curve.

An alternative way to characterize the performance, especially the response time, of a LC mixture is to define a figure of merit. It is given by:

$$\frac{K \cdot \Delta n^2}{\gamma_1} \sim \Delta n^2 \cdot (1 - T/T_c)^3 \cdot \exp(-E/kT)$$

(2-11)

From above discussions, it can be seen that elastic constant, viscosity and birefringence are all dependent on temperature. Accordingly the figure of merit depends on temperature strongly. The temperature-dependent figure of merit for BL038 is depicted in Figure 2-8. At low-temperature region, even though birefringence, dielectric anisotropy, elastic constants and viscosity all drop as increasing temperature, the dropping speed of visco-elastic coefficient $\gamma_1/K$ is faster than that of $(\Delta n)^2$. Therefore the figure of merit first increases with increasing temperature and reaches a maximum value at $\sim 84$ °C. As the temperature approaches the clearing temperature $T_c$, 

24
birefringence has very steep drop as shown in Figure 2-5 which causes a sharp decrease in the figure of merit as well. The higher figure of merit a LC possesses, the faster response time it exhibits. Thus operating a LC device at an elevated temperature is beneficial for reducing response time. However, it brings complication to the driving scheme by the additional temperature control system.

![Temperature-dependent figure of merit of BL038. Purple dots are experimental data and black solid line is theoretical fitting curve.](image)

**Figure 2-8:** Temperature-dependent figure of merit of BL038. Purple dots are experimental data and black solid line is theoretical fitting curve.

### 2.3 Molecular Structures of Liquid Crystal Materials

LC molecular structure affects greatly the physical properties of a LC material, including the LC phase, transition temperature, birefringence, viscosity, dielectric anisotropy, photostability etc. As mentioned before, it is easy to optimize one property but a challenging task to get overall performance. Details will be discussed in this section.
A typical LC material has a molecular structure as shown in Figure 2-9. R1 is the side chain, R2 is the terminal group and X is the linking group. A and B are aromatic rings. The commonly used building blocks of LC are listed in Table 2-1.

![Molecular Structure of LC Compound](image)

Figure 2-9: The typical molecular structure of a LC compound.

Several commonly used side chains are alkyl (C\(_n\)H\(_{2n+1}\)), alkoxy (C\(_n\)H\(_{2n+1}\)O), alkenyl (C\(_n\)H\(_{2n-1}\)) and alkenyloxy (C\(_n\)H\(_{2n-1}\)O). The length and flexibility of a side chain affect the phase transition temperature and the type of mesogenic phase as well. A long side chain usually has a low melting temperature T\(_M\). However the lack of flexibility tends to have a high T\(_M\). Aromatic rings include totally saturated cyclohexanes, cyclocyclohexanes, unsaturated phenyls, biphenyls, terphenyls, or combinations of cyclohexanes and phenyls. The length of the aromatic ring affects T\(_M\) as well. Usually, a LC with longer ring shows a higher T\(_M\). In addition, different aromatic ring affects the LC properties in a different way. For example, a saturated cyclohexane ring contains only \(\sigma\)-electrons. As discussed in section 2.2, \(\sigma\) to \(\sigma^*\) electronic transitions have a very short resonance wavelength resulting in a small birefringence. In addition, cyclohexane ring increases the rotational viscosity due to the large moment of inertia. On the other hand, a phenyl ring consists of both \(\pi\)-electrons and \(\sigma\)-electrons. \(\pi\) to \(\pi^*\) electronic transition has a long resonance wavelength and a large anisotropy resulting in a large contribution to birefringence [6].
Table 2-1: The building blocks of LC materials.

<table>
<thead>
<tr>
<th>R1</th>
<th>A</th>
<th>X</th>
<th>B</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkyl</td>
<td>cyclohexane</td>
<td>O</td>
<td>Alkyl</td>
<td>Alkyl</td>
</tr>
<tr>
<td>(C\textsubscript{n}H\textsubscript{2n+1})</td>
<td></td>
<td>C=O</td>
<td>Alkoxy</td>
<td>Alkoxy</td>
</tr>
<tr>
<td>Alkoxy</td>
<td>Phenyl</td>
<td>C\textsubscript{2}H\textsubscript{4}</td>
<td>CN</td>
<td>CN</td>
</tr>
<tr>
<td>(C\textsubscript{n}H\textsubscript{2n+1}O)</td>
<td></td>
<td>CH=CH</td>
<td>F, Cl</td>
<td>F, Cl</td>
</tr>
<tr>
<td>Alkenyl</td>
<td>biphenyl</td>
<td>N=N</td>
<td>CF\textsubscript{3}</td>
<td>CF\textsubscript{3}</td>
</tr>
<tr>
<td>C\textsubscript{n}H\textsubscript{2n-1}</td>
<td></td>
<td>CH=CH</td>
<td>OCF\textsubscript{3}</td>
<td>OCF\textsubscript{3}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=O</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NCS</td>
<td>NCS</td>
</tr>
</tbody>
</table>

The substitution of hydrogen atoms at different positions on a phenyl ring will significantly change the magnitude and sign of the dielectric anisotropy $\Delta\varepsilon$. In a polar compound, $\Delta\varepsilon$ depends on the dipole moment and its angle $\theta$ with respect to the principle molecular axis, temperature and the applied electric field frequency. $\Delta\varepsilon$ is positive at $\theta<55^\circ$ and negative at $\theta>55^\circ$. By substituting the (2,3) positions by fluoro (F) groups, a negative $\Delta\varepsilon$ is obtained. The relatively large dipole moment of F results in an enhanced dielectric anisotropy. However, the short electronic resonance wavelength of the fluor substituted LC leads to a reduced birefringence and refractive indices.

A LC single compound can have one or more aromatic rings. Aromatic rings can be linked by the linking groups listed in Table 2-1. Saturated linking groups do not contribute electrons to
aromatic rings thus their influence to birefringence is weak. On the other side, unsaturated double and triple bonds contribute \( \pi \) electrons resulting in an elongated conjugation length and thus an enhanced birefringence.

Among the terminal groups listed in Table 2-1, alkyl, alkoxy and sulfide are weak polar groups and have a weak influence on dielectric anisotropy. Alkyl group does not contain any \( \pi \) electrons and shows a slightly shorter conjugation length compared to alkoxy group, cyan (CN), isocyanate (NCS), and fluor (F) are strong polar groups which lead to a large dielectric anisotropy. CN has almost 3X larger dipole moment than that of F group, thus CN group shows much larger dielectric anisotropy than F group. Dielectric anisotropy is an important factor affecting the threshold voltage of LC devices according to equation 2-5. Large dielectric anisotropy produces small drive voltage which is favorable for applications. Considering its influence on birefringence, CN is an electron acceptor and tends to increase conjugation length, consequently enhance the birefringence. On the other side, F group is an electron donor and has a contrary effect on conjugation length and birefringence. CN and NCS have some similarities, such as: (1) both contain \( \pi \) electrons leading to a long electronic resonance wavelength thus an enhanced birefringence and (2) both exhibit large dipole moment thus a large dielectric anisotropy. However, usually NCS group has a longer conjugation length and much lower viscosity than that of CN group. Therefore the NCS compound is very useful in formulating high birefringence and low viscosity LC mixture as will be discussed and demonstrated in Chapter three. A shortcoming of NCS compounds is that they are more difficult to synthesize.
From above discussions, one can see that molecular structures greatly influence the birefringence and dielectric anisotropy of a LC. Actually it affects the viscosity as well. Generally a LC mixture with a small molecular size or weight may have a high birefringence and a low viscosity. A long side chain, even though showing a low melting temperature, possesses a large moment of inertia. As a result, the viscosity is high. Increasing the number of dipole groups increases the dielectric anisotropy and lowers the threshold voltage. However it increases the moment of inertia and leads to a high viscosity. In addition, a linear LC molecular structure might have low viscosity but its melting temperature could be high due to the lack of flexibility. Therefore, the relationship of molecular structure with the physical properties of LC material is quite complicated. On one hand, the molecular structure effects are conflicting with each other, but on the other hand they are interrelated in some degrees. It is very challenging to optimize all the parameters simultaneously. The tradeoffs in molecular designs have to be optimized in order to compromise the conflicting physical properties required for practical applications.

2.4 \textbf{External Forces on Liquid Crystal Modulations}

LC properties can be controlled by various external forces, such as temperature, electric field, magnetic field, light intensity (optical nonlinearity) and light polarization (optical anisotropy). The influence of temperature on birefringence change has been discussed in section 2.2 and is described by equation 2-4. To investigate the temperature influence on refractive index, Khoo and Normandin developed a semi-empirical model to describe the dielectric constants of LC [7]. Recently Li et al. developed a more comprehensive model [8] based on Vuks equation [9]. For most LC materials, the extraordinary refractive index $n_e$ decreases with increasing temperature.
However, the ordinary refractive index $n_o$, depending on the LC material and operating temperature, has either positive or negative temperature gradient.

When an external electric field is applied, the polar LC molecules tend to align along or perpendicular to the field depending on the sign of the dielectric anisotropy. As a result the refractive index of LC is changed. The deformation of LC molecules starts when the strength of the electric field is larger than a certain threshold, so that it overcomes the elastic and viscoelastic forces of liquid crystals. This threshold is called the Freedericksz threshold and the transition from an undistorted director configuration to a distorted one is called the Freedericksz transition. The electro-optic switching behavior of a nematic LC is generally governed by the competing forces among the surface anchoring force, the elastic restoring force, and the applied electric field. The elastic restoring force depends on the director deformation of LC. A larger deformation results in a stronger elastic restoring force.

LCs exhibit large optical nonlinearities as well due to their high dielectric anisotropy and strong molecular correlation [10]. An incident light disturbs the LC director orientation, temperature, density, etc. producing an extraordinarily large nonlinear refractive index change even under a continuous-wave or a long-pulse laser [11,12]. The refractive index change is sensed by the incident light and the optical properties are changed consequently. The disturbance of director orientation comes from the realignment of LC molecules under a polarized laser light due to the large anisotropy of LC. The temperature change originates from the absorption of laser light and the thermo-dynamical coupling with the density change. Such a temperature change, in turn, causes the change of refractive index and birefringence, as discussed in section 2.2. In order to
enhance the nonlinear effect of LC, a small amount of dye can be added to strengthen the optical-field induced reorientation [13,14]. Dye molecules produce an additional torque to assist LC director reorientations. The induced additional torque can be orders of magnitude larger than the optical torque. Photorefractive materials including liquid crystals, polymers, and liquid crystal/polymer composites have been developed. The optical nonlinear effects of LCs are particularly interesting for all-optical configurations as image processing, optical limiting, optical storage and sensor protection.

2.5 References


CHAPTER THREE: POLYMER-NETWORK LIQUID CRYSTAL

Polymer-network LC (PNLC) is an important extension of pure LC systems. They offer more flexibility and much richer functionality than LC systems alone. The complexity of PNLC systems make them difficult to be completely understood. The properties of PNLCs are affected by a number of factors. This chapter provides the understanding and optimizing of such systems. An order of magnitude improvement in PNLC performances has been demonstrated. That makes PNLCs to be finally applicable.

3.1 Introduction of Liquid crystal/Polymer Composites

LC/polymer composites, consisting of LC and monomer, have a wide range of applications, including flexible displays, switchable windows, tunable lenses, optical switches and so on [1,2,3,4]. Depending on the monomer concentration, LC/polymer composites can be divided into two main categories: polymer-stabilized LC (PSLC) [5] and polymer-dispersed LC (PDLC) [6]. PDLCs consist of a high percentage of monomer (>30 wt%) mixed in a LC mixture. An appropriate monomer material should be chosen so that its refractive index \(n_p\) is close to the ordinary refractive index \(n_o\) of the LC. After polymerization, LC micro-sized droplets are formed and dispersed in an optically isotropic polymer matrix. The droplet size and shape are determined by the composition of the PDLC material and condition of the cell fabrication. For example, a high intensity UV irradiation generates small droplets. The LC director axes within an individual droplet are determined by the interaction of LC and polymer at the boundary of the droplet. PDLCs can be operated between a transparent and a scattering state as shown in Figure 3-1. In the voltage-off state, the PDLC material scatters light due to a random distribution of LC.
directors within each individual droplet. When a sufficiently high voltage is applied, all molecules are aligned along the field. In this case, light is transmitted because of the refractive index match between monomer and LC material. PDLC is independent of polarization which is very attractive for many applications, especially for fiber optical communications where polarization dependent loss is an important issue. However PDLCs usually possess a high operating voltage (~5 Vrms/µm).

Figure 3-1: The schematics of PDLC working mechanism. (left) LC droplets in polymer matrix, LC directors are randomly oriented in each individual droplet, incident light is scattered. (right) LC molecules are aligned along the external electric field, incident light is transmitted.

PSLC usually consists of a less than 10 wt% of monomer. After polymerization, an anisotropic, cross-linked polymer network structure is formed. Depending on the surface alignment and initial configuration of the LC cell, different polymer networks are stabilized following the initial distribution of LC directors. The presence of a polymer network in a PSLC not only enhances the LC structure stability, but also helps the LC molecules to return to a desired stable configuration resulting in a reduced response time. Similar to PDLC, PSLC can also be switched between a scattering and a transparent state. The light scattering originates from the LC micro-domains.
within the polymer network structure. Depending on the initial configuration, external voltage is applied either to induce LC multi-domains (index mismatch, scattering state) or to realign LC molecules in a uniform state (index match, transparent state).

### 3.2 Polymer Network Liquid Crystals

The most common PSLC is polymer-network LC (PNLC), representing a polymer-stabilized nematic LC. In a reversed-mode PNLC, a low concentration (<10%) of diacrylate monomer and a small amount of photo-initiator are dissolved in a nematic positive LC host and then injected to an empty cell with homogeneous alignment. Due to the anchoring effect of the alignment layer, LC molecules are aligned parallel to the rubbing direction. A weak UV light is used to induce photo-polymerization. Under the illumination of UV light, free radicals released by the photo-initiator react with the double bonds of the monomer and initiate a chain reaction of polymerization. After polymerization, polymer network is formed parallel to the glass substrate following the LC director direction.
Figure 3-2: Working mechanism of a reverse mode PNLC. (left) Polymer network has the same orientation as LC directors, incident light is transmitted. (right) LC multi-domains are formed under the influence of electric field, light with polarization parallel to the rubbing direction is scattered and the orthogonal polarization is transmitted.

Figure 3-2 depicts the working mechanism of a reverse-mode PNLC. In the voltage-off state, polymer networks and LC molecules have the same orientation and the cell is highly transparent. When a voltage is applied, polymer networks resist LC directors from being reoriented by the electric field. As a result, micro-domains (also called poly-domains) are formed. Under such conditions the threshold voltage increases. Since the monomer has similar refractive index to the ordinary refractive index of LC, the orthogonally polarized light does not see any refractive index mismatch and is transmitted. On the contrary, the parallel polarized light encounters index mismatch between the monomer and the extraordinary refractive index of LC and is scattered. PNLC exhibits an anisotropic light scattering behavior and can be used as VOAs for communication, reflective displays, and switchable polarizers for sensor protection [7].

The major shortcomings of the existing PNLCs are inadequate contrast ratio, relatively high operating voltage and noticeable hysteresis. A ~10.5 µm PNLC cell shows ~300:1 contrast ratio,
~12 $V_{rms}$ drive voltage for visible wavelength ($\lambda=632.8$ nm) [7]. However, for operating at infrared wavelength, the performance drops dramatically. Typically, a 15 $\mu$m PNLC cell shows a contrast ratio <100:1 and a drive voltage ~20 $V_{rms}$ at $\lambda=1550$ nm. A thick cell gap can be used to improve the contrast ratio. The tradeoff is that drive voltage, hysteresis and response time increase. The drive voltage needs to be reduced in order to lower the cost of power supplies. Typically the output voltage is $< 20 V_{rms}$ for a widely used amplifier, $< 10 V_{rms}$ for a complimentary metal oxide silicon-integrated circuit (CMOS-IC), and $< 7 V_{rms}$ for an active matrix addressed flat panel displays. Normally a contrast ratio that exceeds 1000:1 and a drive voltage less than 10 $V_{rms}$ are desirable for applications in industry. There is an urgent need to develop new methods for enhancing the contrast ratio, reducing the operating voltage, and suppressing the hysteresis of PNLCs.

In the work reported here it was discovered that the curing temperature is of great importance in order to control the electro-optical properties of PNLCs. A two-stage curing process was invented to fabricate PNLCs resulting in a high contrast ratio (>1000:1), low operating voltage (~10Vrms), and small hysteresis. Compared to the conventionally fabricated PNLC, the new fabrication method introduced here produces a dramatic improvement on PNLC performances. This solves the shortcomings of PNLC and enables its application in optical communications. The following sections will give abundant experimental results and analyses to the influence of curing temperature on PNLC.
3.3 **Curing Temperature Influences on Polymer Network Liquid Crystals**

In the experiment, the PNLC mixture was consisted of a 4 wt% of bisphenol A dimethacrylate monomer and 96 wt% Merck E48 LC mixture ($\Delta n=0.23$ at $\lambda=589$ nm). The mixture was injected into an 8-µm-thick homogeneous cell. Due to the surface alignment of homogeneous cell, LC directors are aligned parallel to the cell substrate and monomer molecules follow the LC orientation. A weak UV light (100 µW/cm$^2$) was used to induce polymerization. A two-stage curing process was utilized. For the first half an hour the cell was kept at an elevated temperature on a heating stage during the UV illumination. This procedure increased the solubility of the monomer in the LC and generated larger dispersion of LC and polymer. After the first 30 minutes of the UV exposure at the elevated temperature, the cell was further polymerized at room temperature for another 5.5 hours to stabilize the polymer network. The cell was highly transparent after the photo-polymerization.

A linearly polarized He-Ne laser beam was used to characterize the PNLC performance. The laser polarization axis is parallel to the LC cell’s rubbing direction. A large area detector was placed behind the cell with a $\sim 2^\circ$ collection angle. The voltage-dependent light transmission was recorded by a computer-controlled LabVIEW system.
Figure 3-3: The voltage-dependent transmittance of the E48 PNLC at 23, 32, 50 and 70°C curing temperatures (from right to left). Cell gap d=8 µm, monomer concentration 4 wt%, laser wavelength \( \lambda = 633 \) nm and measurement temperature \( T = 23°C \).

Figure 3-3 plots the normalized transmittance of the two-stage fabricated 8-µm-thick PNLC cells. Their curing temperatures are 23, 32, 50, and 70°C, respectively, from right to left: The optical losses from glass substrate reflections were neglected. In the voltage-off state, the cell was highly transparent and transmittance was \( \sim 1 \). When the applied voltage was increased above the threshold, micron-sized LC domains were formed as a result of the competition between the polymer network and the electric field torque. In this case, the laser beam was scattered and transmittance dropped to almost zero. The cell acted like a tunable linear polarizer. As the curing temperature was increased from 23 to 70°C, the dark state voltage was reduced from 11.9 to 5.5 \( V_{\text{rms}} \) as shown in Figure 3-3. At high curing temperatures monomer has a fast diffusion rate and produces coarse polymer networks. As a result, the electric-field-induced LC domain sizes are
large. For a large LC domain, the aligning effect of a polymer network is weak thus a small electric field torque is sufficient to reorient the LC molecules in the multi-domain structure, which results in the reduced dark state voltage. Such a low drive voltage enables the PNLC cells to be addressed by the amorphous silicon thin-film-transistors for displays.

Figure 3-4 shows the curing temperature-dependent contrast ratio of the 8-µm-thick E48 PNLC cells with 4 wt% monomer concentration. Due to the fact that the working principle of PNLC is based on light scattering, the device contrast ratio is highly dependent on the scattering efficiency of the LC micro-domains. If the micro-domain size is comparable to the operating laser wavelength, the maximum light scattering efficiency occurs [8]. A high temperature curing process produces coarser polymer networks and, in turn, generates larger LC micro-domain sizes. For the 8µm E48 PNLC, without the two-stage polarization process, it showed a contrast ratio ~70:1 at ~12 V_{rms}. When the curing temperature was increased, the contrast ratio was also enhanced. For the cell prepared at the T=50 °C curing temperature, the contrast ratio was improved by ~30X. However, as the curing temperature continued to increase to 70 °C, the contrast dropped down to ~400:1 as shown in Figure 3-4. The reason for the reduced contrast ratio at too high curing temperature is that the LC domain size becomes too big in comparison to the He-Ne laser wavelength. Although the dark state voltage was further reduced, the light scattering capability was weakened which resulted in a reduced contrast ratio.
Figure 3-4: The curing temperature dependent contrast ratio of the E48 PNLC containing 4% monomer concentration. Cell gap $d=8$ $\mu$m, laser wavelength $\lambda=633$ nm and measurement temperature $T=23$ °C.

Figure 3-5 shows the camera pictures of the He-Ne laser beam after passing through a 4 wt% monomer E48 PNLC cell. The cell was prepared at 50 °C curing temperature condition. When there was no voltage, the He-Ne laser beam was transmitted. A bright spot was observed on the camera as shown in Figure 3-5 (a). The high intensity of the transmitted laser beam strongly saturated the camera as indicated by the high brightness in the center of the spot. When a 7 V$_{\text{rms}}$ voltage was applied, laser beam was strongly scattered and a speckled light pattern was observed as shown in Figure 3-5(b). The large saturated region on Figure 3-5 (a) and weak intensity light speckles on Figure 3-5 (b) indicated a large magnitude of the intensity difference between the voltage-on and voltage-off states.
Figure 3-5: Camera pictures of the He-Ne laser beam after passing a E48 PNLC cell (a) Transparent when voltage off. Camera is strongly saturated by the transmitted high intensity laser beam and (b) Scattered when voltage on. A weak intensity speckled light pattern is observed. Curing temperature T=50 °C, cell gap d=8 µm, laser wavelength \( \lambda = 633 \) nm and measurement temperature T=23 °C.

Figure 3-6 depicts the curing temperature effect on hysteresis. The hysteresis width \( \Delta V \) is defined as \( V_{\text{down}} - V_{\text{up}} \) where \( V_{\text{down}} \) and \( V_{\text{up}} \) are the voltages corresponding to 50% transmittance for the forward and reverse voltage scans. From the figure, hysteresis width is suppressed by nearly 3X as the curing temperature increases from 23 to 70 °C. For optical switch applications, the major performance criteria are high extinction ratio, low voltage and fast response time; hysteresis is not a big concern. However, for grayscale display and VOA devices, hysteresis is undesirable and should be minimized. Therefore, the two-stage curing fabrication method has extended the potential applications of PNLCs.
Figure 3-6: The curing temperature dependent hysteresis of the E48 PNLC containing 4% monomer concentration. Cell gap d=8 µm, laser wavelength $\lambda=633$ nm and measurement temperature $T=23 \degree C$.

Although high temperature curing lowered the dark state voltage, enhanced the contrast ratio, and suppressed the hysteresis width, it had a drawback in increasing the response time. Figure 3-7 shows the measured rise and decay time of the 8-µm-thick and 4 wt % monomer E48 PNLC cells at various curing temperatures. Turn-on time, also called rise time, defines how fast the cell switches from the transparent state to the scattering state when a voltage is applied. Turn off time or decay time is the relaxation time of LC molecules back to their original state when the voltage is removed.
Figure 3-7: The curing temperature dependent rise time (dark green) and decay time (red) of the 8-µm E48 PNLC with 4 wt% monomer concentration. For each cell, the rise and decay times were measured between V=0 and the corresponding dark state voltage shown in Figure 3-3. Laser wavelength $\lambda=633$ nm and measurement temperature $T=23\, ^{\circ}\text{C}$.

Both turn-on and turn-off times increased as increasing the curing temperature. In general, the LC response time is affected by material properties, cell gap, and electric field as discussed in chapter 2 and defined in equation 2-7. However, for a PNLC, except those factors mentioned, polymer network provides an additional torque affecting the aligning process of LC molecules. The presence of polymer network enhances the elastic constant of the LC and thus the drive voltage is increased and the response time is reduced. Therefore, the formed polymer network morphology has an influence on the LC response time. Benefiting from the driving voltage effect, rise time is faster than decay time as shown in Figure 3-8. As the curing temperature was increased, the dark state voltage was reduced resulting in a slower rise time. As the polymer network got coarser and LC domain size got larger at high curing temperatures, the anchoring
The force of polymer network became weaker. As a result, the assistance coming from the polymer network side for returning LC molecules to their original state was reduced leading to a slower decay time. This is consistent with the lower dark state voltage observed for the higher curing temperature, as shown in Figure 3-3.

The increased response time is a disadvantage of the high curing temperature effect on PNLCs. In order to reduce response time, one can use a thinner cell gap, a lower viscosity LC, an overdrive/undershoot drive scheme, or to operate the cell at an elevated temperature. The using of a thinner cell gap will decrease the contrast ratio. The low viscosity LC method requires development of a new LC material. The overdrive/undershoot method complicates the drive scheme and requires a high drive voltage. Operating at high temperature is an alternative approach. As discussed in Chapter 2, temperature is a very important factor affecting the physical properties of LCs, such as viscosity, elastic constant, birefringence and so on. With increasing temperature, the visco-elastic coefficient $\gamma_1/K$ is reduced which, in turn, reduces the device response time. In Figure 3-8, one can see that when operating at room temperature, the 4 wt% E48 PNLC cell with the 50°C curing temperature has a rise and decay time as 4 and 21 milliseconds, respectively. However as increasing the operating temperature to 60 °C, the rise and decay times decrease to 0.8 and 4.3 ms, respectively. The improvement is 5X for both rise and decay time. The tradeoff is the added complication to the device driving scheme due to the required temperature control module.
Monomer concentration is another important factor affecting the PNLC performance. Five samples with 2, 3, 4, 5, and 6 wt % monomer concentrations, respectively, at 50 °C curing temperature were prepared. The cell gap was 8 µm. Results are shown in Figure 3-9. From the figure, the dark state voltage increased from 5.5 to 9.5 $V_{\text{rms}}$ as the monomer concentration increased from 2 to 6 wt%. The increased threshold and dark state voltages for a higher monomer concentration originated from the smaller domain sizes. For the 2-4 % gels, the device contrast ratio remained as high as 2000:1, but dropped rapidly to 170:1 as the monomer concentration increased to 6 %. In a high monomer concentration PSLC cell, the domain sizes were too small to effectively scatter the He-Ne laser light.
Figure 3-9: The voltage-dependent transmittance of E48 PNLCs with 2, 3, 4, 5 and 6 wt% (from left to right) monomer concentrations. Curing temperature \( T=50 \degree C \). LC cell gap \( d=8 \mu m \), operating temperature \( T=23\degree C \) and \( \lambda=633 \) nm.

The light scattering loss for the laser polarization orthogonal to the cell rubbing direction was measured to be less than 5%. This indicated that the PNLC’s light scattering behavior was indeed very anisotropic. The turn-on and -off times for the PNLC cells with 3, 4, 5, and 6 wt% monomer concentrations were measured to be \((6, 26), (4, 21), (3, 12)\) and \((2, 8)\) milliseconds, respectively, as shown in Figure 3-10. The faster decay time at high monomer concentration attributed to the strong polymer network effect, while the faster rise time came from the high drive voltage effect.
Figure 3-10: The monomer concentration-dependent response time of E48 PNLCs. Curing temperature $T=50\, ^\circ\text{C}$, LC cell gap $d=8\, \mu\text{m}$, operating temperature $T=23\, ^\circ\text{C}$ and $\lambda=633\, \text{nm}$.

From the above experimental investigations, curing temperature and two-stage curing process have demonstrated exciting results in improving the PNLC performances. According to the working wavelength, one can tune the micro-domain size to obtain maximum contrast ratio by simply adjusting the curing temperature. Drive voltage and hysteresis are greatly reduced at high curing temperature. The high performance makes PNLC more applicable in various applications, such as in displays, shutters, and optical switches etc. In the next section, a high performance optical device by using PNLC is proposed for optical communications. It can be seen that the task becomes very challenging when operating at infrared wavelength.
3.4 High Performance PNLCs for Optical Communications

From the aspect of PNLC’s working mechanism, it can be used as switchable polarizers, shutters and VOAs in optical communications. In order to realize a switchable polarizer [7], two such PNLC cells are placed so that their rubbing directions are perpendicular to each other. The working mechanism of such a device is depicted in Figure 3-11.

Figure 3-11: Schematics of a switchable polarizer by using two PNLC cells. (a) no electric field applied, light is transmitted (b) the left PNLC cell is driven by electric field. The vertical polarization is scattered and the orthogonal polarization is transmitted, (c) the right PNLC cell is driven by electric field. The vertical polarization is transmitted and the orthogonal one is scattered and (d) both PNLC cells are driven by electric field and both polarizations are scattered.

In the voltage-off state, light is transmitted. If one cell is driven by a voltage and another is at zero voltage, the light polarized along the rubbing direction of the voltage-driven cell is scattered, and the orthogonal polarization is transmitted. The system acts as a linear polarizer. When both
cells are driven by an external voltage, light is scattered (both polarizations). Such a configuration realizes an electrically controllable polarizer. However, with a poor contrast ratio, the output polarized light is not linearly but rather elliptically polarized.

VOA plays important roles in optical communication for power equalization in optical add/drop modules and gain adjustment in erbium-doped fiber amplifiers in WDM networks. In addition, it can be used in DWDM systems to control the wavelength and output powers of distributed feedback laser diodes (DFB-LDs). VOAs using a PDLC [9] or a PNLC [10,11] have been studied extensively. However the previously reported VOAs by liquid crystal/polymer composites have limited performances. For example, the VOA using PDLC is independent of light polarization and has $\sim$15 dB extinction ratio, $\sim$70 V$_{rms}$ operating voltage at $\lambda$$=1300$ nm wavelength using a d=30 $\mu$m cell gap. For the demonstrated VOA arrays using PNLC, although the voltage is reduced to $\sim$20 V$_{rms}$ with a 20 $\mu$m cell gap, the attenuation is also decreased ($\sim$7.5dB at $\lambda$$=1550$ nm). The inadequate contrast ratio, relatively high drive voltage limits PNLC’s application for optical communications.

In section 3.3, curing temperature is found to have a dramatic improvement on PNLC performance with an enhanced contrast ratio, a reduced drive voltage and hysteresis for He-Ne laser wavelength ($\lambda$=632.8nm). Results are reported in Ref. [12]. The electro-optical properties of PNLC are found to be greatly affected by the size of the electric-field-induced LC domains. If the domain size obtained in a PNLC is comparable to the laser wavelength, maximum scattering efficiency can be achieved and the contrast ratio would be high. In order to obtain a high contrast PNLC at the wavelength $\lambda$$=1550$ nm for optical communications, the micro-domain size has to
be much larger than that for $\lambda=632.8$ nm. Considering that, a relatively high curing temperature is expected in order to get the proper domain size for operating at $\lambda=1550$ nm.

The sample preparation is described in section 3.3 except that a Merck E44 LC mixture ($\Delta n=0.26$ at $\lambda=589$ nm) instead of Merck E48 LC mixture was used. The weight ratio of LC and monomer was 96 wt% and 4 wt%, respectively. The cell gap was 16 µm. As discussed in section 3.3, high monomer concentration leads to small domains and vice versa. Thus in order to form a large domain for 1550 nm wavelength, it is preferable to choose a small monomer concentration. However, with a small monomer concentration, the polymer network is coarse resulting in a slow response time. The curing temperature has the same contradicting effects. At high curing temperature, a large domain is formed leading to a high contrast but response time is sacrificed. In addition, for a 2 wt% monomer concentration, it was found from experiments that the formed polymer network was not sufficiently strong to survive the applied electric field and was destroyed after several operational cycles. The monomer concentration was chosen to be 4 wt% to balance the contrast ratio and the response time. A 16-µm-thick cell was used because a thin cell did not have a sufficient contrast ratio at 1550 nm wavelength. The birefringence of LC decreases as increasing the wavelength and gradually saturates at infrared wavelength, as discussed in Chapter 2 and shown in Figure 2-4. For the E44 mixture, it shows $\Delta n=0.26$ birefringence for $\lambda=589$ nm but $\Delta n=0.22$ for $\lambda=1550$ nm. The reduced birefringence at longer wavelengths is one of the reasons for the inadequate contrast ratio of PNLC for optical communications. Even though a thick cell can enhance the contrast ratio, it has a tradeoff in increasing the drive voltage and response time. Therefore, it became very challenging for a PNLC to obtain overall good performances when operating at infrared wavelength.
Figure 3-12: The experimental setup for reflective E44 PNLC cell. Laser wavelength is $\lambda=1550$ nm. The light polarization is along the LC cell rubbing direction, the incidence angle is $\sim 4^\circ$, and the collection angle is $3^\circ$.

Figure 3-12 shows the experimental setup. A laser diode with $\lambda=1550$ nm was used as a source. The light was polarized along the LC cell rubbing direction. At zero voltage, light was transmitted and represented an “ON” state. At a sufficiently high voltage, the light was strongly scattered by the electric-field-induced LC domains in PNLC and represented an “OFF” state. To demonstrate a reflective type device, a reflector was placed right behind the PNLC cell. The laser light incidence angle was $\sim 4^\circ$ to the LC cell. Voltage-dependent reflectance was measured by a large dynamic range photodiode detector at $3^\circ$ collection angle.

The curing temperature-dependent attenuation and drive voltage of the E44 PNLC cells at curing temperatures from 23 to $85^\circ$C is shown in Figure 3-13. As discussed before, with increasing curing temperature, larger dispersion of LC and monomer was obtained resulting in a lower operating voltage and a higher scattering efficiency. The terminology “attenuation” is more
commonly used in optical communications to identify the dynamic range of an optical switch or VOA instead of contrast ratio. It is defined as \(-10\log{(CR)}\), where CR stands for contrast ratio. For the 16-\(\mu\)m-thick conventional PNLC cell (prepared at room temperature), the attenuation range was only \(\sim 12\)dB and the operating voltage was \(V=22\) V_{rms}. As the curing temperature increased from 23 to 85\(^\circ\)C, the attenuation increased from 12 to 34dB and the driving voltage was reduced almost linearly from 22 to 9 V_{rms}. Difference was that the optimum curing temperature was shifted from around 50\(^\circ\)C for the visible light (\(\lambda=632.8\) nm) to a much higher temperature for infrared wavelength \(\lambda=1550\) nm (higher than 85\(^\circ\)C according to the measurements performed). An optimum curing temperature corresponds to an individual operating wavelength.

Similarly, hysteresis was greatly suppressed as temperature increased, as shown in Figure 3-14. Due to the high drive voltage (22 V_{rms}) caused by the large cell gap (16 \(\mu\)m), the hysteresis for the conventional PNLC prepared at room temperature polymerization condition was as large as 1.3 V_{rms}. Such a large hysteresis made the cell inapplicable for VOA applications. However, as the curing temperature was increased to 85 \(^\circ\)C, the hysteresis was suppressed for 5X to \(~0.25\) V_{rms}. Such small hysteresis makes PNLC significantly more applicable as VOAs.
Figure 3-13: The curing temperature dependent attenuation and drive voltage of the reflective E44 PNLC cell. Cell gap d=16 µm, monomer concentration 4 wt%, laser wavelength \( \lambda = 1550 \) nm and measurement temperature \( T = 23 ^\circ C \).

Figure 3-14: The curing temperature dependent hysteresis of the reflective E44 PNLC cell. Cell gap d=16 µm, monomer concentration 4 wt%, laser wavelength \( \lambda = 1550 \) nm and measurement temperature \( T = 23 ^\circ C \).
Figure 3-15 shows the curing temperature-dependent response time of the 16-µm-thick PNLC cells. For the PNLC with 85 °C curing temperature, the measurements showed a rise/decay time of 20/70 ms, respectively. As discussed in section 3.3, the slow decay time at a high curing temperature was due to the weak anchoring force from the coarse polymer network. Such a slow response time is certainly not desirable. To improve response time, one could use a thinner cell gap or a higher monomer concentration. However, using a thinner cell gap would lead to a reduced dynamic range whereas using a higher monomer concentration would require a much higher operating voltage.

Figure 3-15: The curing temperature-dependent rise (dots)/ decay time (open circles) of the reflective E44 PNLC cells. Cell gap d=16 µm, monomer concentration 4 wt%, laser wavelength λ=1550 nm and measurement temperature T=23 °C.

From above discussions and experimental results, one can see that the major problems of PNLC, such as inadequate contrast ratio, high drive voltage and large hysteresis, become much more
serious when operating at a longer wavelength, such as the $\lambda=1550$ nm for optical communications. Compared to that in visible region, the attenuation of PNLC was greatly degraded at $\lambda=1550$ nm. In order to achieve a high attenuation, a thick cell gap (16 $\mu$m) had to be used, which consequently increased drive voltage, hysteresis, and response time. Even though curing temperature and two-stage curing process were used and showed remarkable improvements on the dynamic range, drive voltage, and hysteresis of PNLC, they suffered from a slow response time due to the weakened polymer network effect. However, even with the relatively slow response time, the high performance PNLC reported here, with $\sim$34 dB attenuation and $\sim$9 $V_{rms}$ drive voltage at $\lambda=1550$ nm, has achieved at least one order of magnitude improvement compared to those reported before and made the PNLC a very promising material for applications in optical communications where response time is not an issue.

3.5 High Birefringence Liquid Crystals

High birefringence and low viscosity LC mixtures are very useful for infrared light modulators in communications, reflective displays, and other LC based devices. For displays, high $\Delta n$ enhances the display brightness and reduces operation voltage. For infrared light modulators, high $\Delta n$ allows using a thinner LC cell for a certain phase change. As a result, switching time is reduced. For LC devices based on a PSLC, high $\Delta n$ enhances light scattering efficiency and thus improves the contrast ratio. When the contrast ratio is not a concern, a low curing temperature or a thinner cell gap can be used, which consequently reduces response time. Therefore, the high birefringence LC approach can be used to further improve the performance of PNLC.
The birefringence of a LC mixture is mainly determined by the $\pi$-electron conjugation length, differential oscillator strength, molecular shape and order parameter as discussed in Chapter 2. Generally speaking, linearly conjugated molecules exhibit a high birefringence. Conjugation length can be elongated by multiple bonds or unsaturated rings in the rigid core. However, a highly conjugated LC molecule structure tends to have high melting temperature, large viscosity, and poor photostability. Photostability is not a concern for applications in optical communications. However, high melting temperature and large viscosity are undesirable. In Chapter 2, it was introduced that isothiocyanato (NCS) tolanes 1) contain $\pi$ electrons leading to a long electronic resonance wavelength thus an enhanced birefringence, 2) exhibit a large dipole moment and a large dielectric anisotropy, and 3) have a low viscosity. Therefore, the NCS tolanes are good candidates for high birefringence and low viscosity LC mixtures [13].

To demonstrate the influence of high birefringence LC on PNLC, two single compounds containing NCS terminal groups were used to enhance the birefringence of E44. Their molecular structures and other properties are shown in Table 3-1.

Table 3-1: The properties of isothiocyanato tolanes used for enhancing E44’s birefringence. K and I represent the crystalline and isotropic phase, respectively. $\Delta n$ is the extrapolated birefringence at room temperature and $\lambda = 633$ nm.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Phase Transitions (°C)</th>
<th>$\Delta n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $\text{C}_2\text{H}_5\text{O}$-(\equiv)(\equiv)-NCS</td>
<td>K 128.3 I</td>
<td>0.41</td>
</tr>
<tr>
<td>2 $\text{C}_3\text{H}_7$-(\equiv)(\equiv)-NCS</td>
<td>K 97.1 I</td>
<td>0.38</td>
</tr>
</tbody>
</table>
Both compounds have linear molecular structure and low molecular weight indicating a high birefringence, low viscosity, and large dielectric anisotropy when used in mixture. Compound 1 is an alkoxy NCS-tolane. The oxygen atom in the alkoxy side chain elongates the \( \pi \)-electron conjugation and enhances the birefringence. Phase transition temperatures were measured by a high sensitivity differential scanning calorimeter (DSC, TA Instrument Model Q-100) at a 2\(^{\circ}\)C/min scanning rate. The phase transitions of both compounds were found to be from crystalline to liquid phase directly as increasing the temperature and no intermediate LC phase was exhibited. In addition, the phase transition temperatures are as high as 128.3\(^{\circ}\)C and 97.1\(^{\circ}\)C, respectively, which means that both compounds are in a solid state at room temperature.

In order to measure/estimate the birefringence of these two NCS compounds, a guest-host method was used. Merck mixture ZLI-1565 (\( \Delta n = 0.12, T_m=-20^{\circ}\)C, and \( T_c=85^{\circ}\)C) was used as a host. When a 10 wt\% of the single NCS compound 1 or compound 2 was mixed with the host LC material ZLI-1565, the melting temperature of the guest-host mixture was lowered showing a nematic LC phase at room temperature. The birefringence of the NCS compound can be estimated from the birefringence of the guest-host system according to the following equation:

\[
(\Delta n)_{GH} = c(\Delta n)_G + (1 - c)(\Delta n)_H
\]  

(3-1)

The subscripts G, H, and GH denote guest, host, and guest-host, respectively, and \( c \) is the weight concentration (in wt\%) of the guest compound.

In order to measure the birefringence of the guest-host mixture, the mixture was filled into a homogeneous empty cell. Cell gap is 8 \( \mu \)m. The cell was then placed between a crossed polarizer
and analyzer configuration. The rubbing direction of the cell was positioned at 45° with respect to the polarizer. A He-Ne laser was used as light source and a LabVIEW controlled computer system was used to measure the voltage-dependent transmittance. The birefringence of the guest-host mixture can be calculated from the following equations [14]:

\[
\begin{align*}
\delta &= m \pi + 2 \tan^{-1} \sqrt{I_\perp / I_\parallel} \quad m = 0,2,4,..2n \\
\delta &= (m + 1) \pi - 2 \tan^{-1} \sqrt{I_\perp / I_\parallel} \quad m = 1,3,5,..2n + 1
\end{align*}
\]

\[
\delta = 2 \pi \Delta n d / \lambda
\]

Here \( \delta \) is the phase retardation (in \( \pi \)) of the mixture, \( d \) is the cell thickness. \( I_\perp \) and \( I_\parallel \) are the transmitted intensity at no applied voltage, \( \perp \) and \( \parallel \) represent the configuration where the polarizer is perpendicular or parallel to the analyzer, respectively.

From the measured voltage-dependent transmittance curve of the guest-host LC cell, one can calculate the phase retardation \( \delta \) from equation 3-2. The cell thickness \( d \) can be measured from an interferometric method [15]. The wavelength-dependent transmission of an empty cell with thickness \( d \) is measured by an interferometer, and then \( d \) can be calculated from the following equation:

\[
d = \frac{m \lambda_1 \lambda_2}{2 \lambda_2 - \lambda_1}
\]

where \( \lambda_1 \) and \( \lambda_2 \) are two wavelengths where transmission maximum is obtained, and \( m \) is the number of interference cycles between these two chosen wavelengths. Once the cell gap and the
phase retardation of the LC cell are known, the birefringence of the guest-host mixture is obtained from equation 3-3.

The birefringence of the single NCS compound 1 was estimated to be \( \Delta n=0.41 \) at \( \lambda=633 \) nm, and \( \Delta n=0.38 \) for the compound 2 as listed in Table 3-1. As expected, NCS tolanes show a high birefringence. The single compound 1 has a slightly higher birefringence than that of the single compound 2. This is due to the elongated conjugation length contributed by the additional \( \pi \)-electrons of alkoxy side chain.

In the next step, these two NCS tolanes were mixed with E44, respectively, to formulate eutectic mixtures to enhance the birefringence of E44. Eutectic mixture is a useful way for lowering the melting temperature of LC. The melting temperature \( T_M \) of an eutectic mixture is defined by Schroder-Van Laar Equation [16,17]:

\[
T_M = \frac{\Delta H_i}{\Delta H_I - R \ell \Delta n X_i}
\]

(3-5)

here subscript \( i \) stands for the \( i^{th} \) component that constitutes the eutectic mixture, \( \Delta H_i \) is the heat enthalpy, \( T_{M,i} \) is the melting temperature, \( R \) is the gas constant (\( R=1.987 \) cal/mol/K), and \( X_i \) is the mole fraction. The clearing temperature \( T_C \) is estimated as [18]

\[
T_C = \sum_i X_i T_{C,i}
\]

(3-6)

where \( T_{C,i} \) is the clearing temperature of component \( i \). From equations 3-5 and 3-6, phase transition temperatures of a eutectic mixture are dependent on the individual compounds and
their compositions. Even if single compound has a high melting temperature and no LC phase, the mixture can show a wide range of mesogenic phase. For example a high birefringence (>0.4 in visible region) and low viscosity LC has been developed based on 8 single NCS compounds [13]. These 8 single NCS tolanes are either with high $T_M$ or without LC phase. However the final mixture exhibits a wide nematic range from -22 °C to 141 °C.

For compound 1, just 8.5 wt% can be mixed with E44 (mixture E44-1) while for compound 2, up to 25 wt% can be mixed (mixture E44-2). The high melting temperature of compound 1 limits its solubility in E44. The solubility of NCS compound affected its contribution on birefringence of the final mixture. Even though compound 1 was estimated to have a higher birefringence than compound 2, its low solubility resulted in a less significant contribution in enhancing the birefringence of E44. The birefringence of E44, E44-1 and E44-2 were measured to be 0.22, 0.23 and 0.25, respectively, at $\lambda$=1550 nm. Thus, by adding a single NCS compound 2, the mixture birefringence increased by ~14% as compared to the undoped E44.

In order to demonstrate the effects of birefringence on PNLC performance, three samples with 4 wt% monomer and LC mixtures E44, E44-1 and E44-2 were prepared respectively at curing temperature 55 °C. The cell gap is 16 µm. Some performance characteristics are listed in Table 3-2. Owing to the enhanced birefringence, the dynamic range of the E44-1 PNLC sample was improved to 27dB and E44-2 PNLC was improved to 32 dB. E44-2 had a more significant improvement compared to E44-1 PNLC due to the higher birefringence from the high solubility of alkyl NCS tolane in E44 mixture. In addition, from the previous section 0, in order to reach a high attenuation >30 dB for the 16-µm-thick E44 PNLC, a curing temperature >75 °C is required.
Such a high curing temperature led to a slow response time. The rise/decay times were 16/40 ms respectively for the 75 °C curing temperature and 20/70 ms for the 85 °C curing temperature. However with the high birefringence LC, the attenuation of PNLC was enhanced. Even for a low curing temperature as 55 °C, a 32 dB attenuation was obtained for the E44-2 PNLC. As the result of the reduced curing temperature, response times were reduced to 7/20 ms for the rise/decay time, respectively.

Table 3-2: Comparisons of three reflective PNLC samples. E44-1 mixture contains E44 and 8.5 wt% alkoxy NCS tolane while E44-2 mixture contains E44 and 25 wt% alkyl NCS tolane. Monomer concentration is 4 wt%, curing temperature is 55 °C, cell gap is 16 µm, laser wavelength \( \lambda = 1550 \text{ nm} \) and measurement temperature \( T = 23 \text{ °C} \).

<table>
<thead>
<tr>
<th></th>
<th>E44 PNLC</th>
<th>E44-1 PNLC</th>
<th>E44-2 PNLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation Mechanism</td>
<td>Scattering</td>
<td>Scattering</td>
<td>Scattering</td>
</tr>
<tr>
<td>Dynamic Range (dB)</td>
<td>22</td>
<td>27</td>
<td>32</td>
</tr>
<tr>
<td>Control Voltage (V_{rms})</td>
<td>0~14.4</td>
<td>0~14</td>
<td>0~12</td>
</tr>
<tr>
<td>Hysteresis Width (V_{rms})</td>
<td>0.65</td>
<td>0.64</td>
<td>0.46</td>
</tr>
<tr>
<td>Rise Time/Fall Time (ms)</td>
<td>8/25</td>
<td>6/25</td>
<td>7/20</td>
</tr>
</tbody>
</table>

Figure 3-16 depicts the voltage-dependent attenuation of the 16-µm-thick E44-2 PNLC cell at 55 °C curing temperature. It shows a maximum 32 dB attenuation at 12 V_{rms}. 

62
Figure 3-16: The voltage-dependent optical attenuation of the reflective 16 $\mu$m E44-2 PNLC cell containing 4 wt% monomer. Curing temperature $T=55^\circ$C, operating temperature $T=23^\circ$C, and $\lambda=1550$ nm.

The results show that the high birefringence and low viscosity LC materials are very helpful to enhance the overall performances of PNLCs for optical communication applications in order to get high attenuation, low operation voltage, and fast response time simultaneously.

As can be seen in this chapter, it is a very challenging task to achieve the overall good performance PNLCs with high attenuation, fast response time and low drive voltage in the optical communication wavelength. However, with the two-stage curing process and high birefringence LC material, the above demonstrated results show an order of magnitude improvement compared to the same category devices used. From this investigation, the insight into the mechanism of PSLC is clearer which will give positive impact to follow-up study in this direction.
3.6 References


CHAPTER FOUR: POLARIZATION-INDEPENDENT POLYMER-STABILIZED LIQUID CRYSTAL-BASED DEVICES

In Chapter 3, a high attenuation, low voltage, and fast-response PNLC has been proposed for applications as light shutters, switchable polarizers, and VOAs in optical communications. However, PNLC is dependent on the incident light polarization. It scatters the light polarized along the cell rubbing direction and transmits the orthogonal polarization light. Thus, a linearly polarized input light or a polarizer is required. Polarization independence feature is of great interests for fiber-optic communications where polarization dependent loss is an important issue. However, due to the birefringence property of LC material, most LC based devices are polarization sensitive. In order to make LC device polarization-independent, polarization conversion schemes have to be incorporated. In the most usual case, polarization beamsplitters or birefringent crystal beam displacers are used to separate and recombine the ordinary and extraordinary polarization. However, by doing so, the non-uniformity of LC cell thickness will induce a high polarization dependent loss due to different paths that ordinary and extraordinary wave travels, respectively. In addition, the use of polarization control system increases the assembly cost, packaging size, and makes it difficult for building arrays.

PDLCs are independent of polarization as introduced at the beginning of Chapter 3. It contains LC droplets dispersed in an optically isotropic polymer matrix as shown in Figure 3-1. In each individual droplet, LC molecules are randomly distributed and scatter light no matter of the light polarization. However, PDLC usually exhibits a high drive voltage ($\sim 5 \text{ V}_{\text{rms}/\mu\text{m}}$) [1]. Therefore, further development of new configurations of LC-based devices with polarization independency
is of practical interests. Especially a single LC cell approach without polarization control system is highly appreciated. It is compact, inexpensive, and easy to integrate.

### 4.1 Polymer-Stabilized Cholesteric Liquid Crystals

A cholesteric LC [2] can be obtained by adding some percentage of chiral dopant into a nematic LC. Similar to nematic LC, cholesteric LC has a long range orientational order but without positional order. The difference lies in the helical structure that cholesteric LC director possesses. Depending on the surface alignment and external electric field, cholesteric LCs can exhibit three possible molecular arrangements: planar structure, focal conic structure, and homeotropic structure. Each structure has different electro-optical properties and will be discussed in the following paragraphs.

In a planar structure, cholesteric LC is injected into a homogeneous cell with anti-parallel surface treatment. As a result of the surface alignment, the helical axis of cholesteric LC is perpendicular to the substrate. The director of molecules next to the substrates is parallel to the rubbing direction. In this configuration, the cell selectively reflects a circularly polarized light with the same handedness as the cholesteric LC material due to periodic variations of the refractive index. The other handedness circularly polarized light is transmitted. The center wavelength of the reflected light is given by

$$\lambda = \langle n \rangle p$$  \hspace{1cm} (4-1)

where $\langle n \rangle$ is the average refractive index, and $p$ is the pitch length.
The pitch length $p$ is determined by:

$$p = \frac{<n>}{a \cdot HTP}$$

(4-2)

where HTP is helical twisting power of chiral dopant, and $a$ is the relative concentration in weight percent.

When an efficiently high voltage is applied to a cholesteric LC, focal conic structure is induced due to the aligning forces of electric field, anchoring effects of substrates, and interactions of molecules. In this case, helical axes are more or less randomly aligned. Incident light is scattered no matter of the light frequency. Homeotropic structure is presented when a high voltage is applied where all the cholesteric molecules are unwound and the LC directors are reoriented normal to the substrates. The LC cell is transparent at this configuration and the incident light is completely transmitted.

Polymer network cholesteric LCs (PSCLCs) [3,4,5] consist of a small percentage of monomer with cholesteric LC. A normal-mode and a revered-mode PSCLC can be achieved by stabilizing in a homeotropic or a planar structure, respectively, with the electric field or surface anchoring effects. Similar to a PNLC, a weak UV light is used to induce photo-polymerization on monomer. After polymerization, a fiber-like, anisotropic polymer network is formed, following the textures of the initial cholesteric LC structure (homeotropic or planar structure).

In a reversed-mode PSCLC, due to the surface rubbing effect and the planar structure of cholesteric LC, the formed polymer networks are parallel to the cell surface and follow the local
helical order of LC directors. Figure 4-1 depicts the working mechanism of a reversed-mode PSCLC cell.

Figure 4-1: Working mechanism of a reversed-mode PSCLC. (a) Cell is in planar structure. Polymer network is parallel to the cell substrate and follow the local helical structure of the cholesteric LC. Incident light is transmitted. (b) Cell is in focal conic structure. LC multi-domains are formed under the influence of an applied electric field, light is scattered no matter of its polarization state.

In the voltage-off state, the cell is stabilized in a planar structure. If a proper concentration of chiral dopant is chosen so that the reflection band is far away from the incident light wavelength, light will be transmitted. When a voltage is applied, the LC system switches into a focal conic state where helical axes are more or less randomly aligned as shown in Figure 4-1 (b). In this configuration, the cell strongly scatters light regardless of the incident polarization or frequency.

The polarization-independent feature of a single PSCLC cell is particularly attractive for fiber-optic communications where polarization dependent loss is an important issue. Compared to the commercially available LC devices which use polarizers or variety of polarization control
systems for polarization independency, PSCLC provides a promising solution for developing a low cost and compact polarization independent optical device.

A polarization independent light shutter or VOA by PSCLC is developed and discussed in the next section. The two-stage elevated temperature curing process and high birefringence LC mixture are used in order to achieve high performances. The detailed influences of curing temperature, chiral dopant concentration and LC material on the electro-optical properties of PSCLCs are investigated and analyzed.

4.2 Polarization-Independent VOA by Polymer-Stabilized Cholesteric Liquid Crystals

PSCLCs have a similar preparation process to that of PNLCs except that a proper chiral dopant was added in the nematic LC mixture to achieve a desired pitch length. To make the fabricated PSCLC cell transparent to the optical communication wavelength $\lambda=1550$ nm, a 0.66 wt% chiral dopant S1011 was used, giving a pitch length $p \approx 3$ $\mu$m and a reflection band in the far-infrared region. The chiral dopant, plus 3 wt% bisphenol-A-dimethacrylate monomer and a small amount of photoinitiator were mixed in a Merck E44 LC mixture ($\Delta n=0.22$ at $\lambda=1550$ nm). The mixture was injected into a $\sim15$ $\mu$m thick, empty homogeneous cell, and exposed to a weak UV light (100 $\mu$W/cm$^2$) to induce polymerization. During the polymerization, the cell was first kept at an elevated temperature for 0.5 h for UV exposure then the UV exposure continued for another 2.5 h at room temperature to further stabilize polymer networks. A thick cell gap was used to enhance the PSCLC attenuation properties at $\lambda=1550$ nm.
Similar to that in a PNLC, there are several factors affecting the polymer network morphology of a PSCLC cell, such as cell gap, monomer concentration, pitch length, and curing conditions [6, 7, 8]. In this dissertation, the focus is on investigating the influences of these factors on the electro-optical properties of PSCLCs. Numerous experimental conditions were studied to optimize the PSCLC performances for the commonly used optical communication wavelength $\lambda=1550$ nm. Monomer concentration had to be optimized as it affects the domain size which, consequently, affects the light scattering efficiency and operating voltage. For display applications in the visible spectral region, the optimum domain is small due to the short wavelength involved. However, for optical communication application at $\lambda=1550$ nm, domain size should be increased, i.e., a small monomer concentration should be employed. A low monomer concentration also leads to a low operating voltage. However, in the experiment it was found that the PSCLC structure was unstable when the monomer concentration was less than 2 wt%. The electro-optic properties of these low-monomer-concentration PSCLC ($\leq 2$ wt%) cells were not repeatable after being switched on and off consecutively several times. Therefore, the monomer concentration should be maintained at more than 2 wt%. On the contrary, if the monomer concentration is too high, the domain would be too small so that attenuation decreases and operating voltage increases. Pitch length was found to be another factor affecting the electro-optic properties of PSCLC. A short pitch indicates a high operating voltage, small domain size, and fast response time. Conversely, a long pitch leads to a low drive voltage, large domain size, and slow response time. Thus compared to PNLC, PSCLC is a more complicated system. All these factors played against each other and affected the cell properties in opposite directions. In the experiments, it was found that a 15-µm-thick cell gap, 0.66 wt% chiral concentration, and 3
wt% polymer concentration provided a reasonably good overall performance for the E44 PSCLC cells.

Figure 4-2: Experimental setup for measuring properties of reflective E44 PSCLC cells.

Figure 4-2 shows the experimental setup used to characterize PSCLC cells. A tunable laser source (ANDO AQ4321D) output a polarized beam at $\lambda=1550$ nm. The light polarization was controlled by a polarization controller in order to test the PSCLC cell performance in different polarization states. A mirror was placed immediately behind the PSCLC cell to demonstrate a reflective type device. The port 1 of a fiber optic circulator was connected to the light source. Port 2 was connected to a collimating lens with a 3 cm working distance. Laser light entered from port 1, went through port 2 to the collimating lens and incidented normally on the PSCLC cell. The reflected light was captured by the collimating lens and coupled back to the fiber. The circulator redirected the reflected beam from the PSCLC cell to an optical power meter through port 3. A computer-controlled LabVIEW system was used to supply voltage to the PSCLC cell and to record the voltage-dependent reflectance as well.
From Chapter 3, curing temperature was found to be an important factor to improve PNLC performance. Even though PSCLC has a different structure from PNLC, there are some similarities as well. To investigate the curing temperature effects on the electro-optical properties of PSCLCs, cells were fabricated at various curing temperatures (from 23 to 70°C) and their voltage-dependent attenuation was measured at $\lambda=1550$ nm as shown in Figure 4-3. Due to the thin LC cell gap (15 $\mu$m) and the small absorption coefficient of the LC mixture at $\lambda=1550$ nm [9], the light absorption loss of PSCLC cell was negligible. In addition, the reflection loss from glass substrates was neglected as well. In the voltage-off state, PSCLC cells were stabilized in a planar structure and highly transparent. With applied voltage, the polymer networks resisted LC directors from being reoriented by the electric field. When the voltage was slightly above the threshold, LC molecules first deformed in the regions where polymer density is low, while the polymer-rich regions remained unchanged. As the voltage was increased further, more LC molecules were rotated. As a result, the cell was gradually switched into focal conic state where multiple micro-domains were formed and incident light was strongly scattered resulting in the decrease of the reflected light from the cell.
Figure 4-3: Voltage-dependent reflectance of E44 PSCLC cell at various curing temperatures. Monomer concentration is 3 wt%, pitch is ~3 µm, cell gap $d=15$ µm. The measurements were taken at $\lambda=1550$ nm and $T=23^\circ C$.

Figure 4-4 shows the optical attenuation range and scattering-state voltage of the PSCLC cells at various curing temperatures. For the cell cured at room temperature, the attenuation range is only ~14 dB at $V=21$ $V_{rms}$. As the curing temperature was increased from 23 to $70^\circ C$, the attenuation was increased to 26 dB and the drive voltage decreased almost linearly from 21 to 11.5 $V_{rms}$. For the PSCLC sample cured at room temperature, the generated micro-domains within the polymer network are too small. As a result, these domains did not scatter 1550 nm laser light efficiently. In addition, a small domain at a low curing temperature implies a strong interaction between the polymer network and LC molecules, which indicates that a high drive voltage is required to unwind the helical order. Conversely, by increasing the curing temperature, large LC domains formed within the polymer network resulting in an increased attenuation and decreased operating voltage.
Figure 4-4: Performance of reflective E44 PSCLC cell at various curing temperatures. Monomer concentration is 3 wt%, pitch is ~3µm, cell gap d=15 µm. The measurements were taken at \( \lambda = 1550 \text{ nm} \) and \( T=23^\circ \text{C} \).

Figure 4-5: Voltage-dependent attenuation of the reflective E44 PSCLC cell. (a) curing temperature \( T=23^\circ \text{C} \) and (b) curing temperature \( T=70^\circ \text{C} \). Monomer concentration is 3 wt%, pitch is ~3µm, cell gap d=15 µm. The measurements were taken at \( \lambda = 1550 \text{ nm} \) and \( T=23^\circ \text{C} \).
The voltage-dependent attenuations of the 3 wt% E44 PSCLC cell at curing temperature $T=23^\circ$C and $T=70^\circ$C are shown in Figure 4-5. The PSCLC cell prepared at room temperature shows a relatively slow slope of the attenuation change in the range of 12 to 21 V$_{\text{rms}}$. However, for the case of $T=70^\circ$C curing temperature, the voltage-dependent attenuation curve has a relatively steep change when voltage is between 9.5 V$_{\text{rms}}$ to 11.5 V$_{\text{rms}}$. This is due to the high threshold voltage resulted from the helical structure and polymer network.

It is highly desirable that the PSCLC has a sufficiently broad bandwidth to cover a whole wavelength band defined by the international telecommunication union (ITU). To investigate the wavelength dependence of the PSCLC cell, an ANDO ASE light source (covering the ITU C-band wavelength range 1525~1575 nm) and an optical spectrum analyzer with a 0.2 nm resolution were employed. Figure 4-6 shows the wavelength-dependent attenuations of the E44 PSCLC cell which was cured at 70$^\circ$C. From the figure, the attenuation of the PSCLC cell is relatively insensitive to the wavelength in the 1525-1575 nm range. From bottom to top, the attenuation variations are 0.2 dB, 0.25 dB, 0.5 dB, 0.6 dB and 0.8 dB. The experimental data have been calibrated to remove the power variation of the ASE light source.

Figure 4-7 shows a plot of the voltage-dependent PDL of the E44 PSCLC cell at 70$^\circ$C curing temperature. The PDL is less than 0.25 dB within the 0-11.5 V$_{\text{rms}}$ range, which corresponds to a 0-26 dB attenuation level. Typically, the acceptable PDL for VOA devices should be less than 0.5 dB within the 0-10 dB range. The presented results indicate that the PSCLC device has overcome the polarization-dependent issue of PNLC.
Figure 4-6: Reflection spectrum of reflective E44 PSCLC cell. Monomer concentration is 3 wt%, pitch is ~3µm, cell gap d=15 µm. The measurements were taken at λ=1550 nm and T=23°C.

Figure 4-7: Voltage-dependent polarization-dependent loss of reflective E44 PSCLC cell. Monomer concentration is 3 wt%, pitch is ~3µm, curing temperature T=70°C, cell gap d=15 µm. The measurements were taken at λ=1550 nm and T=23°C.
Pitch length is another important factor in determining the focal conic domain size. The chiral-concentration-dependent optical attenuation and operating voltage were studied for the PSCLC cell with 62°C curing temperature. The chiral concentration is varied from 0.39%, 0.53% to 0.66%. Figure 4-8 shows a plot of the measured results. A low chiral concentration indicates a long pitch. As indicated in Figure 4-8 if the chiral pitch is too long, the domains are too large to scatter light effectively. However in that case the drive voltage is reduced. For a 1550 nm laser beam, the micro-domain size is more favorable when a 0.66% chiral concentration is used.

![Figure 4-8: Properties of reflective 15 μm E44 PSCLC cell containing various chiral dopant concentrations. Monomer concentration is 3 wt%, curing temperature T=62°C. The measurements were taken at λ=1550 nm and T=23°C.](image)

Polymer networks have two important effects on the PSCLC. The first is to influence the focal conic domain structure and consequently light scattering efficiency. The second effect is to assist LC molecules to relax back to the original state when the voltage is removed. A high monomer concentration leads to a fast response time, except for the increased voltage. However, as
mentioned before, a high monomer concentration generates small micro-domains. If the size of a micro-domain is too small compared to the laser wavelength, the scattering efficiency would be too low and the attenuation would be poor. In order to maximize the optical attenuation for $\lambda=1550$ nm while obtaining stable polymer networks, the employed monomer concentration was chosen to be only 3 wt%. However, even for such a low monomer concentration, together with a high curing temperature at 70 °C, the obtained micro-domain was still not optimal for scattering the $\lambda=1550$ nm laser light. The attenuation is $\sim26$ dB and response times are $\sim50/20$ ms for the rise/decay time, respectively. The slow response time originates from the high curing temperature effect. To further enhance the attenuation, a higher curing temperature had to be employed. The tradeoff would be a further increased response time. A thicker cell gap can increase the light scattering efficiency, but both response time and drive voltage are increased.

In Chapter 3, a high birefringence LC material was proven to be a useful approach to maintain a high attenuation while retaining a low operating voltage and a fast response time for PNLC. The birefringence of an E44 mixture was enhanced by adding alkyl NCS tolanes. E44-2 mixture contained 25% NCS tolane and its birefringence increased to $\Delta n\sim0.25$ at $\lambda=1550$ nm, as compared to 0.22 for E44. Thus a E44-2 PSCLC cell was prepared consisting of an E44-2 LC mixture, 066 wt% chiral dopant, 4 wt% bisphenol A dimethacrylate monomer and photopolymerized at $T=62^\circ$C. Table 4-1 summarizes the performance of the E44-2 PSCLC cell. The use of high birefringence LC is favorable to enhance the attenuation range of PSCLC, thus a higher monomer concentration and lower curing temperature as compared to E44 PSCLC were enabled in order to balance the dynamic range and response time. As discussed above, both high monomer concentration and low curing temperature produce a strong polymer network.
anchoring force, which consequently reduces response time. The 4 wt% E44-2 PSCLC indicated a smaller size micro-domain than that of the 3 wt% E44 PSCLC. However, its optical attenuation was increased to 30 dB, as compared to the 26 dB of the E44 PSCLC due to the enhanced scattering efficiency from the high birefringence LC material. In addition, the response times of E44-2 PSCLC were improved almost 2X, showing a 28 ms (rise) and 11 ms (decay), respectively, due to the enhanced polymer network from the higher monomer concentration and lower curing temperature. The longer rise time resulted from the fact that the applied voltage \( V=12 \text{ V}_{\text{rms}} \) was not too different from the threshold \( V_{\text{th}} \approx 10 \text{ V}_{\text{rms}} \). From equation 2-7, the rise time is related to the applied voltage as \( \frac{\tau_o}{\left(\frac{V}{V_{\text{th}}}\right)^2 - 1} \), where \( \tau_o \) is the free relaxation time of the LC directors. For the given drive voltage and threshold voltage, the rise time is almost 2.3X of the decay time which is consistent with the measured results of 28 ms (rise time) and 11 ms (rise and decay).

Table 4-1: Summary of reflective PSCLC performances. Cell gap \( d=15 \text{ µm} \), pitch is \( \sim 3\text{µm} \), curing temperature \( T=62^\circ\text{C} \). The measurements were taken at \( \lambda=1550 \text{ nm} \) and \( T=23^\circ\text{C} \).

<table>
<thead>
<tr>
<th></th>
<th>E44 PSCLC</th>
<th>E44-2 PSCLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monomer concentration</td>
<td>3 wt%</td>
<td>4 wt%</td>
</tr>
<tr>
<td>Cell gap (µm)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Curing temperature (°C)</td>
<td>70</td>
<td>62</td>
</tr>
<tr>
<td>Dynamic range (dB)</td>
<td>26</td>
<td>30</td>
</tr>
<tr>
<td>Control voltage (( V_{\text{rms}} ))</td>
<td>0~12</td>
<td>0~12</td>
</tr>
<tr>
<td>Polarization dependent loss (dB)</td>
<td>&lt;0.3</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Rise Time/Fall Time (ms)</td>
<td>50/20</td>
<td>28/11</td>
</tr>
<tr>
<td>Wavelength dependence (dB)</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
In addition to the high attenuation and fast response time, the E44-2 PSCLC also shows a low drive voltage (~12 V\text{rms}), small PDL (<0.2 dB), and weak wavelength dependence (<1 dB). Such a high performance of PSCLC meets industry requirements and is applicable as polarization independent optical devices, including shutters, switches, VOAs etc., in optical communications. The use of a high birefringence LC material is once again proven to be a very important and helpful approach, particularly for infrared applications.

4.3 Polymer-Stabilized Twisted-Nematic Liquid Crystals and Applications

In this section, a polymer-stabilized twisted-nematic LC (PS TNLC) is for the first time proposed and investigated. Different from PNLC and PSCLC, whose working mechanisms are based on light scattering from electric-field-induced poly-domains, PS TNLC relies on polarization rotation effect to realize optical attenuation. In addition, the polymer network in PNLC and PSCLC not only assists LC molecules to return to the desired configuration but also helps to determine and maintain poly-domain structure, while the polymer network in PS TNLC is used just to reduce the response time of a conventional TNLC.

Twisted nematic (TN) has many advantages, such as broad bandwidth, high contrast ratio, large temperature and manufacture tolerance. For a 90° TN cell, the rubbing direction of the top substrate is orthogonal to that of the bottom substrate. Thus the LC directors rotate 90° from the bottom to the top substrate. In the voltage-off state, the incident linearly polarized light follows the twist of the LC directors and is rotated by 90° after traversing through the cell and acts as a half waveplate. In a high voltage state, the LC directors are reoriented by the electric field and
the polarization rotation effect is disrupted. As a result, the incident light polarization is unaffected. To enable broadband polarization rotation of a TN cell, the product of cell gap and LC birefringence has to satisfy the Mauguin limit, $\lambda << d\Delta n$ [10], or the Gooch–Tarry first minimum condition, $d\Delta n/\lambda = \sqrt{3}/2$ [11].

Even though TN cell exhibits advantages mentioned above, due to the small twist elastic constant $K_{22}$, it shows a slower response time compared to homogenous and homeotropic cells. Typically, a 5 $\mu$m TN cell has 20–30 ms response time. In order to reduce the response time of a TN cell, several approaches can be used, such as using a low viscosity LC mixture, overdrive/undershoot driving scheme, and polymer network. Among these methods, polymer network is the simplest. The effective elastic constant can be greatly enhanced by the anchoring effect of polymer networks. The detailed dynamic response of the PS TNLC is discussed in the following paragraphs. The device application as a VOA for optical communications is emphasized.

A 3 wt% bisphenol-A-dimethacrylate monomer was mixed with a Merck E45 ($\Delta n=0.19$ at $\lambda=1550$ nm and T=22 $^\circ$C) and injected into a 7.7 $\mu$m thick, 90$^\circ$ TN cell. The cell gap is chosen so that the Gooch-Tarry first minimum is satisfied. The cell was then illuminated under UV light for photo-polymerization. After polymerization, the cell is highly transparent and shows high transmittance when sandwiched between two crossed polarizers which indicates that the polymer network basically follow the TN LC director distribution.
The working mechanism of the PS TNLC VOA is depicted in Figure 4-9. An Ando AQ4321D tunable laser working at λ=1550 nm was used as the light source. Its polarization state was randomly controlled by a polarization controller. The cell was placed between two beam displacers, which were normally 45° cut birefringence crystals such as YVO4 or Calcite. The first beam displacer split the input unpolarized beam into two orthogonally polarized components, ordinary O and extraordinary E waves. The O polarization transmits straight through the beam displacer while the E polarization has a several-degree’s refraction angle resulting in a few mm displacement in the vertical direction compared to the O polarization after traversing through the crystal.

Figure 4-9: The working mechanism of the PS TNLC based variable optical attenuator. (a) no applied voltage, the 90° PS TNLC acts like a broadband half waveplate, (b) with applied voltage, the polarization rotation effect is destroyed and light polarization is not changed after passing through the PS TNLC cell.
In the voltage-off state, the PS TNLC acts like a wide-band half waveplate, thus O polarization becomes E polarization and E becomes O after traversing through the cell. In this case, the second beam displacer combines these two polarizations back to initial unpolarized light and sends it to detector. This stands for the “ON” state. When a sufficiently high voltage is applied on the cell, the polarization rotation effect is erased thus light polarization remains the same after passing though the LC cell. In this case, the second beam displacer separates two polarizations further apart and no light is detected by the detector. This stands for the “OFF” state. Any arbitrary attenuation level could be achieved by controlling the applied voltage.

Figure 4-10: Voltage dependent transmittance of 3 wt% E45 PS TNLC VOA. Cell gap is 7.7 µm. The measurements were taken at λ=1550 nm and T=23℃.

The voltage dependent transmittance of the PS TNLC VOA is depicted in Figure 4-10. It has a 30 dB attenuation at V=23 V_{rms}. Compared to the pure E45 TNLC, the threshold voltage and drive voltage of E45 PS TNLC were increased due to the polymer network effect. The pure E45
TNLC has a 1.1 $V_{\text{rms}}$ threshold and a 2.5 $V_{\text{rms}}$ drive voltage. With such a low drive voltage, the pure E45 TNLC shows a slow response time of 26.6 ms (field-on time) and 46.4 ms (field-off time). By increasing the drive voltage from 2.5 $V_{\text{rms}}$ to 3.75 $V_{\text{rms}}$, the field-on time was reduced to 9.1 ms and field-off time remained almost the same. This observation is consistent with that discussed in Chapter 2. The rise time is dependent on the electric field strength and the decay time is determined by the elastic torque of the LC molecules. Even though a high drive voltage is beneficial to improve the response time of the E45 TNLC cell, it was found that the backflow effect [12] emerges during the LC relaxation process when applied voltage is higher than 3.7 $V_{\text{rms}}$. When the applied voltage was removed, LC directors were reoriented by the hydrodynamic flow first and then pulled back to their original twisted state which induced a small bump in the transmittance in the time domain as shown in Figure 4-11 (a). However in the PS TNLC cell, such backflow effect was suppressed due to the anchoring of polymer network, as can be seen from Figure 4-11 (b).

The switching time shown in Figure 4-11 is the time that cell switches from “OFF” state (no light detected by detector) to “ON” state (light is transmitted and detected by detector), which is also the field-off (decay) time of the device. From the curve, it is clear that the 3 wt% E45 PS TNLC has a much faster decay time than that of E45 TNLC. In fact, the field-on and field-off times of the PS TNLC cell are reduced 78X and 5X, respectively by using the polymer network effect. The comparison of the pure E45 TNLC cell and the E45 PS TNLC cell is summarized in Table 4-2.
Figure 4-11: Time-dependent transmittance showing the dynamic response of a) E45 TNLC, drive voltage $V=10\ V_{rms}$ b) 3 wt% PS TNLC, drive voltage $V=25\ V_{rms}$. Cell gap is 7.7 $\mu$m. The measurements were taken at $\lambda=1550\ nm$ and $T=23^\circ C$.

Table 4-2: Comparison of E45 TNLC and E45 PS TNLC. Cell gap is 7.7 $\mu$m. The measurements were taken at $\lambda=1550\ nm$ and $T=23^\circ C$.

<table>
<thead>
<tr>
<th></th>
<th>E45 TNLC</th>
<th>E45 PS TNLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold ($V_{rms}$)</td>
<td>1.1</td>
<td>4</td>
</tr>
<tr>
<td>Dynamic range (dB)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Control voltage ($V_{rms}$)</td>
<td>0~2.5</td>
<td>0~23</td>
</tr>
<tr>
<td>Rise Time/Fall Time (ms)</td>
<td>27/44</td>
<td>0.3/9</td>
</tr>
<tr>
<td>Backflow</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>

From the experimental results shown in the table, one can see that by adding polymer network effect in a TNLC, the response time is greatly reduced and backflow effect of TNLC is
significantly suppressed. However the presented polymer network resists LC directors from being reoriented by the electric field resulting in a high threshold and drive voltage.

4.4 References


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CHAPTER FIVE: LIQUID CRYSTAL FILLED PHOTONIC CRYSTAL FIBER AND APPLICATIONS

This chapter discusses a category of very interesting and novel photonics systems consisting of LC and photonic crystal fiber (PCF). Two different PCF systems are used in combination of LC materials. They demonstrate different guiding mechanisms and light guiding properties. The electro-optical properties of such system are investigated and discussed. The electrically induced disturbance of LC molecular alignment provides a switchable light guiding property of the LC PCF system offering very promising features and applications.

Periodic photonics structures and particularly photonic crystal fibers have gained large popularity starting with late ‘90s and beginning of this century. That resulted in a constantly increasing number of publications on that topic. Only recently tunable properties of PCFs have been recognized to be of great research interest, offering new capabilities and functionality. The works presented here are one of the pioneering attempts in this direction worldwide. The complexity of the LC PCF systems investigated makes the research on PCF tunable properties interesting, very challenging, and skills demanding. However, it is believed that the potential benefits are large, based on the experimentally demonstrated and theoretically predicted features.

5.1 Background

Photonic crystals [1] are multi-dimensional periodic dielectric or metallic structures. They have a periodic modulation of refractive index on the scale of an optical wavelength. With an appropriate design of the periodic structure, photons in a certain energy range (bandgap) are
forbidden to travel through the crystal when incident on such a material. In addition, by introducing defects in the photonic crystal lattice, light existed in the defect region can be permanently trapped and is unable to propagate through the lattice. Therefore one can control where and how photons propagate by an appropriate design of the photonic crystal lattice.

One dimensional photonic crystal structure has been exploited and used for years. One of the simple examples is the multi-layer dielectric mirror [2] as shown in Figure 5-1. It consists of a stack of quarter-wavelength thick dielectric layers having alternating refractive-index values \( n_1 \) and \( n_2 \), where \( d_1 = \frac{4\lambda}{n_1} \) and \( d_2 = \frac{4\lambda}{n_2} \). For certain wavelengths, the reflections from all interfaces add up in phase resulting in a total internal reflection (TIR). The range of the total reflected wavelengths that are unable to propagate through the multi-layer stack is the so called photonic bandgap.

Figure 5-1: A schematic of the multi-layer dielectric mirror (one-dimensional photonic crystal).
The concepts of photonic bandgap in two and three dimensions were introduced first by Yablonovitch and John in 1987 [3,4], who independently reported inhibited spontaneous emission and localization of photons in disordered dielectric superlattices. The bandgap properties of photonic crystals are analagous to electronic properties of semiconductors where the periodically varying electric potential from the atomic lattice generates electronic bandgap. Due to this appealing analogy, one can guide light in certain engineered photonic crystals in a way similar to guiding electrical currents in semiconductor chips.

With the presented novel and unusual optical phenomena, photonic crystals have attracted worldwide attentions and are considered as an essential building block of future photonic devices. When combined with for instance nonlinear effects, photonic crystals provide many potential applications, including white-light super-continuum generation, ultra-compact lasers, all-optical circuits and waveguides [5,6,7,8]. A well-engineered channel of defects in a photonic crystal can guide light in a 90° bending fashion at negligible loss [9]. It is expected that the development of photonic crystal structures will advance technologies of light controlling and localization. It is potentially useful for developing small, low cost and highly integrated optical devices. Such a new generation of optical systems and components will strongly affect optical communications.

One of the applications of photonic crystals is in new types of optical waveguides, including planar waveguides and micro-structured fibers (or PCFs). A PCF contains an array of air holes running down the length of the fiber. The air hole lattice structure of a PCF provides an additional design freedom. The light propagation properties change with the air-hole periodic structure pattern and structural parameters like pitch, core diameter, and air holes filling. As a
consequence, PCFs are very promising in breaking the limits of conventional optical fibers. The design freedom adds a unique dimension to fiber design possibilities, enabling the previously unthinkable in fiber optics. More details on PCFs and applications will be discussed in the following sections. A very good review of the technology and latest development of PCFs can be found in Ref. [10].

5.2 Photonic Crystal Fibers and Applications

The original idea on the PCF concept was proposed in 1991. However due to the fabrication problems, it was until 1995 that the first working PCF was produced by Russell and coworkers [11]. In general, there are two major types of PCFs. One is index-guiding PCF [11], which has higher refractive index in the core than in the cladding and guides light by modified TIR. The other one is photonic bandgap (PBG) fiber [12], which has lower refractive index in the core and guides light by PBG effect. An illustration of a conventional fiber, index-guiding PCF and PBG fiber is depicted in Figure 5-2. The detailed comparisons of properties of these three types of fibers are discussed later.
Figure 5-2: Illustrations of fiber structures (a) conventional fiber, (b) index-guiding photonic crystal fiber and (c) bandgap guiding photonic crystal fiber. Grey areas represent for instance silica and the white ones air holes.

5.2.1 Index Guiding Photonic Crystal Fibers

Conventional optical fibers have been widely used in telecommunications, sensor technologies, medicine, etc. They consist of a high refractive index core $n_{\text{core}}$ and a low refractive index cladding $n_{\text{clad}}$ as shown in Figure 5-2 (a). The fiber core and cladding can be made of glass, plastic or a combination of both. It is well known that a conventional fiber guides light by TIR. A schematic of TIR is depicted in Figure 5-3. The critical angle $\theta_c$ determines the maximum acceptance angle $\theta_{\text{inc}}$ of the fiber and is defined as $\theta_c = \sin^{-1}(n_{\text{clad}} / n_{\text{core}})$. When the incidence angle $\theta$ is smaller than $\theta_c$, light is total reflected by the fiber core-cladding interface and propagates in the core.
From the propagation constant $\beta$ (the wave vector component along the fiber) point of view, light is guided when $k_0 n_{clad} < \beta < k_0 n_{core}$, where $k_0$ is vacuum wave constant. In a standard conventional optical fiber, a $V$ number is defined to give approximately how many modes can be guided in the fiber. It is given by:

$$V = k_0 \cdot r \cdot \sqrt{n_{core}^2 - n_{clad}^2}$$

where $r$ is the radius of the fiber core. The number of guided modes is $N \approx V^2 / 2$ for a step-index fiber and $N \approx V^2 / 4$ for a graded index fiber.

A typical index guiding PCF is depicted in Figure 5-2 (b), consisting of a solid core and an air-hole periodic structure cladding. It can be made of a single material, such as pure silica. Because of the air holes in the cladding region, the effective refractive index of the cladding is lower than that of the core. Therefore, its guiding mechanism is similar to conventional fibers, a modified TIR effect. One could think that in this case, an index-guiding PCF is just a modified conventional fiber with unnecessarily complicated structures. In fact, despite their similarity in guiding mechanism, the index-guiding PCF offers many novel properties which cannot be achieved by conventional fibers. For example, a so called endlessly single mode index-guiding
PCF [13] is designed to be single-mode at all wavelengths, as long as the fiber material is transparent at the chosen wavelengths. However, a conventional single-mode fiber is usually designed for a certain wavelength and is actually multimode for other wavelengths shorter than the second-mode cutoff wavelength.

Similar to conventional fibers, the propagation constant \( \beta \) of a guided mode, for an index-guiding PCF satisfies:

\[
\beta \leq k_0 n_{\text{core}}
\]

where \( n_{\text{clad},e} \) is the effective refractive index of the PCF cladding. \( k_0 n_{\text{clad},e} \) defines the propagation constant for the lowest order allowed mode. According to equation 4-1, the effective \( V \) value for an index-guiding PCF can be expressed as:

\[
V_{\text{PCF}} = k_0 \cdot r \cdot \sqrt{n_{\text{core}}^2 - n_{\text{clad},e}^2}
\]

Since in a standard index-guiding PCF the core originates from a defect formed by removing one air hole from the periodic structure, thus \( r \) approximately equals to the pitch length \( \Lambda \), which is the center to center distance of the two adjacent cladding air holes. Thus, Birks [3] suggests that:

\[
V_{\text{PCF}} = k_0 \cdot \Lambda \cdot \sqrt{n_{\text{core}}^2 - n_{\text{clad},e}^2}
\]

The ratio of the air hole diameter \( d \) to the pitch length \( \Lambda \) is found to be an important factor affecting the number of guided modes in an index guiding PCF. If the ratio is large, the PCF is more likely to be multi-mode. For a small ratio, the fiber is more likely to be single-mode. However, the relative refractive index difference is decreased as well, what induces other unwanted effects, such as an increased bend loss. The bend loss is unfavorable for an endlessly
single mode fiber because it is typically the primary factor limiting the useful wavelength range on which the fiber can be used. It is always possible to design a PCF structure so that the \( d/\lambda \) ratio is below a certain value thus to obtain single mode guiding.

The above theoretical analysis employs a simple scalar model based on an effective refractive index of a fiber cladding consideration. It gives a good qualitative description of the index-guiding PCF. However for a precise investigation of PCF properties, a full vectorial plane wave expansion method has to be considered.

The air-hole periodic structure in PCF not only enables the endlessly single mode possibility, but also offers extensive opportunities in design variations, which could be useful application-wise. Specifically for example, a large-mode-area PCF realized by a very small refractive index difference between core and cladding can be used to deliver high power laser beam. In addition, it minimizes the occurrence of nonlinear optical effects. On the other side, a large refractive index difference leads to a small mode area and an enhanced nonlinearity. With combined high nonlinear coefficient and designable dispersion properties, this type of fiber shows great potentials in spectroscopy, sensor applications as well as telecommunications [14,15]. On some other circumstances where power is of importance, a large numerical aperture PCF which contains a large solid core and a single ring of air holes has been developed by Wadsworth and coworkers [16]. The large refractive index difference between the PCF core and cladding provides a possibility to achieve a numerical aperture as high as 0.9. Therefore, even though from some degree, an index-guiding PCF is similar to a conventional fiber, it does provide
numerous novel properties resulted from the special air-hole periodic structure. It goes beyond the limits of a conventional fiber and opens up many new possibilities in application.

### 5.2.2 Bandgap Guiding Photonic Crystal Fibers

PBG effect has created a new type of waveguide for controlling and localizing light. In a PBG fiber, light of a certain wavelength bandwidth is confined in the low-index core by a full two-dimensional (2D) PBG effect instead of TIR. The intrinsic need for a 2D PBG requires that the fiber cladding contains a near-perfect periodic array of air holes with a high air-filling fraction and a small pitch.

Due to the PBG guiding mechanism, light can be confined in an air core [17]. An illustration of an air-core PBG fiber is depicted in Figure 5-2 (c). The fiber core is formed by removing a number of air holes in the cladding. Experimentally it has been demonstrated that as much as 97% of the optical power is confined in the air core, and the rest of the light will be in the silica material in the cladding. With more sophisticated designs, it is possible that > 99% of power can be confined in the core. Compared to a solid core fiber, an air-core PCF offers a number of advantages. Due to the fact that light is guided in the air, it does not suffer from the losses and optical nonlinear effects originated from the interaction between guided light and fiber core material. As a consequence, a very low or very high optical power can be transmitted without unwanted effects, which are impossible for conventional fibers. For example, the ultra-short pulses from Ti:Sapphire or Nd:Glass lasers may be delivered by an air-core PCF for micro-machining or in-vivo multi-photon absorption spectroscopy applications. Furthermore, due to the small nonlinearity, the pulse broadening is suppressed. Currently commercially available air-core
PCFs are able to handle pulse energies of several tens of nano-Joule or up to 100 kW peak power for a 800 nm Ti:Sapphire laser [10]. It is expected that significantly higher power delivery will become accessible in the near future.

In addition, the air-core PBG fiber can be filled with gases, particles, or liquids to alter its transmission properties in a variety of ways. The altered properties come from the interactions of these materials with the guided light, or changes of materials themselves by external forces. Various applications have been demonstrated by such an arrangement, such as gas sensing and monitoring [18,19], atom guiding and laser delivery of small particles [20], supercontinuum generation [14], and highly engineering and compact laser sources [21].

### 5.2.3 Combination of Liquid Crystal and Photonic Crystal Structure

As above mentioned, the air-hole lattice structure of PCF not only provides more design freedom, but also broadens the potential applications of PCFs by introducing additional materials, such as polymer, gas, particle etc., into the air holes (including core and cladding holes). Among these materials, LC is of particular interests because of its unique index tuning character. The refractive index of LC can be controlled by temperature, electric field, magnetic field, light intensity (due to optical nonlinearity) and/or the state of light polarization (by optical anisotropy). Some LC photonic bandgap composite structures and slab waveguides have been demonstrated by using thermal effect [22,23,24].
In Ref [24], a LC mixture E7 is filled into a micro-cavity structure formed by 2D photonic crystal mirrors. By changing the temperature, refractive index of the LC is changed, resulting in a shifted resonance wavelength. In addition, Larsen and coauthors proposed and demonstrated a LC photonic bandgap fiber for optical switches using thermo-optical tuning [26]. In their work, a smectic LC mixture is filled into an index-guiding PCF producing a photonic bandgap due to the higher refractive index of the effective LC-silica cladding than that of the silica core. The device is highly sensitive to temperature change. A 0.4 °C change in temperature produces a 60 dB attenuation. With a different smectic LC mixture, even a 0.1 °C temperature change is demonstrated to produce a large dynamic range. However such high temperature sensitivity is not practical for applications due to the environmental oscillations in temperature.

In fact LC materials have a large electro-optical response, which can be more useful in applications. However, the electro-optical properties of LC filled PCF have been unknown and still need to be explored more closely. The goal of this chapter is to introduce some of the recent discoveries in that direction. The detailed experimental demonstrations and results will be discussed in the following sections.

5.3 Index-guiding Liquid Crystal Infiltrated Photonic Crystal Fiber

One air-core PBG fiber manufactured by Blazephotonics was used in the experiment. The center operating wavelength is designed at $\lambda=1550$ nm. It has a 10.9 µm diameter air core and a microstructured cladding containing an array of air holes in undoped fused silica running along the fiber axis. Air filling fraction is over 90%. The distance between two cladding hole centers,
so called pitch, is 3.8 µm and the diameter of the microstructured silica-air holes region is ~70 µm. An additional cladding layer of pure silica surrounding the microstructured region gives a total fiber diameter of 120 µm. Other optical and physical parameters of the air core PBG fiber are listed in Table 5-1. From numerical calculations, such fiber provides a >90% of light propagating within the air core.

Table 5-1: Optical and physical parameters of the air-core PBG fiber.

<table>
<thead>
<tr>
<th>Air-core PBG fiber parameters</th>
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<tbody>
<tr>
<td>Center operating wavelength (nm)</td>
<td>1550</td>
</tr>
<tr>
<td>Light propagation in air core</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Mode field diameter (µm)</td>
<td>7.5</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.12</td>
</tr>
<tr>
<td>Core diameter (µm)</td>
<td>10.9</td>
</tr>
<tr>
<td>Pitch (µm)</td>
<td>3.8</td>
</tr>
<tr>
<td>Air filling fraction</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>Holey cladding diameter (µm)</td>
<td>70</td>
</tr>
<tr>
<td>Silica cladding diameter (µm)</td>
<td>120</td>
</tr>
<tr>
<td>Coating diameter (µm)</td>
<td>220</td>
</tr>
</tbody>
</table>

Figure 5-4 shows the structure of the air-core PBG fiber under an optical microscope. The outer coated jacket was removed in advance. From the microscope picture, one can see that the holey region (consisting of the air core and cladding periodic air-holes) is dark and the outer pure silica
cladding is very bright. The microscope uses a white light bulb to illuminate the air-core PBG fiber for observations. Since the fiber is designed to have a center operating wavelength at $\lambda=1550$ nm which is out of the bandwidth of the white light bulb. Therefore, most of the incident light is propagating in the cladding pure silica region rather than in the air-core giving rise to the high brightness in the silica cladding and darkness in the core. There is also a small amount of light distributed in the silica material within the periodic air-hole lattice due to the fact that light tends to propagate in a higher refractive index material (silica) than a lower one (air).

Figure 5-4: Microscope picture of the Blazephotonics air-core photonic bandgap fiber.

A 13mm long air-core PBG fiber was cleaved and filled with LC E48 by capillary action. E48 is a commercial LC mixture from Merck. It has an ordinary refractive index $n_o=1.52$ and birefringence $\Delta n=0.22$ at $\lambda=632.8$ nm and $T=22$ °C. The E48 filled PCF was then carefully fixed between two parallel flat glass substrates with indium-tin-oxide (ITO) deposited on the inner surfaces. An electric field was applied along the fiber transverse direction, as shown in Figure 5-5. Two spacers were inserted between ITO glass plates to provide a 125 $\mu$m cell gap. The sample was glued together and fixed on one high precision XYZ translation stage.
Figure 5-5: The illustration of the E48 filled photonic crystal fiber sample. Glass substrates have indium-tin-oxide (ITO) deposited on the inner surfaces. Spacers have a 125 $\mu$m diameter.

Figure 5-6 shows the experimental setup for characterizing the electro-optical properties of the E48 filled PCF. A linearly polarized He-Ne laser with polarization parallel to the applied electric field was used as probe light. A set of linear polarizer, half-wave plate, and variable attenuator was used to control the input laser light intensity and polarization. Two 10X microscope objectives were used. The first microscope objective focused the input beam to a 10 $\mu$m spot and coupled it to the fiber core. The second microscope objective served to out couple the laser beam from the E48 PCF and then image the output beam profile onto a charged coupled device (CCD) camera. A computer controlled LabVIEW system and a voltage amplifier were used to provide voltage to the fiber. A non-polarizing beam splitter was used to split the output beam from the fiber to CCD camera and photodiode detector.
Figure 5-6: Experimental setup for characterizing the electro-optic properties of the E48 filled photonic crystal fiber. P = Polarizer, HW = Half-waveplate, VA = Variable attenuator, MO = Microscope objective, PCF = Photonic crystal fiber, NPB = Non-polarizing beamsplitter, D = Detector, AMP = Voltage amplifier. $\lambda$=632.8 nm and $T$=23 °C.

As we introduced in Chapter two, an aligning pretreatment is generally required in order to obtain a certain alignment of LC molecules. Otherwise molecules will be randomly oriented and strongly scatter light. Since no pretreatment was done in the air-core PBG fiber, the LC molecular alignment in the core and cladding holes was highly affected by the interface between the LC and the fiber holes. There have been many studies reported on the molecular alignment of a smectic LC in capillary tubes with a diameter ranging from 20 nm to 200 nm [26,27]. Smectic LC molecules tend to align differently in various tubes, depending on tube diameters. Studies [28,29,30] also showed that nematic LC directors tend to align along the length of the fiber in silica or Pyrex capillaries. In order to examine the director orientation and uniformity of LC alignment, the E48 filled PCF sample was placed under a crossed polarized optical microscope as shown in Figure 5-7 (a). The fiber was oriented in parallel to the microscope polarizer. In such a crossed analyzer-polarizer configuration, no light transmission from the E48 LC-infiltrated
PCF was observed by naked eyes. However, a small amount of light in the microstructured region was captured by the attached high resolution digital camera as in Figure 5-7 (b). Since the observed light throughput is very low, it is suggested that the LC director alignment is mainly along the fiber axis, in agreement with other reports [28,29,30], but with a small tilt resulting in a slight light rotation.

![Diagram](image)

Figure 5-7: (a) Experimental setup for observing LC alignment in the air-core photonic bandgap fiber and (b) the polarizing microscope picture of the E48 filled photonic crystal fiber by a high resolution digital camera.

### 5.3.1 Fiber Guiding Mechanism

Originally, the air-core PBG fiber used in the experiment has a low refractive index in the core (air) and a high refractive index in the cladding (effective refractive index of silica-air-hole lattice) and guides light based on Bragg reflection. The fiber is designed to operate at $\lambda=1550$ nm.
Accordingly, the wavelength of a He-Ne laser ($\lambda=632.8$ nm) is located outside of the photonic bandgap of the fiber and is unable to propagate through the fiber. To verify it, a He-Ne laser was used as input beam and coupled into a 12 mm air-core bandgap PCF (without LC). The output of the fiber was imaged on a CCD camera and shown in Figure 4-8 (a). The picture agrees very well with what is expected. Light is dispersed in the whole cladding holey region. Even though a relatively high intensity light appears in the core region, it is obvious that there is no guided mode in the fiber. This is understandable. For a bandgap PCF, only a certain bandwidth of wavelength which satisfies Bragg condition can be guided. The He-Ne laser wavelength is far from the designed wavelength and will be evanescent to the cladding eventually.

Figure 5-8: The comparison of CCD pictures of photonic crystal fiber outputs (a) air-core photonic bandgap fiber without LC and (b) air-core photonic bandgap fiber filled with E48 LC mixture. Fiber core diameter is 10.9 $\mu$m and cladding holey region is 70 $\mu$m. Laser wavelength $\lambda=632.8$ nm, measurement temperature $T=23$ °C.

When a LC mixture is filled in the air-core PBG fiber, the microstructured region can be approximated as consisting of a LC filled core with refractive index $n_{LC}$ and a uniform cladding with effective refractive index $n_{eff}$ in a simplified picture. Due to the higher refractive index of
E48 than silica, the LC filled fiber core has a higher refractive index than the “effective” cladding that consists of 10% silica (refractive index ~1.45) and 90% E48 (refractive index ~1.52 in the initial LC directors orientation). Such a configuration indicates a TIR as that in conventional fibers. A CCD camera picture of the output of the E48 filled PCF with He-Ne laser source is shown in Figure 4-8 (b). From the picture, it is very clear that a nearly Gaussian-profiled laser beam is guided in the fiber core. The experimental result shows that the guiding mechanism of the air-core PBG fiber is switched from the original PBG effect to a TIR guiding (also called index guiding) after the fiber is filled with E48.

The guided He-Ne laser beam profile in the E48 filled PCF is also shown in Figure 5-9. As it can be seen from the figure, the guided beam is not perfectly Gaussian-shaped. In fact, the experiment shows that the E48 filled PCF supports multi-modes. If the laser beam is not coupled into the fundamental mode, the output beam profile is irregular and less Gaussian-like. This multimode nature of the E48 filled PCF, for the given experimental parameters, has been further confirmed by the finite difference simulations.
5.3.2 Electro-Optical Properties and Discussions

The electro-optical properties of the E48 filled PCF was investigated. Figure 5-10 shows a sequence of CCD camera pictures of the fiber output at various applied voltages. The laser polarization was parallel to the electric field. When $V=0$, the He-Ne laser beam was clearly guided in the fiber core as discussed in section 5.3.1. As increasing the applied voltage, the core guided mode lost symmetry and Gaussian profile, became irregular in shape, dropped in the peak intensity, and gradually coupled more and more to the cladding LC filled holes instead of the core itself. From the CCD camera pictures one can see that at $V \approx 20 \text{ V}_{\text{rms}}$, the beam propagation is mainly confined to the "cladding holes" region, especially in those adjacent holes surrounding the core. With further increasing voltage, light was more and more confined in the "cladding holes" region. When voltage was increased to 60 $\text{V}_{\text{rms}}$, the guided throughput signal was decreased dramatically and obscured by the CCD camera noise. In this case, light propagates not even in the cladding holes region but rather in the pure silica cladding region that surrounds the
PCF structure. In this high voltage regime, light eventually leaked out of the fiber. The observation of light propagating through cladding regions composed of a number of small bright spots, indicated a “guiding” by the LC filled cladding holes.

![Figure 5-10: CCD camera pictures of the E48 filled photonic crystal fiber output at different voltages. The laser polarization is parallel to the direction of electrical field. $\lambda=632.8$ nm and $T=23$ °C.](image)
In order to quantitatively characterize the switching properties of the index guided E48 filled PCF, a photodiode detector was placed in the image plane of the fiber output. The light entering the detector was limited by an aperture so that only the light coming from the fiber core was captured. However, in practice a fraction of the cladding “modes” still might be detected by the detector causing a small fluctuation in the measurements. The voltage dependent transmittance of the fiber output with forward and backward voltage scans is shown in Figure 5-11 where the transmittance is normalized to the initial transmission in the voltage-off state.

Figure 5-11: The voltage dependent normalized transmittance of photonic crystal fiber filled with E48. The laser polarization is parallel to the applied field direction. $\lambda=632.8$ nm and $T=23$ °C.

At zero voltage, He-Ne laser beam was guided in the LC filled core of the PCF. As voltage was increased, the guided light gradually changed to be irregular and leaked to the outer LC-filled holes. As a result, the transmittance is rapidly decreased as shown in Figure 5-11. From the voltage dependence curve, one can see that this occurs at $V > 5 \text{ V}_{\text{rms}}$. When voltage was over 30
$V_{\text{rms}}$, light was already distributed evenly in the whole fiber holey region resulting in a low transmittance in the core. The dynamic range was measured to be over 30 dB at 60 $V_{\text{rms}}$. When voltage was scanned backward from 70 $V_{\text{rms}}$ to 0 $V_{\text{rms}}$, the transmittance curve followed closely to that of the forward voltage scan except for a relatively small hysteresis $\sim 1.3 \, V_{\text{rms}}$. This hysteresis possibly comes from the fluctuation raised in the measurement. The switching property was well reproducible. The rise and decay times were measured at 60 $V_{\text{rms}}$ and $T \sim 23$ °C to be $\sim 10$ and 200 ms, respectively. To improve response time, various methods can be used, including using of a LC mixture with a small visco-elastic coefficient, reducing the fiber core diameter, operating the device at an elevated temperature, or using the overdrive and undershoot voltage effect [31]. Some of these methods have been studied in Chapter three experimentally and proved to be very useful in reducing response times of PSLCs.

The light leakage behavior observed in Figure 5-10 could originate from the disturbance of the guided mode resulting from the non-uniform reorientation of LC molecules in the voltage-on state. From the polarizing microscopy, the LC molecules in the core and the cladding holes show relatively uniform behavior down the whole fiber length with the applied voltage. However, experimentally it is very difficult to precisely determine how LC molecules rotate in the voids when the voltage is applied. The interactions between the LC molecules and the fiber capillaries make the electric field – LC molecules system more complex. From the fiber structure viewpoint, the optical switching behavior is a consequence of an efficient coupling between the LC core and the surrounding LC filled holes. The size of the cladding holes is 3.8 $\mu$m which is much bigger than the He-Ne laser wavelength ($\lambda = 632.8$ nm) allowing the possibility for “guiding” within these LC filled cladding holes.
The electro-optical properties of the E48 filled PCF with an input laser polarization orthogonal to applied electric field were investigated too. Figure 5-12 depicts the corresponding CCD camera pictures of the fiber output at different voltages. Similar phenomena were observed compared to those of the parallel polarization case. In the zero voltage state the laser beam was efficiently guided. However from the camera picture, one can see that there are multiple guided modes in the fiber core resulting in an irregular beam profile. With increasing voltage guiding was quite rapidly lost. The He-Ne laser light first out coupled to the cladding holes region and finally to the pure silica region. When the voltage was further increased to 60 V\textsubscript{rms}, the guided light was decreased dramatically and obscured by the CCD camera noise.

The voltage-dependent transmittance for the case of orthogonal polarization is plotted in Figure 5-13. Results are slightly different from those shown in Figure 5-11. The guided light has a higher threshold voltage. The transmittance remains flat at V~10 V\textsubscript{rms} which shows that the ordinary wave has a higher threshold voltage. This phenomenon is similar to that observed in a LC Fabry-Perot cavity [32]. In an ideal case when there is no scrambling of the LC molecules orientation, the horizontal polarization would not see any change in the refractive index even if the voltage is applied. However, as observed from the polarizing microscope the LC directors are not aligned completely parallel to the fiber axis. A small amount of light transmission of the E48 filled PCF under a crossed polarizer-analyzer configuration is captured by a high resolution digital camera as shown in Figure 5-7 (b). For the 12 mm long fiber, even a small tilt angle in the LC molecules would induce a noticeable polarization rotation after light traversed such a long distance. As a matter of fact, the LC alignment in the fiber holes can be more complicated due to the interactions of the LC molecules with the interface of the fiber holes.
Figure 5-12: CCD camera pictures of the E48 filled photonic crystal fiber output at different voltages. Laser polarization is orthogonal to the direction of electric field. $\lambda=632.8$ nm and $T=23^\circ C$. 
Figure 5-13: The voltage dependent normalized transmittance of E48 filled photonic crystal fiber. The laser polarization is orthogonal to the applied field direction. $\lambda=632.8$ nm and $T=23$ °C.

### 5.3.3 Thermo-optical Properties and Discussions

The refractive indices $n_o$ and $n_e$ of a LC mixture are temperature dependent, representing a possible thermo-optical tuning opportunity. For most LC materials, the extraordinary refractive index $n_e$ decreases as increasing temperature. However, the ordinary refractive index $n_o$ has either positive or negative temperature gradient depending on LC material and temperature as discussed in Chapter two.

The thermo-optical properties of a smectic LC filled PCF has been investigated in Refs [25,33], where a photonic bandgap is obtained by filling a smectic LC into an index-guiding PCF. The temperature change of the fiber system changes the refractive index of the smectic LC mixture
resulting in a bandgap shift. In the case of the E48 filled PCF discussed in section 5.3.2, a nematic LC mixture was filled into an air-core PBG fiber. After LC filling, the fiber guiding mechanism was switched from PBG to TIR effect. Different thermo-optical properties than those reported in Refs. [25,33] are expected in such LC PCF system.

In the experiment, a 12 mm air-core PBG fiber was filled with an E48 LC mixture and placed carefully on a heating stage connected to a temperature controller, which has 0.1 °C precision. The fiber throughput properties as a function of temperature were measured. The measurement was automatized by a LabView program, which synchronized output CCD measurements with the temperature controller. At room temperature (T=23 °C), the He-Ne laser beam was guided in the fiber core as shown in Figure 5-14. As temperature was increased to ~80.7 °C, the light guiding in the core remained the same. However, afterwards guiding became very sensitive to the temperature change, as shown in Figure 5-14. The guided light strongly out-coupled to the cladding holey region and even further in the outer silica cladding layer at T = 81.2 °C. When the temperature was further increased to T=90 °C, the fiber core guided mode recovered completely resulting in even higher light throughput than that at the room temperature. Such experimental outcome can be well understood from the aspects of the LC phase transition temperature. E48 has a clearing temperature at T_c = 85 °C. When the temperature is approaching the T_c of E48, the LC molecules gain mobility, which causes a disturbance to the periodic structure of the PCF. The more randomly aligned LC molecules also means more light scattering. Considering that there is only a small difference in effective index between the core and the cladding, under the given circumstances the guiding becomes very unstable. The light propagating through the fiber
strongly couples from the core to the cladding holes and finally it is completely dispersed in the fiber holey region. Therefore, the fiber core loses its guiding properties.

![Figure 5-14: CCD camera pictures of E48 filled photonic crystal fiber output at various temperatures. $\lambda=632.8$ nm and $T=23 \, ^\circ\text{C}$.](image)

When the temperature is further increased to $T=90 \, ^\circ\text{C}$, which is a few degrees above the clearing temperature for E48, LC is in an isotropic state. In this case, the LC fiber core possesses a uniform refractive index, which is slightly higher than the cladding effective refractive index and guiding of light by TIR is recovered. It is believed that the key parameter in the process is LC uniformity and consequently the scattering efficiency. The lower transmitted light intensity of the E48 filled PCF within nematic phase temperature range is possibly due to the additional light scattering losses resulting from the imperfectly aligned LC molecules in the fiber holes.

In order to further examine this interesting experimental observation, another 12 mm air-core PBG fiber was prepared and filled with 5CB. 5CB is a commercial LC material from Merck. It
has an ordinary refractive index $n_o=1.535$ and birefringence $\Delta n=0.209$ at $\lambda=632.8$ nm and $T=23^\circ C$. The melting and clearing temperatures of 5CB are 24.0 $^\circ C$ and 35.3 $^\circ C$, respectively. Comparing to E48 mixture, 5CB has much lower phase transition temperature. The CCD camera pictures of 5CB filled PCF are shown in Figure 5-15. From the pictures, one can see that the guided light in the fiber core shows the similar behavior as in the case of the E48 filled PCF except that the output changes significantly around $T = 30.9$ $^\circ C$ instead of $T=80.7$ $^\circ C$. This is in agreement with the $T_c=35.3$ $^\circ C$ of 5CB. In addition, when temperature is increased over the clearing temperature of 5CB at $T=37^\circ C$, the light is again well guided in the fiber core.

Figure 5-15: CCD camera pictures of 5CB photonic crystal fiber output at various temperatures. $\lambda=632.8$ nm and $T=23$ $^\circ C$.

From both 5CB and E48 filled PCF experiments, similar behaviors are observed. The He-Ne laser light is guided in the fiber core if the temperature is far below the clearing temperature of the LC mixture used. If the temperature is in vicinity of $T_c$, the disturbance originating from the
nematic-isotropic phase transition results in a gradual coupling of light from the fiber core to the cladding holes and guiding becomes unstable. As the temperature approaching $T_c$ more closely, the He-Ne laser light is completely dispersed in the cladding holey region and no guiding in the fiber core is observed. A number of factors contribute to such outcome. However, it is believed that the key points are: 1) weak initial coupling in the fiber core, 2) coupling of light between core and cladding (notice that individual cladding holes, filled with LC, have tendency to trap light as well) thus making the fiber core guiding very sensitive to disturbances, and 3) scattering caused by the nematic-isotropic phase transition. The third factor triggers the loss of coupling in a similar fashion as that observed in the electrically tunable PCF case, which was comprehensively discussed in section 5.3.2. When the temperature is above $T_c$, the LC becomes isotropic and the light guiding by the fiber core is fully recovered. Due to the lack of alignment pretreatment in the PCF, the switching process is not fully reversible when the temperature is decreased from above $T_c$ back to the room temperature. In order for LC molecules to return back to their original state, an alignment pretreatment in the fiber should be helpful.

In conclusion, by introducing a LC mixture into an air-core PBG fiber, the guiding mechanism is switched from the original PBG to TIR. This occurs since refractive index of the core becomes larger than the one of the cladding after introducing the LC. If a voltage is applied on this index guiding PCF, the disturbance resulting from the electric field-induced LC reorientation leads to a very dramatic and rapid vanishing of the fiber core guiding. The achieved optical attenuation is over 30 dB at $\sim$60 V$_{rms}$ for the 12 mm long E48 filled PCF. The electrical tunability is fully reversible when repeatedly turning on and off drive voltage. Useful applications as optical switches in the fiber-optic systems are foreseeable. In addition, the thermo-optical properties of
such fiber were investigated. The fiber guiding changes in an interesting fashion with the temperature increase. As the temperature approaches the LC mixture’s phase transition temperature, the guiding becomes unstable and finally vanishes completely. When the temperature is further increased so that the LC mixture is in the isotropic state, the guiding is recovered. This interesting behavior has a similar origin to the electrically controllable PCF. Namely, strong coupling between the cladding (leaky) and the core (guiding) modes causes the LC-PCF systems to be very sensitive to even small disturbances, resulting in loss of guiding and drop in light throughput. However, the temperature controllable configuration is not applicable due to irreversibility of the process. Further investigation in this direction is necessary in order to understand more precisely the thermal properties of such fibers. However, that is out of the scope of this dissertation. Very recently Huang et al. [34] presented a simple method for fabricating PCFs with selectively filled air holes with liquid phase materials. Their method could be very valuable in further investigation of the tunable properties presented here.

5.4 Bandgap Guiding Liquid Crystal Filled Photonic Crystal Fiber and Its Properties

In the previous section, an index guiding PCF is realized when a LC mixture is filled into an air-core PBG fiber. The filling of LC mixture results in a higher refractive index in the fiber core than in the cladding, thus a TIR guiding mechanism is obtained. On the contrary, if a LC mixture is filled into an index-guiding PCF, due to the higher refractive index of the LC mixture than that of silica, the silica core has smaller index than the LC-silica cladding structure. Therefore, TIR guiding is not possible any more. However the cladding periodic structure enables photonic
bandgap type guiding. In this case, just certain wavelengths, which satisfy the Bragg condition, can propagate through the fiber. The originally TIR guiding fiber becomes a PBG guiding fiber.

In Ref. [26,34], some of the thermo-optical properties of such LC modified PBG fiber have been investigated. However, the electro-optic properties are entirely unexplored until recently. The goal of this section is to discuss the electro-optic aspect of the LC PBG fiber. A Blazephotonics endlessly single mode PCF was used for the investigation. Such fiber was chosen for the performed experiment is solely because of its availability. The fiber has a 12 µm diameter undoped fused silica core and a microstructured silica cladding containing an array of air holes as shown in Figure 5-16. Pitch is 8 µm and the diameter of the microstructured silica-air holes region is ~60 µm. An additional cladding layer of pure silica surrounding the micro-structured region gives a total fiber diameter of 125 µm. The fiber parameters are listed in Table 5-2.

An important feature of the single mode PCF is that it maintains a single mode property for almost all wavelengths, as long as the fiber material is transparent at a given wavelength. It has a larger mode area than a conventional single mode fiber and transmits light with near Gaussian mode profile.
Figure 5-16: Cross-section structure of an endlessly single mode photonic crystal fiber (Blazephotonics fiber).

Table 5-2: Optical and physical parameters of the endlessly single-mode photonic crystal fiber from Blazephotonics.

<table>
<thead>
<tr>
<th>Single mode PCF fiber parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode field diameter (µm)</td>
<td>6.4</td>
</tr>
<tr>
<td>Core diameter (µm)</td>
<td>12</td>
</tr>
<tr>
<td>Pitch ( \Lambda ) (µm)</td>
<td>8</td>
</tr>
<tr>
<td>Normalized hole diameter ( d/\Lambda )</td>
<td>0.46</td>
</tr>
<tr>
<td>Holey cladding diameter (µm)</td>
<td>60</td>
</tr>
<tr>
<td>Silica cladding diameter (µm)</td>
<td>125</td>
</tr>
<tr>
<td>Coating diameter (µm)</td>
<td>220</td>
</tr>
</tbody>
</table>

Sample was prepared in the same way as the one already introduced in section 5.3.2, except that a 5CB LC material is used instead of E48. The experimental setup is similar as that depicted in Figure 5-6. An ocean optics DH-2000 deuterium tungsten halogen light source was used as an input source. It provides an output within 215-1700 nm wavelength range as shown in Figure
In order to couple the white light into the 12 \( \mu \text{m} \) core PCF, various experimental conditions were investigated for achieving optimum results. A single mode conventional fiber with an 8 \( \mu \text{m} \) core was first used to collect light from the white light source to the PCF. However, due to the insufficient output power of DH-2000 and large coupling loss from source to fiber, the output from the conventional fiber was too low to perform the measurements. In order to get as high as possible light intensity from the source, a 600 \( \mu \text{m} \) core fiber was connected to DH-2000. The output was then focused down by a microscope objective to a \(~115 \mu \text{m}\) spot size. Due to the nature of the DH-2000 white light source, the system’s throughput limits the minimum obtainable spot size. Therefore, it is impossible according to the linear means to achieve a smaller spot size than \(~115 \mu \text{m}\). One could splice a single mode fiber to the PCF to get more efficient coupling. However, that is limited by the available laboratory conditions. The PCF itself has a 125 \( \mu \text{m} \) pure silica cladding and a \(~60 \mu \text{m}\) periodic structure cladding. By using the 115 \( \mu \text{m} \) diameter beam as input beam to the PCF, a large coupling loss is foreseen, along with the measurement errors, which will be discussed later. Two microscope objectives were used to couple light in and out of the PCF, respectively. A computer controlled LabVIEW system and a voltage amplifier were used to apply voltage to the fiber. A flipping mirror/beam splitter was used to reflect the output beam profile from the fiber to a CCD camera. A lens system was placed behind the second microscope objective to couple light into a pigtailed fiber collimator with the fiber end connected to an Ando spectrum analyzer.
Figure 5-18 shows a sequence of CCD camera photos of the 5CB filled endlessly single-mode PCF at various voltages. From the figure, one can see that a certain amount of light propagates through the pure silica cladding (the outer region in the figure) along with the light guided in the fiber core at V=0. This is a result of the poor coupling due to the large mode size mismatch between the input spot size (~115 µm) and the PCF core (12 µm). The input beam practically covers almost the whole fiber cross-section, and thus some light remains in the silica region instead in the fiber core. Even though some light propagates in the cladding region, it is clear that the guided light in the fiber core has a higher intensity. When the voltage is increased, the light intensity in the core region gradually drops, as shown in Figure 5-18. However the light intensity in the pure silica region remains nearly the same, according to the CCD camera. It indicates that some light has leaked completely out of the fiber. The voltage-dependent transmission is shown in Figure 5-19. A contrast of 5:1 is observed when the voltage is increased to $V=100 \text{ V}_{\text{rms}}$. 

Figure 5-17: Spectrum of the DH-2000 (Ocean Optics) white light source.
However, due to the large amount of noise from the originally coupled light in the cladding holey region and the pure silica region as a result of the large diameter input beam, the measurements are not very accurate. The investigation gives only the basic electro-optics behavior (voltage dependent transmission) for the 5CB filled PCF, rather than precise quantitative data.

Figure 5-18: CCD camera pictures of the 5CB filled photonic crystal fiber output at different voltages, A DH-2000 white light source is used as input source and measurement is take at T=23°C.
The spectrum of the 5CB filled PCF was also investigated, as shown in Figure 5-21. The spectrum of the white light source, the 5CB filled PCF at zero voltage and at $V=150 \text{ V}_{\text{rms}}$ are compared. In order to measure the light originating from the fiber core, an aperture was used. The aperture was positioned in the image plane of the fiber output facet. However, it is estimated that some of the cladding light contributes to the measured spectra as well. Unfortunately it is impossible to tell what the exact contribution is except that the fine features in the spectra are lost. This is considered to be one of the reasons that it is unable to notice a shift in the bandgaps at applied voltage, as expected. Instead, only a clear decrease in the throughput resulting from the voltage increase is observed, as demonstrated in Figure 5-19. It is not clear, from the results shown here, if the bandgap structure changes or not. Moreover the spectral features seem to be well maintained (positions of the recesses in the spectra).
Figure 5-20: The spectrum of the 5CB filled photonic crystal fiber output. A DH-2000 white light source is used as input source and measurement is take at T=23 °C.

When an external voltage is applied on the LC filled PCF, the liquid crystal starts to reorient perpendicularly to the fiber axis. This introduces a large anisotropy and makes the system more complex. One expects to observe better mode confinement in such fiber under the given conditions because of the larger LC-silica contrast introduced by the LC reorientation. One could also discuss the light guiding capabilities of the individual LC filled cladding holes. However, Figure 5-19 clearly eliminates that assumption. A significant drawback of the employed BlazePhotonics fiber is in the limited number of holes in the holey region. There are only three to four layers of holes separating the fiber core from the outer silica cladding. Therefore, the bandgap properties are not strongly presented in such fiber and it is not expected to have sharp distinction between the spectral regions of the leaky and the bandgap guided modes.
From above discussions it is clear that under the given experimental conditions there is not enough contrast between the bandgap guided and leaky spectral features to see a large distinction between these two. The decrease in the guided light throughput remains as the major effect. It is a consequence of the degraded periodicity in the holey region, once the LC molecules are forced to reorient. The effect is equivalent to a poorly fabricated photonic bandgap fiber, which has a low quality periodic structure and is consequently lossy.

In conclusion, PBG guiding is demonstrated for a LC-infiltrated index guiding PCF. The voltage induced LC reorientation results in the decrease of the guided light throughput. This is understood as a consequence of LC degradation in the periodic structure quality, which is caused by the LC reorientation. Due to the currently limited experimental conditions on one side, such as the poor coupling, and the PCF-LC system functional complexity on the other side, it is difficult to conduct more detailed analysis of this interesting behavior. Further improvements and innovations are needed in accomplishing more thorough and accurate investigations on the electro-optic properties of the LC modified PBG fiber.

5.5 References


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CHAPTER SIX: SUMMARY AND CONCLUSION

This dissertation investigates liquid crystal materials and devices with objectives to meeting challenges in liquid crystal applications for photonics systems and communications. From the research topics covered here, the dissertation can be divided into two major parts: 1) Polymer-stabilized liquid crystal (PSLC) materials and devices, and 2) LC-infiltrated photonic crystal fiber (PCF) and applications. The study of PSLC is of significant practical value and basic interest in physics. Curing temperature and high birefringence LC are found to greatly improve the PSLC performances. The research conducted in this dissertation enables PSLCs for optical communications. The second part of the dissertation deals with a novel concept combining LC and PCF. For the first time, an electrically tunable nematic LC filled PCF is proposed and demonstrated. The electro-optical properties of such system are thoroughly investigated. It opens possibilities for developing new photonic devices and systems.

The investigation of PSLC materials and applications are discussed in Chapter three. Three different PSLC systems are discussed and experimentally investigated: PNLC, PSCLC and PSTNLC. They operate at different working mechanisms and show some degree of similarity as well. PNLC consists of a nematic LC and a small amount of monomer (<10 wt%). It is polarization dependent. PSCLC is similar to PNLC except that a cholesteric, instead of nematic, LC is used. Due to the helical structure that the cholesteric LC molecules intrinsically have, PSCLC exhibits a polarization-independent feature which is particularly attractive to fiber-optical communications. Both PNLC and PSCLC are fabricated with a homogeneous cell, while PSTNLC utilizes a 90° twisted cell and possesses an intriguing polarization rotation effect.
In the beginning of Chapter three, curing temperature is discovered to have a dramatic influence on PNLC. A thorough investigation is performed and results are analyzed. At high curing temperatures, larger LC micro-domains are formed within the cross-linked polymer network bundles. When the micro-domain size is comparable to the operating laser wavelength, the maximum light scattering efficiency is obtained and the contrast ratio of the PNLC is enhanced. For the He-Ne laser wavelength, the contrast ratio of an 8 \( \mu m \) thick 4 wt% E48 PNLC has an over 30X improvement when the curing temperature is increased from room temperature to 50 \( ^\circ \)C. Meanwhile, the drive voltage is reduced from 11.9 to 6.5 V\(_{\text{rms}}\) and hysteresis is suppressed ~2X. If the curing temperature is further increased, drive voltage and hysteresis can be further reduced. However the contrast ratio is largely dependent on the operating wavelength and LC micro-domain size. The tradeoff of high curing temperature is the increased response time due to weakened polymer network effects.

Following the curing temperature investigation, a reflective type PNLC with a high attenuation, low drive voltage and fast response time is developed as VOAs or scattering polarizers for optical communications. At \( \lambda=1550 \) nm, due to the reduced LC birefringence and small LC micro-domains at long wavelengths, PNLC shows a very poor attenuation. In order to enhance attenuation, a thicker cell gap (16 \( \mu m \)) is used which consequently increases the drive voltage and hysteresis. For a conventional 16-\( \mu m \)-thick 4 wt\% E44 PNLC, it has a ~12 dB attenuation at \( V=22 \) V\(_{\text{rms}}\). Such a poor performance hinders PNLCs from being applied in optical communications. The curing temperature is used in the experiments to improve the performance. At 85 \( ^\circ \)C curing temperature, the 16-\( \mu m \)-thick 4 wt\% E44 PNLC cell shows a ~34 dB attenuation.
at \( V=9 \) \( V_{\text{rms}} \), an impressive performance compared to those conventional ones. However the response time is slow. For further improvement, high birefringence LC is developed by adding a NCS tolane to E44 mixture. The birefringence of E44 is enhanced from 0.22 to 0.25 for \( \lambda=1550 \) \( \text{nm} \) when a 25 wt\% alkyl NCS tolane is used. The high birefringence LC boosts the contrast ratio so that a low curing temperature can be used to reduce the response time. With the high birefringence LC mixture, a 16-\( \mu \)m-thick 4 wt\% monomer PNLC exhibits a 32 dB attenuation at \( V=12 \) \( V_{\text{rms}} \). The rise and decay times are 7 and 20 milliseconds, respectively. Compared with the PNLC prepared at room temperature, the attenuation has a 20 dB improvement, drive voltage is reduced \(~2X\) and hysteresis is suppressed \(~3X\). Such high performance enables PNLC’s applications as shutters, switchable polarizers, and VOAs for optical communications.

The only disadvantage of PNLCs is in the fact that they are polarization sensitive. Therefore in section 3.3, a PSCLC is proposed to overcome this shortcoming. In the experiment, a 0.66 wt\% chiral dopant and 4 wt\% monomer are added in the E44 LC host. The mixture is injected into a homogenous cell and photo-polymerized under a weak UV light. After polymerization, the PSCLC is in a planar structure and transparent at \( \lambda=1550 \) \( \text{nm} \). When a voltage is applied, the cell switches into a focal conic structure where helical axes are randomly aligned and scatters light no matter of light polarization. The monomer concentration, chiral dopant concentration, and curing temperature are studied to optimize the performance. When the monomer concentration is below 2 wt\%, the polymer network formed is unstable and easily destroyed under an applied voltage. At a high monomer concentration, the LC micro-domain size is too small resulting in a poor attenuation and a high drive voltage at \( \lambda=1550 \) \( \text{nm} \). Curing temperature, once again, is proved to be a helpful method for improving attenuation and reducing drive voltage of PSCLC.
For a PSCLC prepared at room temperature, the attenuation is only ~14 dB at $V=21\ V_{\text{rms}}$. However as increasing the curing temperature to 70°C, the attenuation is increased to 26 dB and the drive voltage decreased almost linearly from 21 to 11.5 $V_{\text{rms}}$. Combining with high birefringence LC mixture, a 15 µm 4 wt% monomer PSCLC exhibits a 30 dB attenuation at $V=12\ V_{\text{rms}}$. It has a small polarization dependent loss (<0.2dB) and a small wavelength dependence (<1 dB) between 1525-1575 nm wavelength range. The rise and decay times are 11 and 28 milliseconds, respectively. Such a high performance polarization-independent PSCLC is especially desirable for optical communications. It does not need polarization control systems as a commercially available LC based device does to obtain polarization independence, which consequently reduces packaging size and assembly cost. This research is of significant practical value and may advance the LC based devices to a new level.

At the end of Chapter three, an alternative solution is demonstrated for polarization independent optical devices, specifically VOAs, in optical communications. The system is realized by a PS TNLC combining with two polarization beam displacers. The polarization rotation effect of TNLC is utilized for optical attenuation. A 30 dB attenuation is achieved with such a PSLC system. The turn on and off time are reduced by 78X and 5X, respectively, to 0.9 and 9 milliseconds by introducing a polymer network structure into the TNLC, compared to that of the pure TNLC. In addition, the back flow effect is greatly suppressed at high drive voltages.

Chapter four introduces a novel and intriguing concept combining LC and PCF. Two different PCF systems, index guiding PCF and bandgap guiding PCF are investigated in combination of LC materials. At first, a nematic LC E48 is filled into a 12 mm long air-core PBG fiber. Due to
the fact that E48 has a higher refractive index than fiber material silica, the LC-filled fiber core has a higher refractive index than the effective cladding. Thus the guiding mechanism of the PCF switches from the original PBG to TIR after being filled with E48. For the first time, the electro-optical properties of such nematic LC-filled PCF are experimentally demonstrated. It is discovered that the disturbance of LC molecular alignment from external electric field greatly affects the fiber guiding. At zero voltage, the LC PCF guides light in the core with a near Gaussian profile. When a voltage is applied, the guided light gradually out-couples to the closest LC-filled holes in the cladding and then further to the outer holes. Finally at $V=60 \text{ V}_{\text{rms}}$, light is dispersed in the pure silica cladding and eventually leaked out of the fiber. The fiber guiding can be controlled by switching on and off the external voltage. An attenuation over 30 dB is demonstrated. Its useful applications as compact optical switches in the fiber-optic systems are foreseeable.

Following this, thermo-optical properties of such a LC PCF are investigated as well. The fiber gradually loses guiding when the temperature is approaching the clearing temperature $T_c$ of the filled LC mixture. The strong coupling between cladding and core modes causes the LC PCF systems to be very sensitive to the disturbance originating from the nematic-isotropic phase transition, resulting in the loss of guiding effect. When temperature is further increased so that the LC mixture is in an isotropic phase, the guiding is recovered. However, the fiber guiding is irreversible as temperature decreases from above $T_c$ which makes it not applicable. Further investigation in this direction is necessary in order to understand more precisely the thermal properties of such fibers. Technologies, such as pretreatment of various LC alignments in the PCF, should also be studied so that the LC PCF system can be more controllable.
At the end of the Chapter four, electro-optical properties of a different PCF system are investigated. A LC mixture is filled into an index-guiding PCF. Due to the higher refractive index in the LC-silica cladding than in the silica core, the fiber guiding mechanism is switched from the original index guiding to bandgap guiding after LC filling. A white light source which has a wavelength bandwidth of 215-1700 nm is used as input source. The electric field induced LC molecules reorientation results in a decrease of the guided light throughput. The output spectrum of the fiber is investigated as well. However, it is difficult to conduct more detailed analyses of the bandgap guiding LC PCF due to the problems with the white light source delivery and efficient coupling directly to the fiber core. In addition, the employed PCF is not very well matched with the wavelength region of interest. Quality of the holey region, consisting of only three layers of holes, in the fiber used is debatable as well. Further improvements and innovations in LC PCF technology are expected to provide new capabilities to develop exotic tunable photonics systems.

Overall, the work reported in this dissertation not only extends and deepens the research on PSLCs technology, but also broadens the horizons of the LC technology through the investigation of properties of LC PCF. The author believes that it has an extensive and important contribution for LC applications in optical communications.