Optically Isotropic Liquid Crystals For Display And Photonic Applications

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OPTICALLY ISOTROPIC LIQUID CRYSTALS FOR DISPLAY AND
PHOTONIC APPLICATIONS

by

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

For the past few decades, tremendous progress has been made on liquid crystal display (LCD) technologies in terms of stability, resolution, contrast ratio, and viewing angle. The remaining challenge is response time. The state-of-the-art response time of a nematic liquid crystal is a few milliseconds. Faster response time is desirable in order to reduce motion blur and to realize color sequential display using RGB LEDs, which triples the optical efficiency and resolution density.

Polymer-stabilized blue phase liquid crystal (PS-BPLC) is a strong candidate for achieving fast response time because its self-assembled cubic structure greatly reduces the coherence length. The response time is typically in the submillisecond range and can even reach microsecond under optimized conditions. Moreover, it exhibit several attractive features, such as no need for surface alignment layer, intrinsic wide viewing angle, and cell gap insensitivity if an in-plane-switching (IPS) cell is employed.

In this dissertation, recent progresses in polymer-stabilized blue phases, or more generally optically-isotropic liquid crystals, are presented. Potential applications in display and photonic devices are also demonstrated.

In Chapter 1, a brief introduction of optically isotropic liquid crystals is given.

In Chapter 2, we investigate each component of polymer-stabilized blue phase materials and provide guidelines for material preparation and optimization. In Chapter 3, the electro-optical properties of PS-BPLCs, including electric-field-induced birefringence and dynamic behaviors are characterized. Theoretical models are proposed to explain the physical phenomena. Good agreements between experimental data and models are obtained. The proposed models also
provide useful guidelines for both material and device optimizations.

Four display and photonic devices using PS-BPLCs are demonstrated in Chapter 4. First, by red-shifting the Bragg reflection and using circular polarizers, we reduce the LCD driving voltage by 35% as compared to a short-pitch BPLC while maintaining high contrast ratio and submillisecond response time. Second, a turning film which is critically needed for widening the viewing angle of a vertical field switching (VFS) BPLC mode is designed. With this film, the viewing angle of VFS is widened to ± 80° in horizontal direction and ± 50° in vertical direction. Without this turning film, the viewing angle is only ±30°, which is too narrow for most applications. Third, a reflective BPLC display with vivid colors, submillisecond response time, and natural grayscale is demonstrated for the first time. The proposed BPLC reflective display opens a new gateway for 3D reflective displays; it could make significant impact to display industry. Finally, we demonstrate a tunable phase grating with a high diffraction efficiency of 40% and submillisecond response time. This tunable grating exhibits great potential for photonic and display applications, such as optical interconnects, beam steering, and projection displays.
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<th>Full Form</th>
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<tr>
<td>LC</td>
<td>Liquid Crystal</td>
</tr>
<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>TN</td>
<td>Twist Nematic</td>
</tr>
<tr>
<td>HG</td>
<td>Homogenous</td>
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<tr>
<td>N*</td>
<td>Chiral Nematic</td>
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<tr>
<td>ISO</td>
<td>Isotropic</td>
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<tr>
<td>BP</td>
<td>Blue Phase</td>
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<tr>
<td>BPLC</td>
<td>Blue Phase Liquid Crystal</td>
</tr>
<tr>
<td>PSBP</td>
<td>Polymer-Stabilized Blue Phase</td>
</tr>
<tr>
<td>PS-BPLC</td>
<td>Polymer-Stabilized Blue Phase Liquid Crystal</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra-Violet</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<td>ITO</td>
<td>Indium-Tin-Oxide</td>
</tr>
<tr>
<td>TFT</td>
<td>Thin Film Transistor</td>
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<tr>
<td>IPS</td>
<td>In-Plane Switching</td>
</tr>
<tr>
<td>VFS</td>
<td>Vertical Field Switching</td>
</tr>
<tr>
<td>VT</td>
<td>Voltage-dependent Transmittance</td>
</tr>
<tr>
<td>VR</td>
<td>Voltage-dependent Reflectance</td>
</tr>
<tr>
<td>PDLC</td>
<td>Polymer-dispersed Liquid Crystal</td>
</tr>
<tr>
<td>PI</td>
<td>Polyimide</td>
</tr>
<tr>
<td>FoM</td>
<td>Figure of Merit</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>-------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>LCP</td>
<td>Left-handed Circular Polarizer</td>
</tr>
<tr>
<td>RCP</td>
<td>Right-handed Circular Polarizer</td>
</tr>
<tr>
<td>TIR</td>
<td>Total Internal Reflection</td>
</tr>
<tr>
<td>BLU</td>
<td>Backlight Unit</td>
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CHAPTER 1 INTRODUCTION TO OPTICALLY ISOTROPIC LIQUID CRYSTALS

1.1 Background

Liquid crystal (LC) phase was first discovered in 1888 by Austrian botanist and chemist Friedrich Reinitzer, and German physicist Otto Lehmann. It is an intermediate state of matter between isotropic fluids and crystal solids. Liquid crystals are fluid-like, but the arrangement of molecules within them exhibit structural order [1]. There are several different types of liquid crystal phases, which can be distinguished by the orderings of molecules and their optical properties. Basically, liquid crystals can be divided into three types: thermotropic, lyotropic and polymeric. Among these three, a lot of research work has been done towards the thermotropic phase. Thermotropic LCs exhibit a series of phase transitions as temperature increases: from solid to anisotropic liquid crystal, to isotropic liquid, and finally to vapor phase. Typically, thermotropic LCs can exist in three phases: smectic, nematic, and cholesteric, as illustrated in Figure 1.1 [2].

![Figure 1.1: Illustration of thermotropic liquid crystals: smectic A B C, nematic and cholesteric phase [2.](image)](image)
Chiral nematic mesophase is usually referred to as cholesteric phase. Cholesteric liquid crystals have helical structure, in which the direction of long molecular axes of each layer forms a given angle with that of the successive layer. In the vicinity of its transition to isotropic phase, optically isotropic uniform textures are often observed. This texture is called blue phase (BP) [3]. The most obvious feature of blue phases is selective reflection of incident light. In early investigations, blue phases exhibit blue colors; that is how blue phase got its name. However, blue phases are not always blue; they may reflect light of other colors, depending on the chirality of the liquid crystals. Another important characteristic of blue phases is frustration. They only exist in such a narrow temperature range (0.5-2K) that further investigation of blue phases was not pursued for over 80 years ever since the discovery by Reinitzer in 1888 [4]. Not until 1970s, the study of blue phases became popular and tremendous progresses had been made. It was discovered that blue phase is optically isotropic while exhibiting unusually strong optical activity. Based on this phenomenon, Saupe proposed that blue phases have cubic superstructures, which is the most foresighted proposal in the history of blue phase studies [5]. Later, much effort was devoted to explore the structure of blue phases, both experimentally and theoretically [6-13]. There are up to three types of blue phases: BPI, BPII, and BPIII, in the order of increasing temperature. While BPIII possesses the same symmetry as isotropic phase, BPI and BPII are comprised of double-twist cylinders arranged in cubic lattices, as shown in Figure 1.2(a) and Figure 1.2(c). Inside each cylinder, the LC director rotates spatially about any radius of the cylinder. These double-twist cylinders are then fitted into a three-dimensional structure. However, they cannot fill the full space without defects. Therefore, blue phase is a coexistence of double-twist cylinders and disclinations. Defects occur at the points where the cylinders are in
contact, as illustrated in Figure 1.2(b) and Figure 1.2(d). These defects tend to make the structure less stable which in turn results in a narrow temperature range. Although the delicate structures of blue phases greatly attract scientific attentions, their applications are limited by the narrow temperature range.

![Figure 1.2: Cubic structure of BP-I [(a) and (b)] and BP-II [(c) and (d)] filled with double-twist cylinders. The black lines in (b) and (d) represent defect lines for the structure.](image)

In a cholesteric (chiral nematic) liquid crystal, the selective reflection wavelength $\lambda = n \cdot P$, where $n$ is the average refractive index and $P$ is the pitch length. The reflection band is relatively broad with $\Delta \lambda = \Delta n \cdot P$, where $\Delta n$ is the birefringence of the liquid crystal host. Different from the chiral nematic phase, blue phases do not need any alignment layer and have several reflection wavelengths, corresponding to various crystal planes. The Bragg reflection wavelength can be expressed as:

$$\lambda = \frac{2na}{\sqrt{h^2 + k^2 + l^2}},$$  \hspace{1cm} (1.1)$$

where $n$ and $a$ denote average refractive index and lattice constant of blue phases, and $h$, $k$, and $l$
are the Miller indices. In BPI, the lattice constant corresponds to one pitch length and diffraction peaks appear at (110), (200), and (211), etc. The summation of Miller indices $h + k + l$ is an even number. In BPII, the lattice constant corresponds to half a pitch length and diffraction peaks appear at (100), (110), etc. [14]. The pitch length of a BPLC is slightly different from that of chiral nematic phase. The reflection bandwidth is also much narrower than that of chiral nematic phase. Figure 1.3 shows the platelet textures of three BPLCs under crossed polarizers. The three photos exhibit different colors because of their different pitch lengths. The multiple colors in one photo correspond to the different crystal planes.

Figure 1.3: BPLC platelet textures under a polarizing optical microscope with different chiral concentrations.

1.2 Recent Progresses

Several methods have been proposed to widen the temperature range [15-17]. The one that attracts the most interest is the polymer-stabilization method developed by Kikuchi et al.[16]. It is considered that the cross-linked polymer network is selectively concentrated in the defect lines to stabilize the lattice structure of blue phases. As a result, the temperature range of BPLC has been extended to more than 60K, including room temperature (260-326K). Moreover, the
polymer-stabilized blue phase exhibits fast electro-optic switching property. This approach opens a new gateway for display and photonic applications of blue phases. Later, it was found that optically isotropic medium can also be obtained even if curing the composite in an isotropic phase, where no blue phase structure is observed [18,19]. The electro-optical properties of the polymer-stabilized isotropic phase are similar to that of the polymer-stabilized blue phase liquid crystal (PS-BPLC). Therefore, in the following discussion, we will refer to both of them as optically isotropic liquid crystals, regardless curing at blue phase or isotropic phase. However, from the application point of view, we will emphasize on polymer-stabilized blue phase liquid crystal, because it has lower scattering and faster response time [20].

Macroscopically, when there is no electric field applied the polymer-stabilized mixture appears to be optically isotropic because the molecules can be regarded as randomly distributed. Applying an electric field causes the molecules to be reoriented along the electric field direction if the LC has a positive dielectric anisotropy (Δε). As a result, birefringence is induced. Although the microscopic picture of the interaction between the electric field and LC molecules is not completely understood; macroscopically, this optically isotropic-to-anisotropic transition can be treated as Kerr effect [21,22]. The polymer-stabilized optically isotropic LCs exhibit a fairly large Kerr constant, three orders of magnitude larger than a well-known Kerr medium nitrobenzene. The large Kerr constant, coupled with fast response time, makes the optically isotropic LC material a potential candidate for high speed light modulators and tunable photonic devices.

From display viewpoint, polymer-stabilized optically isotropic liquid crystals exhibit several attractive advantages, such as no need for surface alignment layer, submillisecond gray-
to-gray response time, intrinsic wide viewing angle, and cell gap insensitivity for in-plane-switching (IPS) mode. Especially, the submillisecond response time enables color sequential display using RGB LEDs, which triples the optical efficiency and resolution density. However, several technical challenges, such as high operating voltage, hysteresis, and residual birefringence, remain to be addressed before widespread commercialization can be realized.

Based on Kerr effect, Ge et al. developed a simulation method to calculate the electro-optical properties of PS-BPLC [23,24]. This simulation method helps predict the electro-optical performance of BPLC materials, and moreover, serves as a tool for designing different device structures in order to lower their operating voltage. The JNC JC-BP01M exhibits a high Kerr constant of ~13.7 nm/V$^2$ and ~50V driving voltage, based on an in-plane-switching (IPS) cell with 10 µm electrode width and 10 µm electrode gap [25]. With this newly developed material, different electrode designs have been proposed [26-28]. For example, with protruded electrodes the driving voltage of a PS-BPLC device can be reduced to below 10 V, which, for the first time, enables amorphous silicon thin-film-transistor (TFT) driving [26].
CHAPTER 2  POLYMER STABILIZED BLUE PHASE MATERIALS

Recently, new blue phase materials are developed in various ways [29-31]. Here, we focus on the blue phases induced by incorporating chiral dopants into a nematic LC host. To make a polymer-stabilized blue phase liquid crystal, a small fraction of monomers (~8%) and photoinitiator (~0.5%) is added to the blue phase system. Figure 2.1 shows some exemplary nematic LC compounds [32], chiral dopants, and monomers. Then we control the temperature within the narrow blue phase range to conduct the UV curing process. After UV irradiation, monomers are polymerized to form polymer network which stabilizes the blue phase lattice structures.

![Figure 2.1: Examples of nematic liquid crystals, chiral dopants, and monomers.](image)

LC compounds

Chiral dopants

Monomers

(a) mono-functional

(b) di-functional

(c) tri-functional

EHA  C12A  TMPTA

Figure 2.1: Examples of nematic liquid crystals, chiral dopants, and monomers.
In a polymer-stabilized self-assembled blue phase system, each material component plays an important role while interacting with each other. We will discuss the optimization of materials in terms of nematic LC host, chiral dopant, and monomers, respectively.

2.1 Nematic LC Host

Nematic liquid crystal host occupies the highest concentration in a polymer-stabilized BPLC material system. Therefore, it plays major role in determining the performance of the system, such as temperature range, driving voltage, and response time. For display and photonics applications, the blue phase temperature range should cover from -40°C to 80°C. To obtain a wide-temperature-range polymer-stabilized BPLC, a nematic LC host should first have a wide nematic range. While the lower temperature limit is less a concern, the higher temperature limit is mainly determined by the clearing point of the nematic LC host. Since other components in the polymer-stabilized BPLC system tend to lower the clearing temperature, it is essential to choose a nematic LC host with clearing temperature $T_c > 80$°C.

The driving voltage of a BPLC device depends on the device structure and the Kerr constant ($K$) of the material employed. The on-state voltage ($V_{on}$) is inversely proportional to the square-root of $K$ [26]. For example, if $K$ increases by 4X then $V_{on}$ would decrease by 2X. The development goals for BPLC materials are: 1) to increase Kerr constant for lowering the driving voltage ($V_{on} < 10$V), 2) to eliminate hysteresis for accurate grayscale control and to minimize residual birefringence for high contrast ratio, and 3) to form sturdy BPLC composite with long term stability.

The Kerr constant of a BPLC is determined by several LC parameters as [22]:

\[ K = \text{const.} \times \frac{\Delta n}{\Delta r} \]

where $\Delta n$ is the change in refractive index and $\Delta r$ is the change in birefringence.
\[ K \approx \Delta n \cdot \Delta \varepsilon - \frac{\varepsilon \gamma P^2}{k \lambda (2\pi)^2}, \tag{2.1} \]

where \( \Delta n, \Delta \varepsilon, \) and \( k \) are the intrinsic birefringence, dielectric anisotropy, and elastic constant of the host LC material, and \( P \) is the pitch length. From Eq. (2.1), to enhance Kerr constant, a liquid crystal with high \( \Delta n \) and large \( \Delta \varepsilon \) is highly desirable. Birefringence of a LC is determined by the conjugation length and dielectric anisotropy by the dipole moment. As shown in Figure 2.1, the exemplary compounds have 3-4 phenyl rings in order to obtain a high birefringence. They also have several polar groups for achieving a large \( \Delta \varepsilon \). Moreover, to keep a high voltage holding ratio fluoro compounds are preferred. An obvious shortcoming for having so many polar groups is the increased viscosity.

Pitch length also plays an important role in determining the Kerr constant. For display and photonic applications, the device should be clear in the visible spectral region. Thus, the Bragg reflection is usually designed to be at \(~350\) nm. As a result, the pitch length is normally \(~200\) nm. Such a short pitch would lead to increased voltage. One possible strategy to enhance Kerr constant is to increase pitch length, i.e., to shift the Bragg reflection to a longer wavelength. The long pitch BPLC will be discussed in Chapter 4.

The response time of a polymer-stabilized BPLC material is related to the LC parameters as [33]:

\[ \tau \approx \frac{\gamma_1 P^2}{k (2\pi)^2}, \tag{2.2} \]

where \( \gamma_1 \) is the rotational viscosity of the BPLC system, which is closely related to the viscosity of the LC host and the chiral dopant. A low viscosity LC host is always favorable from the response time viewpoint. However, there are compromises between the large Kerr constant and
fast response time. For example, large $\Delta \varepsilon$ is favorable for boosting Kerr constant, but its viscosity is usually large. Similarly, increasing pitch length helps to enhance Kerr constant, but it will slow down the response time as Eq. (2.2) shows. All these factors should be taken into consideration in order to develop a high Kerr constant BPLC while remaining the fast response time feature. For example, JNC JC-BP01M has a high Kerr constant $\sim 13.7 \text{ nm/V}^2$ because its host LC has $\Delta n \sim 0.17$ and $\Delta \varepsilon \sim 94$ [25]. Meanwhile, the clearing temperature of JC-BP01M is $\sim 70^\circ \text{C}$ and the response time in an IPS cell is $\sim 1 \text{ ms}$ at $\sim 30^\circ \text{C}$.

### 2.2 Chiral Dopants

Chiral dopants induce twist in blue phases. Blue phases only appear as the chirality ($q_0 = 2\pi/P$) exceeds a certain value. To increase chirality, we can either increase the chiral dopant concentration or employ a chiral dopant with a high helical twisting power (HTP). Since the solubility of chiral dopants would limit the maximum concentration, it is preferred to use a high HTP chiral dopant. For example, Merck developed a chiral dopant with HTP $\sim 170\mu\text{m}^{-1}$, which to our best knowledge has the highest helical twisting power [34].

Another important parameter to consider for selecting a chiral dopant is the melting point. For example, CB15 shown in Figure 2.1 has a very low melting point $\sim 4^\circ \text{C}$. Therefore, after mixing with the LC host, the clearing temperature of the mixture drops substantially as compared to the LC host. To make a wide temperature BPLC, the chiral dopant should have a higher melting point while keeping good solubility. The solubility of chiral dopant in a nematic host depends on its melting point and heat fusion enthalpy. High melting point and large heat fusion enthalpy are two key factors limiting the solubility. As shown in Figure 2.1, the chiral dopant
ISO-(6OBA)$_2$ has a melting point of 90°C, the solubility is ~10 wt%, and the HTP is ~35µm$^{-1}$, which depends on the LC host. ISO-(6OBA)$_2$ has a similar HTP to ZLI-4572, but its solubility is better because of its lower melting point.

### 2.3 Monomers

Monomers are essential in determining the stability of BPLC. Typically, a polymer-stabilized BPLC requires two types of monomers: mono-functional (EHA or C12A) and di-functional (RM257) monomers. The overall monomer concentration, as well as the ratios between the two monomers needs to be optimized. We have investigated the effect of polymer concentration and composition [35]. We prepared a BPLC mixture consisting of 65 wt% Merck BL038 and 35 wt% chiral dopants (25% CB15 and 10% ZLI-4572). Two types of monomers (C12A and RM257), as well as a small amount of photoinitiator (~0.5 wt%) were added to the BPLC mixture. The concentration of C12A should be lower than 6% in order to observe blue phase in the precursor. To investigate the polymer effects, seven precursors with different monomer concentrations were prepared, as listed in Table 2.1. The total concentration of monomers varies from 9% to 15%, and the ratio between RM257 and C12A varies from 1:1 to 3:1. IPS cells with 10 µm electrode width and 10 µm electrode gap were employed to generate horizontal electric field so that phase retardation can be accumulated by a normally incident light. From Table 2.1, it is found that as the polymer concentration increases, the polymer network becomes more stable which in turn leads to faster response time and higher operating voltage. Once the overall polymer concentration is fixed, monomer ratio also affects the stability of polymer network. The 1:1 ratio is preferred since it gives a faster response time and less residual
birefringence [35].

Table 2.1: Operation voltage, hysteresis and response time of seven samples

<table>
<thead>
<tr>
<th></th>
<th>RM257: C12A Concentration</th>
<th>1:1</th>
<th>2:1</th>
<th>3:1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V&lt;sub&gt;on&lt;/sub&gt;</td>
<td>Hysteresis</td>
<td>τ (ms)</td>
<td>V&lt;sub&gt;on&lt;/sub&gt;</td>
</tr>
<tr>
<td>9%</td>
<td>157</td>
<td>4%</td>
<td>0.44</td>
<td>147</td>
</tr>
<tr>
<td>12%</td>
<td>176</td>
<td>3.5%</td>
<td>0.34</td>
<td>180</td>
</tr>
<tr>
<td>15%</td>
<td>N/A</td>
<td>V&lt;sub&gt;on&lt;/sub&gt; &gt;200V</td>
<td>0.30</td>
<td>N/A</td>
</tr>
</tbody>
</table>

In addition to short pitch length and low viscosity described in Eq. (2.2), a strong polymer network is also helpful for reducing response time and suppressing hysteresis. As shown in Figure 2.1, TMPTA is a tri-functional monomer, while the normally used EHA or C12A are mono-functional monomers. The crosslink between TMPTA and RM257 is much stronger, resulting in an increased elastic constant (which is favorable for response time) and decreased hysteresis. However, the downside is the increased operation voltage. Therefore, a delicate balance between operation voltage and response time needs to be taken.

Besides material optimizations, photoinitiator and UV irradiation conditions also affect the performance of a PS-BPLC composite, such as photoinitiator concentration, the wavelength and intensity of UV light, exposure time, and curing temperature. For example, a typical UV dosage for preparing polymer-stabilized BPLC composite is ~3.6 J/cm<sup>2</sup> and the intensity varies from 1 mW/cm<sup>2</sup> to 20 mW/cm<sup>2</sup> [25,35]. The UV wavelength is ~365 nm and the curing
temperature is near the chiral nematic to blue phase transition temperature [36].

Long-term stability is another critical issue for the PS-BPLC devices. Here we prepared an IPS cell with JNC JC-BP01M [25]. To evaluate the long-term stability, the sample was baked in an oven at 70°C. Figure 2.2 shows the baking time dependent on-state voltage and response time. The measurements were conducted at room temperature (~23°C) with 100Hz driving frequency. Overall speaking, both on-state voltage and response time do not change much within one month of baking. The fluctuation of the response time is within 20%.

![Figure 2.2](image.png)

Figure 2.2: Baking time dependent (a) on-state voltage and (b) response time. The dashed lines are averaged rise and decay time.
CHAPTER 3  ELECTRO-OPTICAL PROPERTIES OF OPTICALLY ISOTROPIC LIQUID CRYSTALS

3.1 Extended Kerr Effect Model

At off-resonance wavelengths, blue phases are optically isotropic. When an electric field (E) is applied, liquid crystal molecules tend to align with the electric field if the dielectric anisotropy $\Delta \varepsilon > 0$ (or perpendicular to the electric field if $\Delta \varepsilon < 0$). As a result, birefringence is induced. In the low field region, the induced birefringence can be described by Kerr effect as:

$$\Delta n_{\text{ind}} = \lambda KE^2,$$

where $\lambda$ is the wavelength of incident light, $K$ is Kerr constant which depends on the wavelength, temperature and driving frequency [37]. Kerr effect exhibits a fast response time (<1 ms) because of the short coherent length of BPLC, which is quite attractive for both display and photonics applications. A higher electric field could lead to lattice distortion (electrostriction effect), which results in a shift in the Bragg reflection wavelength [38]. For a sufficiently high electric field, blue phase may transform to new phases, to chiral nematic phases, and ultimately to nematic phases [39]. This transition is usually the slowest process (in the order of a few seconds) and is irreversible, which causes undesirable hysteresis, residual birefringence, or permanent structural damage.

In a polymer-stabilized blue phase liquid crystal, the polymer network restricts the lattice structure so that color switching behavior is hardly observed [16]. The response time is very fast (<1 ms), which originates from the Kerr effect. However, Kerr effect is only valid in the low field region because Eq. (3.1) would lead to divergence if the electric field keeps on increasing.
For a finite material system, the induced birefringence should gradually saturate in the high field region once all the molecules have been reoriented. To verify this assumption, we measured the ordinary refractive index change and developed an extended Kerr effect model to explain the saturation phenomenon.

The BPLC precursor employed in our study consists of nematic LC (49 wt% Merck BL038), chiral dopants (21% Merck CB15 and 6% ZLI-4572) and monomers (9% EHA and 15% RM257). The mixture was then cured with UV light at 1 mW/cm² for 30 min under a temperature where blue phase appears. The PS-BPLC was sandwiched between two ITO (indium tin oxide) glass substrates with a cell gap of 8 µm. To investigate its electro-optical properties, we used Michelson interferometer as depicted in Figure 3.1 in order to double the phase shift because of double pass. The light source was an unpolarized He-Ne laser (λ=633 nm). The laser beam was split equally into two arms by a beam splitter (BS). The BPLC cell was placed in one arm and was driven by a square-wave voltage with 1 kHz frequency. Fringes were observed after the objective lens and an iris was placed in front of the photodiode detector (D). Through the measured interference fringes, we can obtain the induced birefringence. The whole system was built on a floating optical table to minimize any environment-induced fluctuation. Figure 3.2 depicts the measured ordinary refractive index change (δn) of the BPLC cell under different voltages.
In a voltage-off state, the BPLC is optically isotropic. Its refractive index can be written as [40]:

\[ n_i = \sqrt{(2n_o^2 + n_e^2)/3}, \]

(3.2)

where \( n_o \) and \( n_e \) are the ordinary and extraordinary refractive indices of the LC composite, respectively. When the birefringence is small, Eq. (3.2) can be approximated by:

\[ n_i \approx (2n_o + n_e)/3. \]

(3.3)

To validate this approximation, let us assume the LC composite has \( n_o=1.50 \) and \( n_e=1.70 \). The difference between Eq.(3.2) and Eq.(3.3) is only ~0.2%. When an electric field is applied, birefringence is induced. The optic axis of the induced refractive-index ellipsoid is along the electric field direction. For the PS-BPLC, the induced birefringence results from local reorientation of the molecules [16]; therefore, it is quite reasonable to assume that the average refractive index keeps constant at any electric field:
$$n_{\text{average}} = \frac{2n_o(E) + n_e(E)}{3} = n_i.$$  \hspace{1cm} (3.4)$$

Here, \(n_o(E)\) and \(n_e(E)\) are the field dependent refractive index perpendicular and parallel to the electric field, respectively. With this assumption, the ordinary refractive index change under an electric field can be expressed as:

$$\delta n = n_i - n_o(E) = \frac{n_e(E) - n_o(E)}{3}.$$  \hspace{1cm} (3.5)$$

Eq. (3.5) correlates the ordinary refractive index change we measured with the induced birefringence. The induced birefringence \(\Delta n_{\text{ind}}\) of PS-BPLC under an external electric field is governed by Kerr effect as:

$$\Delta n_{\text{ind}} = n_e(E) - n_o(E) = \lambda K E^2.$$  \hspace{1cm} (3.6)$$

Here, \(\lambda\) is the wavelength, \(K\) is the Kerr constant, and \(E\) is the amplitude of the electric field. Eq. (3.6) is valid only in the low electric field region; otherwise, it leads to a divergence as \(E\) keeps increasing. Physically, the induced birefringence cannot exceed the intrinsic effective birefringence of the BPLC composite when all the LC directors are reoriented by the strong electric field.

To avoid divergence of the induced birefringence in high field region, a saturation field \(E_s\) has been introduced and Eq. (3.6) is modified as [23,24]:

$$\Delta n_{\text{ind}} = (\Delta n)_o \left(\frac{E}{E_s}\right)^2,$$  \hspace{1cm} (3.7)$$

where \((\Delta n)_o\) denotes the maximum induced birefringence of the LC composite. For the convenience of discussion, let us refer Eq. (3.7) as truncation model. In the truncation model, the induced birefringence is described as \(\Delta n_{\text{ind}} = (\Delta n)_o \left(\frac{E}{E_s}\right)^2\) when \(E<E_s\) and \(\Delta n_{\text{ind}} = (\Delta n)_o\) when
Such an abrupt change in the induced birefringence serves the purpose to prevent divergence, but in reality as the electric field increases the induced birefringence will gradually saturate because all the LC directors will be eventually reoriented by the electric field.

Figure 3.2: Measured refractive index change (circles) and fittings with Eq. (3.7) (black lines), Eq. (3.8) (red), the model including 2nd, 4th, and 6th order terms (blue), and the extended Kerr effect Eq. (3.9) (magenta).

In Figure 3.2, the measured refractive index change is linearly proportional to $E^2$ as expected from Kerr effect in the weak field region. As the electric field increases, the induced refractive index change ($\delta n$) gradually saturates. To explain this trend, higher order electro-optical effects have been considered [41]. For a centrosymmetric crystal, the odd-order terms vanish due to the inversion symmetry, and only the even-order terms remain. Including the fourth-order term, the refractive index change can be written as:

$$\delta n = \frac{\lambda(K_1 E^2 + K_2 E^4)}{3}, \quad (3.8)$$

where $K_1$ and $K_2$ are the Kerr constant and fourth-order coefficient, respectively. Eq. (3.8) is used
to fit the experimental data with $K_1$ and $K_2$ as adjustable parameters. As depicted in Figure 3.2, the fitting (red curve) is good when $E^2$ is below 200 V$^2/\mu$m$^2$. However, above this field the fourth-order term begins to dominate and the curve eventually bends down because Eq. (3.8) is a downward parabola if $K_2$ is negative. To avoid this bending-down phenomenon, one may further include the sixth-order term. Indeed, the fitting (using $K_1$, $K_2$ and $K_3$ as adjustable parameters) is very good in the entire region (blue curve). Nevertheless, this curve predicts a fast divergent trend in the high field region, as shown in Figure 3.2.

To explain the saturation trend of our experimental data, we propose the following exponential convergence model:

$$
\delta n = \delta n_s \left[ 1 - \exp \left( -\left( \frac{E}{E_s} \right)^2 \right) \right],
$$

(3.9)

where $\delta n_s$ stands for the saturated refractive index change and $E_s$ represents the saturation field. We used Eq. (3.9) to fit the experimental data leaving $\delta n_s$ and $E_s$ as adjustable parameters. The fitting with the experimental data is quite good in the entire region and, more importantly, it shows anticipated saturation trend in the high field region. For convenience, we call this convergence model as extended Kerr effect.

From Eq. (3.5), the induced birefringence is related to the ordinary refractive index change as:

$$
\Delta n_{ind} = n_o(E) - n_e(E) = 3 \delta n .
$$

(3.10)

It is interesting to note that if we expand Eq. (3.9) into power series and then combine it with Eqs. (3.6) and (3.10), we indeed obtain the $E^2$ term (Kerr effect) under weak field approximation and
the Kerr constant can be written as:

\[ K = 3\delta n_s / (\lambda E_s^2) \]  

(3.11)

The fourth- and the sixth-order terms become increasingly important as \( E \) increases. However, the inclusion up to the sixth-order term still does not lead to the saturation phenomenon in the high fields, as shown in Figure 3.2.

The parameters obtained through fitting are \( \delta n_s = 0.038 \) and \( E_s = 13.9 \) V/\( \mu \)m, which implies a Kerr constant of 0.93 nm/V\(^2\). The employed LC host has an intrinsic birefringence of 0.272. Taking into account the LC concentration (~50%) and the factor of 1/3 shown in Eq. (3.5), the obtained refractive index change is still ~18% smaller than the ideal value, which is 0.045. This difference could be attributed to following two factors: 1) a portion of LC is embedded in the polymer network, and some BPLCs are strongly anchored by the nano-structured double-twist cylinder boundaries so that they do not respond to the electric field, and 2) the relatively low clearing temperature (~60°C) of the PS-BPLC so that the order parameter at the room temperature (~23°C) is reduced accordingly [42].

To validate the extended Kerr effect in a real display device, we incorporated Eq. (3.9) into our simulation program [21] and tried to fit the experimental VT curve reported in Ref. [43] in an IPS cell with 5-\( \mu \)m electrode width and 10-\( \mu \)m electrode gap. Here, the induced birefringence (\( \Delta n_{ind} \)) instead of the refractive index change (\( \delta n \)) is used by taking the factor of 3 as shown in Eq. (3.10). Fitting is achieved by adjusting \( \Delta n \) and \( E_s \), where \( \Delta n_s \) is the maximum induced birefringence. For comparison, the fitting result using the truncation model [Eq. (3.7)] is also included in Figure 3.3. The fitting using the extended Kerr effect (red curve) matches better
with the experimental data than the truncation model (dashed blue lines). The slight mismatch below 20 V is due to the poor dark state of the experiment. Through fittings, we find: $\Delta n_s \sim 0.06$ for both cases and $E_s \sim 2.15$ V/$\mu$m which implies to a Kerr constant $K \sim 20$ nm/V$^2$ in the low voltage region. On the other hand, the Kerr constant obtained using the truncation model is 16.2 nm/V$^2$. A larger Kerr constant leads to a higher transmittance in the low voltage region. Besides, the slower increase of induced birefringence at high voltage region results in a smoother transition near the peak transmittance.

![Normalized Transmittance vs Voltage](image.png)

**Figure 3.3:** Model fittings with experimental data (circles; Ref. [43]) of an IPS cell using the truncation model (dashed blue lines) and extended Kerr effect (red). The sample is a polymer-stabilized isotropic liquid crystal.

In summary, the extended Kerr effect correctly predicts the saturation behavior of the induced birefringence and fits well with the VT curve of an IPS display device. It leads to a more accurate simulation of the electro-optical properties of polymer stabilized optically isotropic LCs.
3.2 Direct Measurement of Electric-field-induced Birefringence

In section 3.1, we did not measure the induced birefringence directly but instead, used an assumption that the ordinary refractive index change is 1/3 of the induced birefringence. In order to directly measure the induced birefringence, and meanwhile, verify our assumption, we developed the following measurement method [44].

The optically isotropic LC employed in this study is a mixture comprising of nematic LC (48.6% Merck BL038), chiral dopants (20.2% Merck CB15 and 6% ZLI-4572) and monomers (10% EHA and 15.2% RM257). A small drop of the mixture was put on the main prism of an Abbe refractometer and covered by a lighting glass, as shown in Figure 3.4 [45]. The lighting glass was used to compensate for the weak light since the BPLC layer is thin. The refractive index of the lighting glass is 1.6198, higher than that of the mixture. The lighting glass was pressed to get rid of bubbles in the BPLC layer. We controlled the temperature of the main prism at 45°C and cured the sample with UV light at 1 mW/cm² for 30 min.

![Figure 3.4: Abbe refractometer for measuring the refractive index of PS-BPLC in voltage-off state](image)

After UV curing, the sample was cooled down to room temperature (~23°C). By adjusting the height and angle of the light guide, we observed a clear boundary line through the
eyepiece. The position of this line was adjusted to make it passing through the cross hairs and the measured refractive index was \( n_i = 1.588 \).

The same mixture was also sandwiched between two ITO glass substrates with an 8-\( \mu \)m cell gap. The sample was UV cured under the same condition as the one on the Abbe refractometer. We used Michelson interferometer to measure the change of refractive indices (\( \delta n \)) perpendicular to the electric field as described in Sec. 3.1. The PS-BPLC cell was placed in one arm and was driven by a 1 kHz square-wave voltage. The ordinary refractive index change under an electric field is written as follows:

\[
\delta n(E) = n_i - n_o(E).
\] (3.12)

Here, \( n_i \) is the refractive index at voltage-off state, \( n_o(E) \) is the field dependent refractive index perpendicular to the electric field. Since we have obtained \( n_i \) from Abbe refractometer, \( n_o(E) \) can be calculated from Eq. (3.12).

To find the extraordinary refractive index of PS-BPLC, Senarmont method [46] was employed. The optical setup is shown in Figure 3.5. The angles indicate the azimuthal angles of the transmission axes (for the polarizer and analyzer) or fast axes (for the sample and \( \lambda/4 \) plate). The PS-BPLC cell is tilted by an angle of \( \theta \) to introduce phase retardation.

![Optical setup for Senarmont method](image)

**Figure 3.5:** Optical setup for Senarmont method. P: Polarizer, \( \lambda/4 \): quarter-wave plate, A: analyzer. The angle are the azimuthal angle of the transmission axis (for P and A) or fast axis (for sample and \( \lambda/4 \) plate).
The change of polarization state can be explained using Jones Matrix method. Since the transmission axis of the polarizer is $45^\circ$ to the horizontal axis, the input field $E_{in} = \begin{bmatrix} \cos 45^\circ \\ \sin 45^\circ \end{bmatrix}$.

After passing through the $\lambda/4$ plate, the output field can be denoted as:

$$E_{out} = W(\pi/2)R(45^\circ)W(\Gamma)E_{in},$$  \hfill (3.13)

where $W(\Gamma) = \begin{bmatrix} e^{-\Gamma/2} & 0 \\ 0 & e^{\Gamma/2} \end{bmatrix}$, $R(\varphi) = \begin{bmatrix} \cos \varphi & \sin \varphi \\ -\sin \varphi & \cos \varphi \end{bmatrix}$, $\Gamma$ is the phase retardation introduced by the PS-BPLC sample. The x-y coordinates of output field are rotated by $45^\circ$ so that they coincide with the axes of the $\lambda/4$ plate. Substituting $W$ and $R$ functions in Eq. (3.13) with the given matrixes gives $E_{out} = \begin{bmatrix} \cos \Gamma/2 \\ \sin \Gamma/2 \end{bmatrix}$. This output light is a linearly polarized light and can be blocked by rotating the analyzer. The rotation angle $\alpha = \Gamma/2$.

In the voltage-off state, the PS-BPLC cell is optically isotropic and does not introduce any phase retardation. The fast axis of the $\lambda/4$ plate coincides with the transmission axis of the polarizer, thus the polarization state does not change. Since the polarizer and the analyzer are crossed, the linearly polarized light is absorbed by the analyzer. As voltage is applied to the sample, the introduced phase retardation has following form:

$$\Gamma(E) = \frac{2\pi}{\lambda} n_\perp(E) d \left[ \sqrt{1 - \frac{\sin^2 \theta}{n_\parallel^2(E)}} - \sqrt{1 - \frac{\sin^2 \theta}{n_\perp^2(E)}} \right].$$  \hfill (3.14)

In Eq. (3.14), $d$ is the cell gap and $\lambda$ is the laser wavelength. For a given voltage, this phase retardation is measured at different incident angles and $n_\perp(E)$ is obtained through fitting.
Figure 3.6: Measured effective birefringence at different incident angles (circle) at V=140 Vrms and the fitting curve (red line) using Eq. (3.15). \( \lambda = 633 \text{ nm} \) and \( T \approx 23^\circ C \).

Figure 3.6 shows \( \Delta n_{\text{eff}} \) for different incident angles at 140 \( V_{\text{rms}} \). Here we define

\[
\Delta n_{\text{eff}}(E) = \frac{\lambda \Gamma(E)}{2\pi d} = n_{o}(E)\left\{ \sqrt{1 - \frac{\sin^2 \theta}{n_{e}^2(E)}} - \sqrt{1 - \frac{\sin^2 \theta}{n_{o}^2(E)}} \right\}.
\]  

(3.15)

The red curve is the fitting using Eq. (3.15) in which \( n_e \) is the fitting parameter, while \( n_o = 1.558 \) was obtained from the Abbe and Michelson measurements through Eq. (3.12). Through fitting, we get \( n_e = 1.634 \) at \( V = 140 \text{ V}_{\text{rms}} \).

The same fitting process was carried out at other voltages. Figure 3.7(a) shows the obtained \( n_o \) and \( n_e \) at different electric fields and Figure 3.7(b) shows the induced birefringence obtained from \( n_e - n_o \). In the high field region, the deviation of the induced birefringence from Kerr effect is observed. This phenomenon, as we discussed before, was called extended Kerr effect [47]. In the extended Kerr effect, the convergence model was given by:

\[
\Delta n_{\text{pol}} = \Delta n_e \left[ 1 - \exp \left( - \left( \frac{E}{E_s} \right)^2 \right) \right],
\]

(3.16)
where $\Delta n_s$ stands for the saturated birefringence and $E_s$ represents the saturation field. The red curve in Figure 3.7(b) is the fitting using Eq. (3.16). The parameters obtained through fitting are $\Delta n_s = 0.0873$ and $E_s = 12.15 \text{ V/µm}$. The Kerr constant under low field approximation is 0.93 nm/V$^2$, which is the same as the Kerr constant in Sec. 3.1.

![Figure 3.7](image)

Figure 3.7 (a) Electric field dependent ordinary refractive index (black squares) and extraordinary refractive index (red circles); (b) induced birefringence (circles), linear fitting in the low field region (blue straight line) and fitting using Eq. (3.16) (red curve). $\lambda=633 \text{ nm}$ and $T \sim 23^\circ \text{C}$.

The ratio of $\Delta n$ to $\delta n$ is plotted in Figure 3.8. In Sec. 3.1, we assumed that the average refractive index keeps constant at any electric field. With this assumption, the induced birefringence $\Delta n$ is related to $\delta n$ by a factor of three. This ratio of three is within the error bar below 80 V$_{\text{rms}}$. However, above 80 V$_{\text{rms}}$ the ratio of $\Delta n$ to $\delta n$ slightly deviates from three. It is considered that at high field the induced birefringence is not only due to the local reorientation of molecules, but lattice distortion could also come into play.
Figure 3.8: Ratio of $\Delta n$ to $\delta n$. The assumption ($\Delta n / \delta n = 3$) is shown in red line.

To validate our data, we filled an in-plane switching (IPS) cell with the same material and measured the voltage-dependent transmittance (VT) curve of this PS-BPLC device. The IPS cell has a cell gap of 7.5 µm with 10-µm electrode width and 10-µm electrode gap. Meanwhile, we incorporated Eq. (3.16) into our simulation program [23] and used the experimental data extrapolated from Figure 3.7(b) to calculate the VT curve of this device.

Figure 3.9: Comparison of experimental data (solid blue line) of an IPS cell with simulation results (dashed red lines). $\lambda=633$ nm and $T\sim23^\circ$C.
Figure 3.9 shows the comparison of the experimental data with the simulation result. Since this IPS cell also behaves as a phase grating, it exhibits diffraction effects and this diffraction effect is also voltage dependent. To eliminate the influence of diffraction, we measured the VT curves with BPLC sample sandwiched between two crossed polarizers and two parallel polarizers, respectively. Only the intensity of zeroth order is recorded by the detector. The VT curve under two crossed polarizers is normalized to the summation of these two VT curves. This normalized VT curve was again normalized to one in order to compare with the simulation result. Good agreement was obtained.

In summary, the proposed method enables direct measurement of the induced birefringence for different PS-BPLC materials and will help develop materials with high $\Delta n_s$ and low $E_s$, which will lead to low operating voltage of display devices.

3.3 Vertical Field Switching Method

The abovementioned methods can directly measure the ordinary and extraordinary refractive indices; however, the experimental setups are complicated and errors accumulate during each step. To simplify the measurements, we further revised the experimental setup. The reason for using the Senarmont method in Sec. 3.2 is because of the small phase retardation ($<\pi$). From Eq. (3.14) and Figure 3.6, a larger incident angle leads to larger phase retardation. However, although the incident angle can be as large as 70°, the angle inside the BPLC cell is reduced due to Snell’s law. Therefore, the phase retardation is small. To increase the angle inside the BPLC cell, glycerol ($n=1.47$ @ $\lambda=633$ nm) is employed as an index matching liquid. Although the refractive indices of glycerol and BPLC are not well matched, the light can still
pass through BPLC with a fairly large angle, since glycerol has a much larger index than air. Figure 3.10 shows the experimental setup. The cell was immersed in the glycerol liquid and it can be oriented at an arbitrary angle. The absorption axes of polarizer and analyzer are at 45° and -45° azimuthal angles with respect to the incident plane, respectively, to maximize the transmittance. Different from Senarmont method, in which the phase retardation needs to be calculated from the rotation angle of the analyzer for each applied voltage, here the phase retardation can be directly converted from the measured transmittance for different voltages. Based on this experimental setup, a vertical field switching (VFS) mode [48] is proposed for display applications with lower driving voltage, faster response time and much smaller hysteresis than in-plane-switching mode. Therefore, this kind of BPLC cell made of two planar ITO substrates is called VFS cell.

![Diagram](image)

Figure 3.10: Experimental setup for characterizing VFS cell.

The transmittance is related to phase retardation as:

\[ T = \sin^2(\phi/2). \quad (3.17) \]

The phase retardation can be expressed as:

\[ \phi(E) = \frac{2\pi}{\lambda} n_o(E) d \left| \sqrt{1 - \frac{n_r^2 \sin^2 \theta}{n_r^2(E)}} - \sqrt{1 - \frac{n_g^2 \sin^2 \theta}{n_g^2(E)}} \right|, \quad (3.18) \]

Comparing Eq. (3.18) with Eq. (3.14), the only difference is that the refractive index of glycerol
\( n_g \) needs to be taken into account here. \( \lambda \) is the laser wavelength and \( \theta \) is the incident angle in the glycerol. \( n_o(E) \) and \( n_e(E) \) are electric field dependent ordinary and extraordinary refractive indices of the PS-BPLC composite, which can be described as:

\[
\begin{align*}
    n_o(E) &= n_i - \Delta n_{\text{ind}}(E)/3, \\
    n_e(E) &= n_i + 2\Delta n_{\text{ind}}(E)/3,
\end{align*}
\]

Combining Eqs. (3.16) - (3.20), we are able to calculate the voltage dependent transmittance curve and fit it with experimental data. There are two adjustable parameters: \( \Delta n_i \) and \( E_s \), while \( n_i \) can be either measured with Abbe refractometer or assumed in the range of 1.5 - 1.6. Figure 3.11 shows the measured voltage-dependent transmittance (VT) curve for a BPLC material Chisso JC-BP01M [25] and fitting by assuming \( n_i = 1.55 \). From fitting, \( \Delta n_i = 0.11 \) and \( E_s = 6V/\mu m \).

In Figure 3.11, the first peak appears at 18V, which is the driving voltage for display application. To reduce the driving voltage, we can optimize the cell gap. By using the parameters obtained from fitting, we calculated the driving voltages for different cell gaps and different incident angles at \( \lambda = 550 \text{nm} \), as shown in Figure 3.12. There are two factors determining the phase retardation: induced birefringence and optical path length. For a given voltage \( V \), as the cell gap decreases the electric field gets stronger because \( E = V/d \). According to Kerr effect, the induced birefringence is proportional to \( E^2 \). Thus, the induced birefringence is larger as the cell gap decreases. On the other hand, as shown in Eq. (2.17), for a given incident angle, the optical path length in the BPLC cell for accumulating phase retardation decreases as the cell gap decreases. When the cell gap is large, the induced birefringence dominates since it is proportional to \( 1/d^2 \) in the weak electric field region. Therefore, the driving voltage reduces as the cell gap decreases. However, if the cell gap is too thin, the electric field will be very strong
and the induced birefringence will saturate according to extended Kerr effect equation (3.16) [47]. With this saturated birefringence, the thin cell gap may not be adequate for achieving \( \pi \) phase retardation. Therefore, in Figure 3.12, there is an optimal cell gap for achieving \( \pi \) phase retardation.

![Graph](image1.png)

**Figure 3.11:** Measured VT curve (solid red line) using the setup in Figure 3.10 and fitting using Eqs. (3.16) – (3.20) (blue dashed lines).

![Graph](image2.png)

**Figure 3.12:** Simulated operating voltage of VFS cells vs. cell gap at different incident angles. \( \lambda = 550 \) nm, \( \Delta n_s = 0.11 \) and \( E_s = 6 \) V/\( \mu \)m.
Although the curves in Figure 3.12 are calculated numerically, analytical solutions of the driving voltages and optimized cell gap are desirable. To obtain analytical solutions, we first set Eq. (3.18) to be \( \pi \). With some algebra and making some approximations, we finally derive the operating voltage as:

\[
V_{on} = E_s d \sqrt{-\ln(1 - \Delta n / \Delta n_s)},
\]  
(3.21)

with \( \Delta n = \frac{\lambda n_i}{2 d n_g^2 \sin^2 \theta} \sqrt{n_i^2 - n_s^2 \sin^2 \theta}. \)  
(3.22)

Figure 3.13 shows the comparison between the numerical solution and analytical solution using the same parameters in Figure 3.12. The two curves agree quite well, especially when the cell gap is larger than 4 \( \mu \)m.

![Graph showing comparison between analytical and numerical solutions](image)

Figure 3.13: Comparison between analytical solution [Eq. (3.21)] and numerical solution of cell gap dependent operating voltages at incident angle \( \theta = 70^\circ \). \( \lambda = 550 \) nm, \( \Delta n_s = 0.11 \) and \( E_s = 6V/\mu \)m.

The optimized cell gap for achieving the lowest driving voltage can be obtained by taking the derivative of \( V_{on} \) in Eq. (3.21) and let it be zero. The optimized cell gap is:
In summary, the vertically field switching method provides a simple way to characterize the electro-optical properties of blue phase liquid crystals. The results directly reflect the intrinsic properties of the material due to the uniform electric field. From the measurement results, we are able to predict the driving voltage by changing the incident angle as well as the cell gap. As a result, for a given BPLC material, optimized cell gap for achieving the lowest driving voltage is obtained.

3.4 Dynamic Response Behavior

Among several advantages of PS-BPLC, fast response time is the most attractive feature because it reduces motion blur and enables color sequential displays using RGB LEDs, which in turn eliminates the spatial color filters. Consequently, the optical efficiency and resolution density are all tripled. The response time of a PS-BPLC is related to the viscosity of the host LC materials, pitch length, anchoring force of polymer network [49] and also the strength and distribution of electric fields [48]. Therefore, there is an urgent need to understand the dynamic response behavior of a BPLC device in order to keep fast response time.

In this study, we investigated the dynamic response behaviors of a PS-BPLC composite under different electric fields. We focus on the phase decay response instead of transmittance decay response [25,49,50], because the latter usually smears the underlying physics of the dynamic response due to the sinusoidal modulation. It is found that there is a critical field, which not only determines the onset of hysteresis but also plays an important role in the response time.
The BPLC host employed in this study consists of 94.11 wt% JM2069-145 (ITRI, Taiwan) and 5.89 wt% of a high helical twisting power chiral dopant (HTP ≈ 100/µm). The nematic LC host JM2069-145 has the following physical properties: $\Delta n = 0.215$ at $\lambda = 633$ nm, $\Delta \varepsilon = 50$ at 1 kHz and 21 °C, and clearing temperature $T_c = 80$°C. The BPLC host is then mixed with 10 wt% of photocurable monomers [4 wt% TMPTA (1,1,1-Trimethylolpropane Triacrylate, Sigma Aldrich) and 6 wt% RM257, Merck], as well as a small amount of photoinitiator (~0.65 wt%) to form a precursor. The transition temperature between chiral nematic and blue phase is 43.5°C during heating process and 38.6°C during cooling process. To investigate the dynamic response of the BPLC composite, a uniform electric field is preferred. Therefore, we injected the precursor to a vertical field switching (VFS) cell. The VFS cell is made of two ITO glass substrates and the cell gap is 5.15 µm. We controlled the temperature of the cell at 43.5°C during the cooling process and irradiated UV light with an intensity of 2 mW/cm² for 30 min. After UV exposure, a self-assembled BPLC composite was stabilized.

We used the experimental setup shown in Figure 3.10. Figure 3.14(a) depicts the electric field dependent phase retardation. The transmittance is related to the phase retardation as expressed in Eq. (3.17). Here we converted the transmittance to phase retardation. The small light leakage at voltage-off state is due to the stress birefringence of the glass substrates employed. This light leakage is not of our concern in this specific study since we focus on the dynamic response of the PS-BPLC sample. Through fitting with Eqs. (3.16)-(3.20), we obtained $\Delta n_s = 0.12$ and $E_s = 12.8$ V/µm, the Kerr constant $K = \Delta n_s/(\lambda E_s^2) = 1.2$ nm/V². From Figure 3.14(a), it is interesting to notice that the hysteresis starts to appear when $E > 8.5$ V/µm, which we call critical field ($E_c$). Semi-empirically, we found that the critical field is related to the Kerr
constant of the BPLC material as:

\[ E_c \propto 1/\sqrt{K}. \] (3.24)

For instance, the Kerr constant \( K_1 \) here is \( \sim1.2 \text{ nm/V}^2 \) and the critical field \( E_{c1}\sim8.5 \text{ V/µm} \); while in Ref. [51] the Kerr constant \( K_2 \sim7.5 \text{ nm/V}^2 \) and the critical field \( E_{c2} \sim3.5 \text{ V/µm} \). The ratio between \( E_{c1} \) and \( E_{c2} \) is \( \sim2.4 \) and \( \sqrt{K_2/K_1} \sim2.5 \). The agreement is reasonably good although the two BPLC material systems are quite different. Since the driving voltage of a BPLC system is proportional to \( 1/\sqrt{K} \) [26], it is considered that the critical field is also related to the liquid crystal orientation and as a result, the unwinding of the helical twist. A BPLC with a larger Kerr constant is easier to be unwound, which corresponds to a smaller critical field.

![Figure 3.14](image)

Figure 3.14 (a) Electric field dependent phase retardation and hysteresis; (b) Phase retardation and transmittance decay time (100%-10%) when different electric fields are removed.

To measure response time, we let the PS-BPLC sample relax from different applied voltages and recorded the dynamic relaxation process by a digital oscilloscope. The measured amplitude relaxation was also converted to phase relaxation according to Eq. (3.17). Figure 3.14(b) shows the amplitude and phase decay times from 100% to 10% of the modulation depth.
It is found the phase decay time is slower than the amplitude decay time, especially when the phase retardation is less than \( \pi \). This is because of the sinusoidal modulation as Eq. (3.17) shows. Although amplitude response time is commonly used for display applications, phase retardation response time can better reveal the underlying physical mechanism. From Figure 3.14(b), it is found that the phase decay time is almost a constant when the applied field is below 8.5V/\( \mu \)m, but starts to increase as \( E>E_c \).

To further investigate the dynamic response of the PS-BPLC sample, we fitted the phase decay curves with a double relaxation equation:

\[
\phi(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + \phi_0. \tag{3.25}
\]

The first term in Eq. (3.25) represents slow process and the second term represents fast process. \( \tau_1 \) and \( \tau_2 \) are the averaged time constants, and \( A_1 \) and \( A_2 \) are the phase retardations contributed by the slow and fast processes, respectively. \( \phi_0 \) is the phase retardation caused by the initial light leakage and residual birefringence. The reason that we use the double relaxation equation will be explained in more details later. Figure 3.15(a) shows the measured phase decay process and the fitting using Eq. (3.25) when a voltage of 44V is removed at \( t = 0 \). As shown in Figure 3.15(a), the fitting with Eq. (3.25) is quite good.
Figure 3.15: (a) Transient decay process at 44V; (b) decay time constants $\tau_1$ and $\tau_2$ when different electric fields are removed; (c) phase retardation amplitude $A_1$ and $A_2$ under different electric fields and (d) normalized phase retardation amplitude $a_1$ and $a_2$ for different electric fields.

For other applied fields, we also fitted the experimental curves with Eq. (3.25). The values of $\tau_1$, $\tau_2$, $A_1$ and $A_2$ for different electric fields are plotted in Figure 3.15(b) and (c). It is interesting to note that $\tau_2$ remains constant for all the applied electric fields but $\tau_1$ starts to decrease when $E > 8.5\text{V/\mu m}$, which is the critical field for hysteresis to occur. In Figure 3.15(c), the phase retardations for both fast and slow processes first increase linearly with $E$, but at $\sim 8.5\text{V/\mu m}$ there is a transition point, after which $A_1$ starts to increase more quickly while $A_2$ decreases. We also plotted the contributions of $A_1$ and $A_2$ to the overall phase retardation in Figure 3.15(d). Here we define $a_1 = A_1/(A_1 + A_2)$ and $a_2 = A_2/(A_1 + A_2)$. Below $E_c$, $a_1$ and $a_2$ remain
constants but \( a_1 \) starts to increase when \( E > E_c \) while \( a_2 \) starts to decrease, which means the slow process makes more contribution to the overall phase retardation.

![Diagram](image)

**Figure 3.16:** (a) Schematic diagram of the liquid crystals surrounded by polymer network and (b) Schematic diagram of how fast and slow processes change with the applied electric field.

We proposed the following physical model to qualitatively explain the data in Figure 3.15. For a nematic LC with a fixed pretilt angle, the phase decay process can be described by a single exponential decay under small angle approximation [52]. However, in blue phases, similar to a polymer-dispersed liquid crystal (PDLC) system, except the LC directors are arranged in a double-twisted structure, the pretilt angles are distributed in all the directions. Without loss of generality, we draw a schematic diagram to represent the randomly distributed LC directors surrounded by polymer network, as shown in Figure 3.16(a). The LC directors have different pretilt angles with respect to the applied electric field. Therefore, they will rotate by different
angles under an electric field. Those who rotate by a larger angle will have slower response time. Moreover, the anchoring force provided by the polymer network is not uniform over the entire LC medium. For example, the LC directors close to the polymer network experience a stronger anchoring force while those in the center experience a weaker force. A stronger anchoring force helps restore the LCs with faster response time. As a result, the responses of LC directors are different and there are multiple decay processes going on. Here, we take an average effect and approximate the decay process as a double relaxation process.

When the electric field is weak, the LC directors only rotate by a relatively small angle. Let us assume there are multiple time constants with \( \tau_a < \tau_b < \tau_c < \tau_d < \tau_e \). The LCs with small pretilt angle and strong anchoring force have fastest response time, while those with large pretilt angle and weak anchoring force have slowest response time. The overall effect is approximated by a double relaxation process, with \( \tau_2 \) representing the averaged effects of \( \tau_a \) to \( \tau_d \), and \( \tau_1 \) representing the slow response time \( \tau_e \), as shown in Figure 3.16(b). As the electric field increases but below the critical field, the LC rotation angles increase, but still within a certain limit. Therefore, the time constants and the ratio between \( A_1 \) and \( A_2 \) are insensitive to the applied electric field. However, when \( E > E_c \) some LC directors have been reoriented by a large angle which is above the critical angle and causes unwinding of helical twist. As a result, the LC relaxation process does not follow the same route as the rising path, which leads to hysteresis. Similarly, the large rotation angle also leads to a significant change in the dynamic decay process. For example, \( \tau_c \) and \( \tau_d \) become much slower so that they join \( \tau_e \) to contribute to the slow process. But they are still faster than \( \tau_e \) so the averaged time constant \( \tau_1 \) decreases as \( E > E_c \). As to the fast process, \( A_2 \) decreases because LCs with time constants \( \tau_c \) and \( \tau_d \) join the slow process and only
those LCs with time constants $\tau_a$ and $\tau_b$ make contribution to the phase retardation of the fast process. Moreover, since $\tau_a$ and $\tau_b$ are faster than $\tau_c$ and $\tau_d$, the averaged time constant $\tau_2$ also slightly decreases.

The response time information plays an important role in device design and optimization. From our results, the response time becomes slower and the hysteresis starts to appear as the electric field exceeds the critical field. Therefore, it is very important to keep the maximum electric field below this critical field in order to achieve fast response time and hysteresis free performance. A thicker cell gap helps reduce the peak electric field which is helpful for eliminating hysteresis and improve response time but the operation voltage increases accordingly. Therefore, a delicate balance between hysteresis, response time and voltage is required in device design.

In summary, we investigated the dynamic relaxation of a polymer-stabilized BPLC composite and found that the response time becomes slower as the electric field exceeds the critical field, which is also the critical field for hysteresis to occur. The critical field is related to the Kerr constant of the BPLC material. We also proposed a possible mechanism to explain the relaxation behavior. These results will guide the future device design for keeping fast response time while suppressing hysteresis.[53]

### 3.5 Figure of Merit

Both Kerr constant and response time are important in material optimization. However, they have contradicting requirements. For example, from Eq. (2.1) and Eq. (2.2), a longer pitch length and a smaller elastic constant are favorable for enhancing Kerr constant, but unfavorable
for response time. Therefore, we define a figure of merit (FoM) as:

\[
FoM = \frac{K}{\tau} \propto \frac{\Delta n \Delta \varepsilon}{\gamma_1},
\]

(3.26)

for comparing and optimizing the BPLC performance at a given pitch length and probing wavelength. A large Kerr constant and a fast response time would lead to a high FoM.

To improve Kerr constant, much effort has been devoted to developing high dielectric anisotropy (\(\Delta \varepsilon > 100\)) LC hosts which in turn increases the viscosity and response time drastically [25,34]. For such a large \(\Delta \varepsilon\) LC host, the conventional capacitance measurement method would be inaccurate if the voltage shielding effect from the polyimide (PI) alignment layers is neglected. Moreover, the mean field theory [54] for describing the dielectric anisotropy has a presumption that \(\Delta \varepsilon\) is small. Therefore, before comparing the figure of merit, we need to improve the method to characterize the high \(\Delta \varepsilon\) LC hosts.

First, we studied four different nematic LC hosts with different dielectric anisotropies designated as LC 1-4. Table 3.1 lists the measured \(\Delta n, \Delta \varepsilon\) and \(\gamma_1\) of the four LC hosts at room temperature (~22°C) and \(f=1\) kHz driving frequency. The dielectric anisotropies are measured using a LCR meter (HIOKI LCR HiTESTER 3532-50). Homogenously aligned cells are used when we measure \(\varepsilon_\perp\) and vertically aligned cells are employed while measuring \(\varepsilon_\parallel\). Special caution has to be taken when characterizing a large \(\Delta \varepsilon\) LC. Since a LC cell can be treated as three capacitors [one LC layer and two ultrathin PI layers] in series [55], the measured dielectric constant \(\varepsilon\) is derived as:

\[
\varepsilon = \frac{1}{2d_p / d + \frac{1 - 2d_p / d}{\varepsilon_p} + \frac{d_p}{\varepsilon_1c}},
\]

(3.27)
where \( d \) is the cell gap, \( d_p \) and \( \varepsilon_p \) are the effective thickness and dielectric constant of the PI layer, and \( \varepsilon_{LC} \) is the dielectric constant (\( \varepsilon// \) or \( \varepsilon\perp \)) of the LC host. If \( \varepsilon_{LC} \) is comparable to \( \varepsilon_p \) (~3), the first term in the denominator can be neglected since \( d_p \ll d \) so that \( \varepsilon \approx \varepsilon_{LC} \). For a strong polar LC, its \( \varepsilon// \) is very large so that the capacitance of the PI layers cannot be ignored. For example, let us assume \( \varepsilon_{LC} = 200 \), \( d = 8 \mu \text{m} \), and \( d_p = 30 \text{ nm} \) (the deposited PI layer thickness is \( \approx 80 \text{ nm} \), but the rubbing process would reduce its effective thickness), the obtained \( \varepsilon \) from Eq. (3.27) is only 134. The discrepancy is as large as 33%. Therefore, the measured value is often smaller than it should be because of the shielding effect from the PI layers.

Table 3.1: Physical parameters of the four LC hosts studied at room temperature and \( f = 1 \text{ kHz} \). \( K \) and \( \tau \) are Kerr constant and response time of the PSBP samples.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta n )</td>
<td>0.24</td>
<td>0.16</td>
<td>0.2</td>
<td>0.17</td>
</tr>
<tr>
<td>( \Delta \varepsilon )</td>
<td>13.76</td>
<td>56.71</td>
<td>95.53</td>
<td>251.41</td>
</tr>
<tr>
<td>( \gamma_1 \text{ (pa's)} )</td>
<td>0.35</td>
<td>0.45</td>
<td>0.40</td>
<td>2.14</td>
</tr>
<tr>
<td>( K \text{ (nm/V^2)} )</td>
<td>0.43</td>
<td>1.07</td>
<td>2.65</td>
<td>3.71</td>
</tr>
<tr>
<td>( \tau \text{ (ms)} )</td>
<td>0.107</td>
<td>0.114</td>
<td>0.119</td>
<td>0.347</td>
</tr>
</tbody>
</table>

Figure 3.17 shows the measured \( \varepsilon// \) of LC4 at 30°C using two cells with different cell gaps \( d_1 \) and \( d_2 \). The \( \varepsilon\perp \) of a LC is usually small so the PI effect can be neglected. Since LC4 has a very large \( \varepsilon// \), the PI effect should be taken into account for the measurement of \( \varepsilon// \). For different cell gaps, the measured \( \varepsilon// \) are different because of the different \( d_p/d \) in Eq. (3.27), as shown in Figure 3.17. Therefore, the measured value needs to be corrected in order to obtain the real value of \( \varepsilon// \). Assuming the PI layers in the two cells have the same thickness \( d_p \), we obtain the corrected
expression for $\varepsilon_{//}$ after some algebra:

$$\varepsilon_{//} = \frac{d_1 - d_2}{d_1 / \varepsilon_1 - d_2 / \varepsilon_2}, \quad (3.28)$$

where $\varepsilon_1$ and $\varepsilon_2$ are the measured values using these two cells. The corrected $\varepsilon_{//}$ is plotted in Figure 3.17. The values shown in Table 3.1 are also corrected.

Figure 3.17: Measured $\varepsilon_{//}$ of LC4 at 30°C using two cells with 3.4 μm and 8.1 μm cell gaps, and corrected $\varepsilon_{//}$ according to Eq. (3.28).

Figure 3.18 shows the dielectric relaxation of $\varepsilon_{//}$ for the four LC hosts at 30°C. $\varepsilon_\perp$ is almost a constant (not shown here) in the entire plotted region. The data are fitted using Debye relaxation equation:

$$\varepsilon_{//} = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + (f / f_r)^2}, \quad (3.29)$$

where $\varepsilon_0$ is the static permittivity at low frequency, $\varepsilon_\infty$ is the permittivity at the high frequency limit, and $f_r$ is the relaxation frequency. The fitting parameters $\varepsilon_0$, $\varepsilon_\infty$, and $f_r$ are listed in Table II. From Table 3.2, we find that a larger $\Delta \varepsilon$ LC has a lower relaxation frequency as expected.
Generally speaking, a larger $\Delta \varepsilon$ LC consists of more polar groups and therefore it is more bulky and viscous. So it is more difficult for the molecules to follow the electric field, which results in a lower relaxation frequency. A low relaxation frequency implies that the Kerr constant decreases sharply as the electric field frequency approaches $f_r$ [56]. This could be problematic for high frequency (say, a few kHz) operation of BPLC devices.

![Image](image-url)

Figure 3.18: Frequency dependent $\varepsilon//$ of four LCs at 30°C. Dots are corrected experimental data and lines are fitting with Eq. (3.29).

Table 3.2: Fitting parameters for the four LC hosts at 30°C.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LC1</th>
<th>LC2</th>
<th>LC3</th>
<th>LC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_0$</td>
<td>19.02</td>
<td>64.58</td>
<td>97.53</td>
<td>231.45</td>
</tr>
<tr>
<td>$\varepsilon_\infty$</td>
<td>5.63</td>
<td>8.98</td>
<td>11.72</td>
<td>5.47</td>
</tr>
<tr>
<td>$f_r$(kHz)</td>
<td>278.3</td>
<td>75.7</td>
<td>44.7</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Next, we prepared four PS-BPLC samples using the four LC hosts. The BPLC precursors consist of a LC host, a chiral dopant (R5011, HCCH), 10 wt% monomers [6% RM257 (Merck) and 4% TMPTA (1,1,1-Trimethylolpropane Triacrylate, Sigma Aldrich)] [57], and a small
amount (~0.6%) of photoinitiator. Since the helical twist power of chiral dopant changes in different LC hosts, the concentration of the chiral dopant varies from 4.5% to 7% in order to obtain similar pitch length. The four precursors were cured by UV light with an intensity of 2 mW/cm² for 30 min. near the transition temperature from chiral nematic phase to blue phase. We used vertical-field switching (VFS) cells [48,51] instead of in-plane-switching (IPS) cells because a uniform electric field is preferable to characterize the electro-optic performance of PS-BPLC materials.

![Normalized Transmittance vs Voltage](image)

Figure 3.19: Measured VT (dots) of PS-BPLCs at room temperature and 1 kHz frequency and fitting (lines) using extended Kerr effect model. The incident angle $\theta = 70^\circ$.

Figure 3.19 depicts the measured voltage-dependent transmittance (VT) curves of the four VFS cells. The measurement method has been discussed in Sec. 3.3. Here, the light incident angle is $70^\circ$. The experimental data are fitted by a simulation program incorporating extended Kerr effect model [47]. Table 3.1 lists the obtained Kerr constants. Response time is also measured and results are included in the bottom row of Table 3.1. While measuring response time, we remove the voltage instantaneously from $V_p$ which corresponds to the peak
transmittance. Response time is defined as the transmittance change from 90% to 10%. Although
the optical decay time is different from the phase decay time [58], it is proportional to the phase
decay time for the same grayscale operation.

In Figure 3.19, theoretically there is no threshold for the VT curves because the induced
birefringence can be expressed by the extended Kerr effect model Eq. (3.16) [47]. In Eq. (3.16),
the induced birefringence increases with the electric field. The threshold-like behavior in Figure
3.19 is because the transmittance is related to the phase retardation \( \delta \) by a sinusoidal equation as:

\[
T = \sin^2(\delta / 2)
\]

( 3.30 )

The transmittance increases slowly when the phase retardation is small. With amorphous silicon
thin-film-transistor (TFT) addressing, the fluctuation voltage \( (V_f) \) could reach 0.5-0.8V. For a LC
device without a threshold voltage, the dark state could be degraded. Although BPLC has no
threshold voltage, the threshold-like performance promises a good dark state. Let us assume the
on-state voltage is \( \sim \)10V. Through simulation we found that a contrast ratio over 1000:1 can be
achieved if \( V_f < 1.3V \).

Figure 3.20 shows the linear relationship between FoM and \( \Delta n \Delta \varepsilon / \gamma_1 \) of the LC host. Good
agreement between experimental data and linear fitting is obtained. The slope will be affected by
the type and concentration of monomer and chiral agent employed, as well as device structures
and probing wavelength. For the four PS-BPLC samples, we used same amount of monomer and
similar pitch length; the employed device structure and the laser wavelength is also the same for
the four BPLC samples. Therefore, we obtained a good linear fitting in Figure 3.20. By
increasing the dielectric anisotropy of the LC hosts, FoM first increases due to the improved Kerr
constant. However, the improvement on Kerr constant gradually saturates when \( \Delta \varepsilon > 100 \), but in
the meantime viscosity increases dramatically so that the response time slows down. As a result, PS-BPLC4 has a smaller FoM than PS-BPLC3. Moreover, LC4 has a low relaxation frequency which will cause a strong frequency dependency on Kerr constant and also dielectric heating, which are undesirable for display applications. PS-BPLC3 exhibits the highest FoM among the four samples studied; it has a good balance between Kerr constant and response time.

Figure 3.20: FoM of four PS-BPLCs using VFS cells. Red line is linear fitting with Eq. (3.26).

One question that arises is the voltage shielding effect from the polymer network because ~10 wt% polymer is employed. However, the polymer network in BPLC is uniformly distributed in the composites, instead of being separated from the LC layer (such as PI layers), so the polymer is not only in series but also in parallel with the BPLC composite. We have attempted to estimate the voltage shielding effect from the polymer microscopically and found that it is not too significant. In terms of applications, the macroscopic performance is the major concern. Here, we treat the PS-BPLC system as a whole; the Kerr constant is a macroscopic parameter obtained from the experimentally measured VT curves.
FoM is temperature dependent since $\Delta n$, $\Delta \varepsilon$, and $\gamma_1$ are all temperature sensitive. The temperature dependency of $\Delta n$ and $\gamma_1$ is described as follows [42,59,60]:

$$\Delta n = \Delta n_0 S , \quad \gamma_1 = a S \exp( E / k_B T) ,$$

where $S$ is the order parameter, $\Delta n_0$ is the extrapolated birefringence at $T=0 \, K$, $E$ is the activation energy, $k_B$ is the Boltzmann constant, and $a$ is a proportionality constant. The order parameter $S$ can be approximated well by Haller’s equation [61,62]:

$$S = (1 - T / T_c)^\beta ,$$

where $T_c$ stands for the nematic-isotropic phase transition temperature of a LC and $\beta$ is a material constant. The order parameters are determined from the temperature dependent birefringence. The activation energy in Eq. (3.32) can be obtained from the measured temperature dependent visco-elastic constant of the LC host using anti-parallel rubbed cells. The obtained $\beta$ and $E$ for the LC3 and LC4 are listed in Table 3.3.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LC3</th>
<th>LC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c$ (°C)</td>
<td>96</td>
<td>75.5</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.225</td>
<td>0.205</td>
</tr>
<tr>
<td>$E$ (meV)</td>
<td>478</td>
<td>762</td>
</tr>
<tr>
<td>$U$ (meV)</td>
<td>123</td>
<td>276</td>
</tr>
<tr>
<td>$b$</td>
<td>1.13</td>
<td>0.0086</td>
</tr>
</tbody>
</table>

From Maier and Meier’s mean field theory [54], $\Delta \varepsilon$ is proportional to $S/T$. But in the derivation of mean field theory, an approximation that $\Delta \varepsilon \ll \bar{\varepsilon}$ ($\bar{\varepsilon}$ is the averaged dielectric...
constant) was made so that the local fields are treated as isotropic. However, for LCs with a large dielectric anisotropy, the local field effect would be much stronger and cannot be taken as isotropic. Therefore, mean field theory is no longer valid for large $\Delta \varepsilon$ materials.

Figure 3.21 depicts the measured temperature dependent dielectric constants of LC3 and LC4. All the data are taken at low frequencies before the dielectric relaxation occurs and corrected according to Eq. (3.28). From Figure 3.20, $\Delta \varepsilon$ has a strong temperature dependency which mainly comes from $\varepsilon_\parallel$, while $\varepsilon_\perp$ does not change much with the temperature. Since it is very difficult to address the anisotropy of local fields, here we propose an empirical equation for describing the temperature dependency of large $\Delta \varepsilon$ LCs:

$$\Delta \varepsilon = b \cdot S \exp\left(\frac{U}{k_BT}\right),$$  \hfill (3.34)

where $U$ is a parameter related to the dipole moment and $b$ is a proportionality constant. The order parameter can be determined from the temperature dependent birefringence, so there are only two adjustable parameters in Eq. (3.34): $U$ and $b$. The fittings with experimental data are very good for both LC hosts. The two fitting parameters are also included in Table 3.3.

![Figure 3.21: Measured $\varepsilon_\parallel$, $\varepsilon_\perp$, and $\Delta \varepsilon$ (dots) of LC3 (a) and LC4 (b) and fittings (lines) using Eq. (3.34).](image)
It is interesting to note that when the dipole moment is small (i.e., $U \ll k_B T$), the exponential term can be expanded as $\exp(U/k_B T) \approx 1 + U/k_B T$ and Eq. (3.34) is reduced to:

$$\Delta \varepsilon = b \cdot S(1 + U/k_B T).$$

Eq. (3.35) has the same form as mean field theory. Therefore, Eq. (3.34) is applicable for both large and small $\Delta \varepsilon$ LC materials. Although it seems Eq. (3.34) tends to be divergent at low temperature, the relaxation frequency also shifts to a lower frequency as the temperature decreases. Eq. (3.34) will not be valid if $\Delta \varepsilon$ starts to relax at the measurement frequency.

Combining Eqs. (3.31) - (3.34), the temperature dependency of FoM is derived as:

$$FoM = cS \exp[(U - E)/k_B T].$$

Here $c$ is a proportionality constant. For a polymer-stabilized BPLC, the clearing temperature $T_{c, BP}$ is often few degrees lower than that of the LC host after adding chiral dopant. As a result, the order parameter $S$ is slightly different from that of the LC host, by substituting $T_c$ with $T_{c, BP}$.

To verify Eq. (3.36), we prepared two PS-BPLC cells using LC3 and LC4. Here IPS cells with electrode width $w = 10 \mu m$ and electrode gap $g = 10 \mu m$ are employed because it is difficult to control the temperature of a VFS cell. The FoM for an IPS cell is somewhat different from a VFS cell because their Kerr constant and response time are different. The response time difference is due to the non-uniform electric field distribution in the IPS cell [48], while the reason for the Kerr constant difference is still under investigation. In spite of different FoM, the temperature dependency of IPS cells should still roughly follow Eq. (3.36).
Figure 3.22: Temperature dependent FoM for two PS-BPLCs using IPS cells and fittings (lines) with Eq. (3.36).

Figure 3.22 shows the FoM of the two IPS cells. The Kerr constants are obtained by fitting the VT curves using a simulation program [23] which has taken the nonuniform electric field into account. The response time is also defined as 90%-10% transmittance change. The data are fitted with Eq. (3.36) with only one adjustable parameter $c$. Other parameters $U$, $E$ and $\beta$ are obtained from LC hosts, and $T_{c,BP}$ is measured using a polarized optical microscope. The fittings with Eq. (3.36) are very good for both cells, which indicates that the temperature dependent FoM is basically determined by the LC host, while the polymer and chiral will only affect the adjustable parameter $c$. For a given PSBP, an optimal temperature ($T_{op}$) exists which gives the maximum FoM [63]. This can be understood qualitatively as follows: as the temperature increases, Kerr constant decreases mainly due to the reduced $\Delta \varepsilon$, but the decreasing rate in Kerr constant is slower than that of response time, resulting in an increased FoM. As the temperature gets closer to $T_c$, Kerr constant decreases dramatically which leads to a sharp decrease in FoM. To derive the optimal temperature, we set $d(FoM)/dT = 0$ and find:
Substituting Eq. (3.37) with the parameters of PS-BPLC3, we found the optimal temperature is \( \sim 7^\circ\text{C} \) below \( T_c \). At the optimal temperature, maximum FoM is achieved mainly because of the fast response time, but the Kerr constant is fairly small which demands a high driving voltage. For some photonics applications which require fast response time while the driving voltage is less concerned, the device can be operated at this optimal temperature. Material systems can also be optimized to achieve maximum FoM at room temperature.

In summary, we defined a FoM to characterize and compare the performance of PS-BPLC materials. FoM is closely related to the properties of host LCs. Good agreement between experimental results and theory is obtained. Although increasing the \( \Delta \varepsilon \) of a LC host enhances Kerr constant which is favorable for reducing voltage, these strong polar materials also increase the viscosity and response time dramatically. As a result, the overall FoM may not gain. For a given material, there is an optimal temperature for achieving maximum FoM. We also found that conventional method needs correction for measuring the dielectric constants of large \( \Delta \varepsilon \) LC materials. Moreover, mean field theory is no longer valid for large \( \Delta \varepsilon \) LCs and an empirical equation was proposed to illustrate the divergence behavior of \( \Delta \varepsilon \) at low temperature. Again, the proposed model fits well with experimental results. This study will make a significant impact on both LC materials and BPLC materials characterization and optimization.
CHAPTER 4  DISPLAY AND PHOTONIC APPLICATIONS OF BLUE PHSE LIQUID CRYSTALS

4.1 Transmissive Display

Blue phase liquid crystal is a strong contender for next generation display applications. The most common display mode for BPLC is IPS mode, which provides horizontal electric field to generate phase retardation. The challenges for IPS mode include high driving voltage and insufficient transmittance. To reduce the driving voltage, different device structures are proposed, which can be separated into two categories: the first type is IPS-like mode with strong horizontal electric field, such as protruded electrodes [26], wall electrodes [27], and etched substrate [64], etc.; another type is to use vertical electric field and obliquely incident light to generate phase retardation, such as vertical field switching mode [48,65], proposed by Cheng et al. and Kim et al., respectively. In this section, the two types of devices will be discussed respectively.

4.1.1 Low Voltage IPS Mode with Long Pitch BPLC

For IPS mode, although the abovementioned modified device structures are helpful for reducing voltage, they do increase the cell manufacturing complexity. Therefore, there is an urgent need to reduce the operation voltage from material composition aspect.

A polymer-stabilized BPLC composite contains three major ingredients: nematic host as switching molecules, chiral agent with a strong helical twisting power to induce blue phases, and mono- and di-functional monomers to stabilize the blue-phase networks [57]. The Kerr constant of a BPLC composite is primarily governed by three parameters: birefringence ($\Delta n$), dielectric...
anisotropy ($\Delta \varepsilon$), and pitch length (P). Increasing birefringence is a straightforward way to enhance Kerr constant. However, there is a limit because we also have to consider other properties: high resistivity, good UV stability, low melting temperature, and wide nematic range. To satisfy all the above mentioned properties, the $\Delta n$ is in the vicinity of ~0.2. Another method to boost Kerr constant is to increase dielectric anisotropy. Indeed, some BPLC hosts with $\Delta \varepsilon > 100$ have been recently developed [25,34]. However, these high $\Delta \varepsilon$ LC hosts usually exhibit a large viscosity which slows down the response time dramatically [66]. Moreover, a high $\Delta \varepsilon$ LC host also causes insufficient charging capability of the active matrix driving circuits, which in turn lowers the transmittance significantly [67]. The third approach is to increase the pitch length. This approach seems simple, but increasing pitch length would shift the Bragg reflection toward the visible spectral region, which in turn degrades the dark state dramatically and leads to a poor contrast ratio. Besides abovementioned factors, the Kerr constant of a BPLC composite can also be improved by optimizing the monomer composition [35,68] and preparation conditions, such as curing temperature [36], UV intensity, and curing time.

In this section, we demonstrate a method to enhance the Kerr constant of BPLC by shifting the Bragg reflection from ~350 nm to ~600 nm without sacrificing contrast ratio. To retain high contrast ratio, in the experiment we take following precautions: 1) we choose a right-handed circular polarizer (RCP) as the front polarizer so that the transmitted light before entering the BPLC cell is right handed; 2) we use a left-handed chiral dopant so that in the voltage-off state the BPLC cell transmits the incoming right-handed circular light; and 3) we choose a left-handed circular polarizer (LCP) as the analyzer so that the outgoing right-handed circular light from the BPLC cell is absorbed. As a result, we reduce the driving voltage by 35% while
keeping a high contrast ratio and submillisecond response time.

From Eq. (3.1), the Kerr constant is proportional to $P^2$, so increasing the pitch length can effectively improve the Kerr constant. On the other hand, the on-state driving voltage is related to the Kerr constant as: [26]

$$V_{on} = A \cdot \frac{1}{\sqrt{K}},$$  \hspace{1cm} (4.1)

where $A$ is the device parameter. Combining Eq. (3.1) and Eq. (4.1), and assuming all the other parameters except pitch length remain unchanged, we obtain:

$$V_{on} \sim \frac{1}{P}. \hspace{1cm} (4.2)$$

It is desirable to shift the reflection band to near infrared region so that the operating voltage can be reduced significantly and the Bragg reflection does not occur in the visible region. However, one important factor has to be taken into account, which is blue phase appears only when the chirality exceeds a certain value. If the chiral concentration is too low, then the blue phase may not exist. Since the pitch length is inversely proportional to chiral concentration, the pitch length cannot be increased unlimitedly. Moreover, response time will also become slower as pitch length increases. Here due to the limitation of employed materials we choose to shift the Bragg reflection wavelength to $\sim600$ nm.

The Bragg reflection wavelength for a PS-BPLC can be expressed as [14]:

$$\lambda = \frac{2na}{\sqrt{h^2 + k^2 + l^2}}, \hspace{1cm} (4.3)$$

where $n$ and $a$ denote average refractive index and lattice constant of blue phases, and $h$, $k$, and $l$ are the Miller indices of a crystal plane. For BP-I, the lattice constant $a = P$ and the crystal plane
corresponding to the longest reflection peak is (110) plane. Therefore, the longest reflection wavelength is $\lambda_0 = \sqrt{2}np$ and $\lambda_0 = 600$ nm corresponds to a pitch length of ~267 nm by assuming the average refractive index $n = 1.59$.

To compare the performance of short-pitch and long-pitch PS-BPLCs, we prepared two samples. The recipes are listed in Table 4.1. The BPLC precursors consist of nematic LC host HTG 135200 (HCCH, China), chiral dopant S5011 (HCCH, HTP~120/μm), two kinds of monomers [RM257 (Merck) and TMPTA (1,1,1-Trimethylolpropane Triacrylate, Sigma Aldrich)], and a small amount of photoinitiator (~0.5 wt%, not included in Table 4.1). The nematic LC host has following properties: $\Delta n=0.2$ at $\lambda = 633$ nm, $\Delta \varepsilon=96$ at 1 kHz and 21°C, and clearing temperature $T_c = 96$ °C. The differences between these two samples are the concentrations of chiral dopant and LC host. As a result, the reflection peak of sample I occurs at ~350 nm and that of sample II at ~600 nm. For each sample, we prepared three IPS cells. The interdigitated electrodes are on the bottom substrate and both the electrode width and gap are 5μm. The cell gaps are ~ 8.5 μm. The differences between these three cells are threefold: 1) cell 1 has no alignment layer, 2) cell 2 has one rubbed alignment layer on top substrate, and 3) cell 3 has two rubbed alignment layers on both top and bottom substrates. The three cells were prepared under the same conditions. UV curing process was performed near the transition temperature between chiral nematic phase and blue phase with an intensity of 2 mW/cm$^2$ for 30 min. After UV curing, the clearing temperature of sample I was found to be ~80°C, while that of sample II was ~90°C. This difference is because sample II contains less chiral dopant, so its clearing temperature does not drop too much. A wider temperature range is always more preferable.
Table 4.1: Recipes of two PS-BPLC samples.

<table>
<thead>
<tr>
<th>Samples</th>
<th>LC host (wt%)</th>
<th>Chiral dopant (wt%)</th>
<th>RM257 (wt%)</th>
<th>TMPTA (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>84.52</td>
<td>5.48</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>II</td>
<td>86.85</td>
<td>3.15</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4.1 shows the polarizing optical microscope (POM) images with two crossed linear polarizers. Since the reflection wavelength of sample I is in UV region, it is optically isotropic in the visible region. Therefore, all of the three cells appear dark under crossed polarizers. Here, we choose one cell to represent sample I, as shown in Figure 4.1(a). Sample II reflects visible light and the reflection changes the incident polarization state, so that a color image can be observed. For cell 1 without alignment, the blue phase lattices have different orientations (multi-domain) and therefore reflect different colors. As a result, we can observe several colors in the transmission mode [Figure 4.1(b)]. The rubbed alignment layers in cell 2 and cell 3 help form a mono-domain texture [69,70] so that a single color can be observed in Figure 4.1(c) and Figure 4.1 (d). From Figure 4.1, we found the dark state of sample II is degraded significantly as compared to sample I.
Figure 4.1: Polarizing optical microscope (POM) images with two crossed linear polarizers: (a) sample I cell 2, (b) sample II cell 1, (c) sample II cell 2, and (d) sample II cell 3.

To obtain a good dark state, we used two broadband and wide-view circular polarizers, as Figure 4.2(a) depicts. A white light source was employed and a few collimating lens were used (not shown in the figure). In the experiment, we chose a right-handed circular polarizer (RCP) as the front polarizer so that the transmitted light was right handed. Next, we used a left-handed chiral dopant so that our PS-BPLC transmitted the incoming right-handed circular light [71-74] in the voltage-off state. Finally, this right-handed circular light was absorbed by the rear left-handed circular polarizer (LCP) resulting in a good dark state.
Figure 4.2: (a) Diagram of experimental setup using circular polarizers. RCP: right-handed circular polarizer; LCP: left-handed circular polarizer. (b) Dark state spectrum using two crossed linear polarizers. (c) Dark state spectrum using two crossed circular polarizers.

Figure 4.2(b) shows the measured dark state of the six PS-BPLC cells between two crossed linear polarizers. Sample I (short-pitch) shows a good dark state while sample II (long pitch) exhibits a large light leakage in the visible spectrum. With circular polarizers, the dark state of sample II is greatly improved, as shown in Figure 4.2(c).

Figure 4.3 shows the measured transmittance of four PS-BPLC cells in the voltage-off state with a white light source. In Figure 4.3(a), a linear polarizer was placed in front of the cells. Sample I is transparent in the displayed spectrum. For sample II, the cell without alignment layer (cell 1) exhibits a fairly large scattering, especially in the shorter wavelength region. Cell 2 and cell 3 show a reflection band near 600 nm. The differences between cell 2 and cell 3 originate from the non-uniformity of the cells due to the capillary filling. In Figure 4.3(b), a RCP was
placed in front of the cells. With this circular polarizer, the transmittance of sample II is similar to that of sample I. The reason is that these BPLC cells are designed to reflect left-handed circular light so that the right-handed circular light can pass through the cells with high transmittance.

Figure 4.3: Measured transmittance of four BPLC cells in the voltage-off state. (a) A linear polarizer is placed in front of the cells. (b) A right-handed circular polarizer is placed in front of the cells.

Figure 4.4 depicts the measured voltage-dependent transmittance (VT) curves using two circular polarizers. An Argon-ion laser with $\lambda = 514$ nm was employed as probing light source. In the voltage-on state, the BPLC cell behaves like a phase grating [75] which will be discussed in the Chapter 5 and a portion of the energy is transferred to the diffracted orders. Therefore, we used a similar experimental setup to Figure 4.2 (a) except placing a lens in front of the detector in order to collect the diffracted beams. The measurements were conducted at room temperature ($21^\circ$C) and driving frequency $f = 1$ kHz. For sample I, using linear polarizers or circular polarizers make no difference because it is optically isotropic in the visible region. From Figure 4.4, sample I cell 1 has an on-state voltage of 54V and the corresponding Kerr constant is $K \sim 7.4$.
nm/V². Sample I cell 3 requires a much higher voltage than sample I cell 1, because the alignment layer shields a large portion of the applied voltage, especially for PS-BPLC composites with a large dielectric constant. It is interesting to note that sample I cell 2 has a similar or slightly lower driving voltage than sample I cell 1. This is because the electric fields are concentrated near the bottom substrates so the alignment layer on the top substrate does not shield voltage. Meanwhile, the top alignment layer helps create mono-domain structure to reduce light scattering. Therefore, sample II cell 2 shows a higher transmittance than sample II cell 1. The uniform lattice orientation also helps to reduce the driving voltage. Most importantly, the driving voltage for sample II cell 2 is only 35 V, which is reduced by 35% in comparison with sample I cell 1. The corresponding Kerr constant is $K \approx 17$ nm/V².

![Graph](image)

Figure 4.4: Measured voltage-dependent transmittance curves using two crossed circular polarizers. $\lambda = 514$nm, $T = 21^\circ$C, and $f = 1$ kHz.

Table 4.2 summarizes the performances of the five cells. Transmittance is related to the device structure. The IPS cells we employed have 5-μm electrode width and gap. The measured
transmittance is slightly lower than the simulated value, which is ~56% [24]. This is because the lens in front of the detector only collects ±1 diffract orders, which carry most of the energy among all the diffracted orders. The energy carried by the higher orders is lost, although it is weak. Higher transmittance can be achieved by modifying device structures or employing an incoherent backlight unit.

Table 4.2: Summarized performance of five BPLC cells. \( \tau \): decay time; CR: contrast ratio. \( \lambda = 514 \text{nm}, T = 21^\circ C, \) and \( f = 1 \text{ kHz} \).

<table>
<thead>
<tr>
<th>Cell</th>
<th>Voltage (V)</th>
<th>Transmittance</th>
<th>( \tau ) (( \mu \text{s} ))</th>
<th>Hysteresis</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample I - cell1</td>
<td>54</td>
<td>47%</td>
<td>382</td>
<td>5.3%</td>
<td>6300:1</td>
</tr>
<tr>
<td>Sample I - cell2</td>
<td>49</td>
<td>49%</td>
<td>324</td>
<td>3.5%</td>
<td>&gt;10000:1</td>
</tr>
<tr>
<td>Sample I - cell3</td>
<td>70</td>
<td>48%</td>
<td>360</td>
<td>5%</td>
<td>10000:1</td>
</tr>
<tr>
<td>Sample II - cell1</td>
<td>40</td>
<td>39%</td>
<td>648</td>
<td>8%</td>
<td>300:1</td>
</tr>
<tr>
<td>Sample II - cell2</td>
<td>35</td>
<td>47%</td>
<td>814</td>
<td>6%</td>
<td>6500:1</td>
</tr>
</tbody>
</table>

Although increasing the pitch length reduces the driving voltage, there are tradeoffs. The first one is that it slows down the response time. In Table 4.2, the decay time for sample II is slower than that of sample I due to the longer pitch length, but it is still in the submillisecond range.

The second tradeoff is the larger hysteresis. Hysteresis is related to the peak electric field strength [51,58]. For a BPLC with an increased pitch length, the lattice structure is looser and easier to be distorted. Therefore, the critical field of sample II should be lower than that of sample I. The hysteresis can be improved by designing smooth electrode shape to reduce the peak electric field [53]. It is also interesting to notice that cell 2 shows reduced hysteresis than cell 1 for both samples. The strong anchoring from the alignment layer provides a restoring force.
which might be helpful for reconstructing the BPLC structure during the backward scan. On the other hand, the larger hysteresis of sample I cell 3 compared to cell 2 might be due to the higher applied voltage.

Contrast ratio is affected by both intrinsic light leakage at voltage-off state and residual birefringence after voltage actuation. Table 4.2 lists the intrinsic contrast ratio before voltage actuation at $\lambda = 514$ nm. The contrast ratio for sample II has been greatly improved by using circular polarizers. Although sample II cell 1 shows a low contrast ratio because the scattering degrades the dark state, the contrast ratio for cell 2 is comparable to sample I cell 1. The contrast ratio for $\lambda = 633$ nm would be lower because it is closer to the reflection band and the broadband circular polarizer is not designed for reflection band at ~600 nm. After driving, the contrast ratio would also be degraded due to the residual birefringence.

One drawback for the configuration in Figure 4.2(a) is that reflection could be observed from the viewer’s side under strong ambient light because the BPLC cell reflects left-handed circular light and it can pass through the LCP. Another possible configuration is to use LCP as the first polarizer and RCP as the second polarizer. The dark state will be similar to the configuration in Figure 4.2(a) and there is negligible reflection from viewer’s side, but the transmittance will decrease because of the reflection of backlight. However, the backlight unit typically has recycling function therefore the reflected light will be recycled. Another way is to tune the reflection band of BPLC out of the transmission spectrum of RGB color filters or RGB LEDs. Therefore, high transmittance can still be maintained.

In conclusion, we have demonstrated a low voltage blue phase liquid crystal device by red-shifting the pitch length and using circular polarizers. The driving voltage is reduced by 35%
and the Kerr constant is improved by 2.3X. The response time is still in submillisecond range. The contrast ratio is comparable to the BPLC sample with a short pitch length. If we further use a larger Kerr constant material, i.e. Chisso JC-BP01M [25], the driving voltage is expected to be reduced from 33V to 22V with our IPS 5-5 structure at $\lambda = 514$ nm. With a slightly protruded electrode, the operation voltage could be reduced to below 10V for low power consumption.

4.1.2. Wide-view Vertical Field Switching Mode

Compared to IPS mode, vertical field switching mode [48,51] has the advantages of low driving voltage, hysteresis-free, and faster response time due to the uniform and weaker electric field to achieve $\pi$ phase retardation. However, the drawbacks include cell gap sensitivity, complicated backlight design and narrow viewing angle. Especially, the viewing angle is an important factor while evaluating the performance of a large size display.

We have investigated the phase compensation scheme to achieve wide view in terms of contrast ratio [76]. Contrast ratio is mainly determined by dark state. On the other hand, wide view in terms of brightness is equally important because contrast ratio can be very high as long as the dark state is good, even if the bright state is poor. Therefore, it is desirable to obtain uniform and wide brightness distribution by designing the turning film structure.

In the VFS mode [48], shown in Figure 4.5, obliquely incident light can be extracted by the top coupling film and then rotated to the normal direction by the turning film. This design requires precise alignment between the top coupling film and the turning film, which increases the manufacturing complexity. Moreover, the sharp tips of the turning film would either be easily damaged or introduce scratches to the coupling film.
To solve the alignment problem, we try to combine the coupling film and turning film as one turning film sheet. Because the light sources are usually placed on the top or bottom of the panel, we assume the central light is propagating along vertical direction with incident angle \( \theta = 70^\circ \) and azimuthal angle \( \psi = 90^\circ \) (corresponding to x axis). Figure 4.6 shows the structure of a single prism. \( \phi_v \) and \( \phi_v' \) can be optimized to make sure all the incident light experience total internal reflection (TIR) at the right surface and exit at the top surface. For example, to redirect the central light to the normal direction, \( \phi_v \) should be 55\(^\circ\) and \( \phi_v' \) should be chosen according to the bottom width \( w \) and the divergence angle of incident beam.

Figure 4.5: Structure of vertical field switching (VFS) mode

Figure 4.6: Proposed structure of a single prism on the turning film.
Figure 4.7 shows the configuration of a VFS structure as a reference. In this configuration, $\phi_v = 55^\circ$, $\phi_v' = 42^\circ$, $h = 30\mu m$ and $w = 36\mu m$ for each individual prism. All the prisms are the same in order to redirect the incident light to the normal direction. A light diffuser was placed on top of the turning film to further widen the viewing angle. The diffuser converts a single ray to a Gaussian distribution with standard deviation $\sigma = 20^\circ$. In the calculation, we assume the light source has a divergence angle of $\pm 5^\circ$ around the central light with Lambertian distribution, designated as BLU_1. The phase retardation of the VFS cell depends on the incident angle. However, since the backlight is quite collimated, we assume it has ideal $\pi$ phase retardation regardless of the incident angle. Figure 4.8(a) and Figure 4.8(b) show the calculated angular distribution without and with diffuser, respectively.

![Reference configuration of a VFS structure.](image)
Figure 4.8: Angular brightness distribution for the reference configuration (a) without diffuser and (b) with diffuser.

To further widen the viewing angle, one method is to use a heavy diffuser. However, heavy diffuser usually has lower transmittance and more haze, which would reduce the image quality. Therefore, we prefer to achieve wide viewing angle by designing the turning film. Figure 4.9 shows the proposed 3D turning film design (Config.1). In the x-z plane, one period is consist of three prisms with different $\phi_v$ and $\phi_v'$ to redirect the incident beam to different directions. One pixel can be covered by one or two periods. In the y-z plane, we created V-cut prisms so that some light can experience (TIR) at the left and right surfaces of the prisms in Figure 4.9(b). $\phi_h$ is the angle between the cut surface and the z axis. Here we choose $\phi_v = 47^\circ, 55^\circ, 63^\circ$, $\phi_v' = 36^\circ, 42^\circ, 51^\circ$, and $\phi_h = 15^\circ$. The bottom width for one prism in the vertical direction (x axis) is 36 $\mu$m and in the horizontal direction (y axis) is 30 $\mu$m. The other components are the same as Figure 4.7.
Figure 4.9: Optimized configuration (Config.1) of a VFS structure.

Figure 4.10 shows the calculated results for the configuration in Figure 4.9. The viewing angle is widened in both horizontal and vertical directions. The maximum luminance is reduced compared to Figure 4.8, because the total energy is conserved, a wider viewing angle leads to a lower peak luminance.

Figure 4.10: Angular brightness distribution for the optimized configuration (a) without diffuser and (b) with diffuser.
We further employ a more practical backlight unit for the VFS mode, designated as BLU_2. Instead of having a cone distribution, this backlight has narrow polar angle distribution but wide azimuthal angle distribution. The purpose for employing such a backlight is to achieve intrinsic wide viewing angle in the horizontal direction (y axis). The phase retardation of the VFS cell is independent of the azimuthal angle if circular polarizers are employed. Figure 4.11 shows the calculated angular brightness distribution for the reference configuration in Figure 4.7 by replacing the backlight unit with BLU_2. Therefore, after passing through the turning film, the light is redirected and has wide angular distribution in the horizontal direction.

![Figure 4.11: Angular brightness distribution for the reference configuration by replacing the backlight unit. (a) without diffuser and (b) with diffuser.](image)

Since the backlight itself has wide azimuthal angle distribution, it is not necessary to make the V-cut shapes in the horizontal direction. Figure 4.12 (a) shows the calculated results for a turning film similar to Figure 4.9 but without the V-cut shapes, called Config. 2. Figure 4.12 (b) is for the turning film in Figure 4.9 and called Config. 3. Both configurations employ the backlight unit BLU_2. With the turning film design, the viewing angle is greatly widened.
Figure 4.12: Angular brightness distribution for the optimized configuration with diffuser and BLU_2. (a) without and (b) with the V-cut shapes in horizontal direction.

Figure 4.13 summarizes performance of the described configurations. Figure 4.13 (a) and Figure 4.13 (b) depict the horizontal and vertical distribution for the five configurations, respectively. With the turning film design, the viewing angle in terms of brightness is greatly widened.

Figure 4.13: Brightness distribution in (a) horizontal direction and (b) vertical direction.

In summary, we have demonstrated a vertical field switching mode with wide brightness distribution by designing the turning film structure. The viewing angle (FWHM) was widened to
± 80° in horizontal direction and ± 50° in vertical direction. The viewing angle in horizontal direction is more important than vertical direction since the viewer is more likely to watch the display from different angles in horizontal direction. Our proposed turning film design will accelerate the development of VFS mode.

4.2 Reflective Display

Compared to transmissive displays, a direct-view reflective display exhibits several advantages, such as good sunlight readability, low power consumption, and no need for a polarizer. In the past five decades, several types of reflective displays have been developed, such as twisted-nematic (TN) liquid crystal wrist watch [77], mixed-mode twisted nematic for Nintendo Gameboy Color [78], cholesteric liquid crystal display for electronic paper [10,79], electrowetting display [80], electrofluidic display [80], electrophoretic display [80], just to name a few. The major challenges of most reflective displays are unsaturated color, insufficiently fast response time to display videos, difficult to achieve natural grayscales for bistable devices, and relatively low contrast ratio due to surface reflection.

In this section, we propose a reflective display using polymer-stabilized blue phase liquid crystal (PS-BPLC) [14,16,57,66,81]. It exhibits several attractive features, such as no need for polarizer and color filters, relatively narrow reflection band, submillisecond response time, and analogous grayscales by controlling the applied voltage.

Blue phases appear between chiral-nematic phase and isotropic phase in a highly twisted chiral-nematic liquid crystal [10]. They exhibit self-assembled cubic structures and the local refractive index variation results in selective Bragg reflections in the spectral range. The
reflection wavelength can be described by Eq. (4.3). For transmissive displays [24,26,34,48], the reflection bands should be shifted to ultraviolet region by employing a high concentration chiral dopant so that it is optically isotropic in the visible spectral region. However for reflective displays, we intentionally adjust the pitch lengths to obtain reflective colors in the visible region. Since blue phases have delicate and fragile structures, the lattices of the cubic structures can be deformed by an electric field, which leads to a shift of the reflection wavelength. Based on the lattice deformation, electrically tunable colors [82,83] using BPLCs have been demonstrated. However, for polymer-stabilized blue phases, the cubic structures are stabilized by polymer network so that the lattice deformation can only take place at a relatively high field [84]. In the low field region, the applied electric field mainly reorients the LC molecules, but not deforms the lattices.

Figure 4.14 illustrates the device structure and operation principles of the reflective BPLC display. Each pixel consists of three sub-pixels which reflect red, green and blue colors, respectively. The bright state is achieved in the voltage-off state, as shown in Figure 4.14 (a). Here, the sub-pixels are separated by striped wall structures [85]. Another way to obtain full color is to stack RGB layers, similar to a cholesteric display [86]. As voltage increases, the LC molecules tend to align with the electric field because the employed LC has a positive dielectric anisotropy. As a result, the local refractive index difference is reduced and the reflectance gradually decreases. The transmitted light is absorbed by the painted absorption layer on the substrate to achieve dark state, Figure 4.14 (b) shows.
To prove concept of the proposed reflective display, we first prepared a BPLC sample which reflected green color. To study the effect of surface alignment, the BPLC precursor was injected into three cells: 1) cell-1 made of two ITO glass substrates without polyimide (no PI); 2) a TN cell with polyimide and orthogonal rubbing on top and bottom substrates; 3) a homogeneous (HG) cell with antiparallel rubbing on the two substrates. The cell gaps for the three cells were \( \sim 5 \) μm. UV irradiation was performed near the transition temperature from blue phase to chiral-nematic phase during cooling process. The light intensity was 2 mW/cm\(^2\) and the curing time was 30 min. After polymerization, the blue phase composites were stabilized.

Figure 4.15 (a) shows the reflective photo of cell-1 taken under an optical microscope with crossed polarizers. Without alignment, the lattices have different orientations so that the platelets can be observed. Figure 4.15 (b) shows the photo of the TN cell. Different from cell-1, this cell exhibits uniform texture, because the surface alignment provides anchoring energy to confine the orientation of lattices. The HG cell has a similar texture to the TN cell; the photo is not shown here. Figure 4.15 (c) depicts the transmittance and reflectance for the three cells. The baseline reflection is due to the surface and ITO reflections. The cell without PI shows a very
small reflection band at \(~560\) nm, and the transmittance decreases dramatically for wavelengths shorter than 560 nm; green-bluish colors can be observed. From the measured spectra, we consider that the observed colors are originated from both reflection and scattering, because the blue phase has multiple domains when there is no surface alignment. Both TN and HG cells show a clear and fairly narrow reflection band at \(~520\) nm; the full-width half maximum is \(~25\) nm. The similar performances of TN and HG cells are expected since the cell gap is much larger than the lattice constant of the blue phase. Therefore, the alignment direction is not critical in the proposed reflective display, as long as there is surface alignment. The scattering at shorter wavelengths is much weaker than that of the cell without PI. Thus, the observed color mainly comes from Bragg reflection and the color is more saturated.

Figure 4.15: (a) Reflective photo of cell-1 without polyimide. (b) Reflective photo of TN cell. (c) Transmittance and reflectance of three cells with difference surface alignments.
In the following sections, we choose TN cells for further investigating its electro-optic performance, because the available TN cells have more uniform cell gap. We prepared three TN PS-BPLC cells that reflect blue, green and red colors, respectively. The employed material consists of nematic LC host HTG-135200 (HCCH, China), chiral dopant with HTP ≈ 126/μm (HCCH, China), 10 wt% monomers [6 wt% RM257 (Merck) and 4 wt% TMPTA (1,1,1-Trimethylolpropane Triacrylate, Sigma Aldrich)], and 0.6 wt% photoinitiator. The concentrations of LC host and chiral dopant are adjusted to achieve different pitch lengths. The nematic LC host has following physical properties: Δn = 0.2 at λ = 633 nm, Δε = 96 at 1 kHz and 22°C, and clearing temperature $T_c = 97^\circ$C. The cell gaps are ~5 μm.

Figure 4.16 depicts the measured reflectance spectra of the three cells under different voltages. The insets show reflective photos under microscope with crossed polarizers. The three cells are laminated with anti-reflection films so that surface reflection from the interface between the glass and air is reduced to ~1%. The baselines are the interface reflections due to refractive index mismatch between ITO electrodes and glass substrates. All the reflection curves are normalized to that of a mirror. From Figure 4.16, all the reflectance spectra exhibit a relatively narrow bandwidth which indicates saturated colors. The blue and green cells show a reflectance over 35%, but the red cell has a slightly lower reflectance (26%) because of its longer pitch length, which leads to fewer periods within the 5-μm cell gap. The reflectance can be improved by employing a thicker cell gap, but the tradeoff is increased voltage. As the voltage increases, LC molecules are reoriented along the electric field and the double twist structures are gradually unwound so the reflectance decreases. When most of the LC molecules are reoriented by the electric field, the cell becomes transparent and the reflectance touches the baseline. Therefore,
natural grayscales are achieved. On the other hand, the lattices are stabilized by the polymer network so the resonance wavelengths hardly shift. The small blue shifts are due to the electric-field-induced refractive index change.

Figures 4.16: Voltage-dependent reflection spectrum of (a) blue cell, peak wavelength $\lambda_0 = 477$ nm; (b) green cell, $\lambda_0 = 514$ nm; and (c) red cell, $\lambda_0 = 634$ nm. The insets are reflective microscope photos with crossed polarizers.

In Figure 4.16, the peak wavelength of the green cell was intentionally adjusted to match an Argon-ion laser line at $\lambda = 514$ nm. We choose the green cell to further study the voltage-dependent reflectance (VR) behavior. The experimental setup for measuring the VR curve is shown in Figure 4.17. When we look toward the source, the absorption axis of the polarizer is at $0^\circ$ azimuthal angle, while the slow axis of the $\lambda/4$ plate is at $-45^\circ$, so the light incident on the BPLC sample is counterclockwise circularly polarized, or left-handed circularly polarized. The incident angle is $\sim 5^\circ$. If we rotate the $\lambda/4$ plate by $90^\circ$, the polarization state of the incident light would become right-handed circular polarization and the reflectance would become very low. Therefore, the BPLC cell reflects left-handed circularly polarized light, which is consistent with the handedness of the employed chiral dopant.
Figure 4.17: Experimental setup for measuring the VR curve.

Figure 4.18 depicts the measured VR curves for the green cell with a linearly polarized light and a left-handed circularly polarized light. The reflectance is normalized to that of a mirror. With circularly polarized light, the reflectance is expected to be 2X of the linearly polarized light, but the measured ratio is only ~1.5X. The reason is that the reflected light is not perfectly circularly polarized. The contrast ratio is ~17:1 for the linearly polarized light and ~15:1 for the circularly polarized light at a voltage of 70V. Hysteresis is related to the driving voltage. When the cell is driven to 70 V, the hysteresis is ~9% (ΔV/Vmax, ΔV is the voltage difference at half of the peak reflectance and Vmax is the maximum driving voltage). The hysteresis is reduced when the cell is driven to a lower voltage 50V, with a tradeoff of contrast ratio. We also measured the response time of the reflective BPLC at room temperature. The rise time is ~75 μs and the decay time is ~436 μs with an applied voltage of 70V and f = 1 kHz.
It has been reported that the light reflected by blue phases are circularly or partially circularly polarized [71-74]. In our case, we experimentally investigated the polarization state of the reflected light. An analyzer was placed before the detector to examine the polarization state. We measured the intensity in 360° and then calculated the polarization state through the measured intensity data, as shown in Figure 4.19. From Figure 4.19 (a), the reflected light is elliptically polarized, with axial ratio ~0.68. Then we choose a linearly incident light by removing the λ/4 plate, the polarization state of the reflected light is shown in Figure 4.19 (b). The axial ratio is ~0.55. In both cases, the reflected light is left-handed elliptically polarized. For an unpolarized incident light, the reflectance is similar to that of linearly incident light since the unpolarized light can also be decomposed into a left-handed and a right-handed circular polarization. The reflected light is also left-handed elliptically polarized (not shown here). Since the reflected light is a superposition of the reflection from blue phases and the interface reflections, and the alignment layers can also affect the orientation of LC molecules at the
surfaces which would further change the polarization state, the reflected right cannot be a perfectly circular polarization, but indeed the reflection of polymer-stabilized blue phases favors left-handed circular polarization provided that left-handed chiral dopant is employed.

Figure 4.19: Calculated polarization state of reflected light through measured data. (a) Incident light is circularly polarized. (b) Incident light is linearly polarized. $x$ is the absorption axis of the polarizer.

Another method to induce monodomain blue phase is by applying electric field during cooling process before UV curing [87]. This method does not require alignment layers, which would shield the voltage and also change the polarization state. Therefore, the electric-field-induced monodomain blue phase can help reduce the driving voltage and obtain a better circularly polarized reflected light when used in reflective display.

Due to the property of selective reflection of polarization, the proposed reflective display has potential application in 3D displays. One color pixel can be divided into two sub-pixels, which employs left-handed chiral dopant and right-handed chiral dopant, respectively. Figure 4.20 shows two adjacent sub-pixels, wherein the left pixel employs left-handed chiral dopant and the right pixel employs right-handed chiral dopant. Therefore, the left pixel reflects left-handed circularly polarized light, while the right pixel reflects right-handed circular light. Circularly
polarized eyeglasses are required for this 3D display. For the left eye wearing left-handed circular polarizer, it sees the reflection from the left pixel [Figure 4.20 (a)]. Similarly, for the right eye wearing right-handed circular polarizer, it sees the reflection from the right pixel [Figure 4.20 (b)]. With absorptive layer on the bottom substrate and anti-reflection coating on the top substrate, the right pixel would look dark for the left eye and the left pixel would look dark for the right eye. Therefore, the left eye can only see the left pixel which displays left-eye image, and the right eye can only see the right pixel which displays right-eye image. In this way, we will be able to observe 3D images. In Figure 4.20, the fringes and the color difference in the center and edge of the cells are due to the cell gap variations across the cell. The cell gap d should satisfy $d = N \times a$, where N is an integer number and $a$ is the lattice constant. Therefore, the cell gap variations would make the reflection wavelength slightly different.

Figure 4.20: Concept of proposed 3D reflective display. The left pixel employs left-handed chiral dopant and the right pixel employs right-handed chiral dopant. (a) Photo is taken with a left-handed circular polarizer. (b) Photo is taken with a right-handed circular polarizer.

We also investigated the viewing angle of the proposed reflective display. Because blue phase has photonic crystalline structure, the intrinsic viewing angle is narrow. To widen the viewing angle, we laminated a diffuser on top of the left part of the cell for comparison, as
Figure 4.21 depicts. The light source was placed in the normal direction. When viewing at normal direction (0°), we can observe vivid green color on both pixels. The left part has a slightly lower reflectance because part of the reflected light is diffused to other directions. However, as the viewing angle gets larger than 20°, the right pixel appears dark blue while the left pixel remains visible up to 60°, although a significant color shift occurs. In practical applications, the viewing angle should be wider because the ambient light impinges from all the directions.

![Figure 4.21: Viewing angle of the reflective display. Diffuser was laminated on top of the left part of the cell.](image)

In conclusion, we have demonstrated a reflective display using polymer-stabilized blue phase liquid crystals. Such a vivid-color reflective display is polarizer-free and color-filter-free, which gives potential for flexible displays. It shows narrow reflection bandwidth, submillisecond response time, and natural grayscale. It also exhibits potential for 3D applications. The proposed display opens a new gateway for 3D reflective displays and will make significant impacts to display industry.
4.3 Tunable Phase Gratings

Besides display applications, the electric-field-tunable blue phase liquid crystals are also promising candidates for photonics applications, such as tunable color devices [15,38], tunable lenses [88-91], and lasing [73,92]. In this part, we demonstrated a tunable phase grating [75] using PS-BPLC. This device shows a high diffraction efficiency and submillisecond response time. Simulation was carried out to explain the experimental results. Good agreement between simulation and experiment is obtained.

The BPLC employed in this study is a mixture comprising of nematic LC (65% Merck BL038) and chiral dopants (10% Merck CB15 and 25% ZLI-4572). This BPLC host was then mixed with monomers (4.4% C12A and 4.5% RM257) and 0.7% photoinitiator to form the PS-BPLC precursor. The phase transition temperature of the precursor is ISO 46.7°C BP 37.6°C N* during the cooling process and N* 40.1°C BP 47.2°C ISO during the heating process, where ISO represents isotropic phase, and N* stands for chiral nematic phase. The precursor was injected into an in-plane-switching (IPS) cell with electrode width ~10 µm, electrode gap ~10 µm, and cell gap ~7.5 µm, as shown in Figure 4.22. Afterwards, UV curing process was performed at 39°C for 30 min, with an intensity of 2mW/cm². After UV stabilization, PS-BPLC was formed.
Figure 4.22 shows the device configuration and the phase change profiles. At the voltage-off state (V=0), PS-BPLC is optically isotropic. Diffraction only comes from the index mismatch between the indium tin oxide (ITO) electrodes and the LC medium. Because the ITO layer is very thin (~40nm), this diffraction effect is very small and can be neglected. As an electric field is applied, the liquid crystal director tends to align with the electric field since the host nematic LC has a positive dielectric anisotropy ($\Delta\varepsilon$). As a result, birefringence is induced. The induced birefringence can be described by extended Kerr effect in Eq. (2.15). The induced ordinary and extraordinary refractive indices can be expressed by Eqs. (2.18) and (2.19), respectively. Due to the nonuniform electric field in the IPS cell, the LC director distribution is also not uniform. On top of the electrodes, the electric fields are vertical; both TE and TM polarizations experience the ordinary refractive index $n_o$, which is smaller than $n_i$. Therefore, the accumulated phase is
decreased. On the other hand, at the gaps between the electrodes, TE and TM waves experience different refractive indices. As a result, the accumulated phase is increased for TM wave since it sees \( n_e \) but decreased for TE wave since it sees \( n_o \). From Figure 4.22, TM wave has more phase change than TE. Therefore, we will focus only on the TM wave in the following discussion.

![Figure 4.23](image)

Figure 4.23: (a) Experimental setup for measuring the diffraction efficiency. Iris can be relocated to select the diffraction order. P: polarizer. (b) Recorded diffraction patterns at voltage-off state. (c) Diffraction pattern at 160 V. \( \lambda = 632.8 \) nm.

Figure 4.23(a) shows the experimental setup for optical measurement. The polarizer was used to select the TM polarized light. An iris was placed behind the prepared sample to select the diffraction orders. The intensity of the diffraction orders was detected by a photodiode. At the voltage-off state, the diffraction effect is weak and the energy is mostly on 0\(^{\text{th}}\) order, as shown in Figure 4.23(b). Although the higher orders can be observed because our eyes are quite sensitive, the intensity is negligible as compared to that of the 0\(^{\text{th}}\) order. The sample was driven by a square-wave voltage with 1 kHz frequency. As the applied voltage increases, the periodic phase
distribution serves as a diffraction grating. As a result, the energy is transferred from the 0\textsuperscript{th} order to the 1\textsuperscript{st} order, as Figure 4.23(c) shows.

![Image](image_url)

**Figure 4.24:** Diffraction efficiency of the 0\textsuperscript{th}, 1\textsuperscript{st}, and 2\textsuperscript{nd} orders. Dots represent experimental data, and solid lines are simulation results.

Figure 4.24 shows the diffraction efficiency of the 0\textsuperscript{th}, 1\textsuperscript{st}, and 2\textsuperscript{nd} orders. The diffraction efficiency was calculated as a ratio between the intensity of diffracted order \( N \) and the total intensity at \( V=0 \), described by Eq. (4.4):

\[
\eta_N(V) = \frac{I_N(V)}{I_0}.
\]  

(4.4)

The diffraction efficiency is similar for the +1 and -1 orders and both can achieve 40% at 160V. This high efficiency is due to the reduced coherence length \( \xi \) of the PS-BPLC. For conventional nematic liquid crystals, the LC director distribution does not exactly follow the electric field distribution, and is usually smooth due to the long coherence length. With polymer stabilization method, liquid crystals are separated by the polymer network. As a result, \( \xi \) is greatly reduced. Therefore, the directors follow the electric field distribution and sharp spatial phase profile was obtained, as shown in Figure 4.22. This rectangular-like phase profile helps
improve the diffraction efficiency.

Simulation was carried out to fit the experimental data. First, we calculated the electric field distribution in our IPS cell at voltage-on states using finite element method [93]. Next step, for each applied voltage extended Kerr effect model [Eqs. (2.15), (2.18), (2.19)] was applied to calculate the induced $n_o$ and $n_e$ based on the electric field distribution. With the induced refractive indices, the phase profile can be calculated using Eq. (4.5):

$$\varphi(x) = \int_0^d n_e(x,z)dz.$$  \hspace{1cm} (4.5)

Here, $d$ is the cell gap; $z$ is normal to the substrate and $x$ is parallel to the substrate but perpendicular to the electrode direction. Afterwards, Fourier transform of the phase profile was conducted to calculate the diffracted intensity of each order. The calculated result agrees quite well with the experimental data. The two fitting parameters are $\Delta n_s = 0.2$ and $E_s = 14 \text{ V/\mu m}$. Compared with the host nematic liquid crystal which has an intrinsic birefringence of 0.272 at 589 nm, the reduced $\Delta n_s$ is a reasonable value since there are other components such as chiral dopants and polymers in this mixture.

Response times of the $0^{\text{th}}$ and $1^{\text{st}}$ orders were also measured as shown in Figure 4.25. The solid black line represents the $0^{\text{th}}$ order. At 170V, the transmittance is almost zero. Although the transmittance decreases, this process is still defined as rise process. On the other hand, when the voltage is removed, decay process takes place. The dashed red line shows the response time for the $1^{\text{st}}$ order diffraction under 160V, where the maximum efficiency occurs. The rise time and decay time are defined as 10% to 90% of the transmittance change. From Figure 4.25, we find that the rise time is 360 $\mu$s and decay time is 640 $\mu$s for $0^{\text{th}}$ order. For the $1^{\text{st}}$ order, the rise time is 560 $\mu$s and decay time is 480 $\mu$s. All the response time is in the submillisecond range.
The only drawback for this tunable phase grating is the high driving voltage (160V). However, with the development of new blue phase materials, the driving voltage has been greatly reduced to 50V [25]. On the other hand, with new device configurations, such as the configuration (B) proposed in Ref. [94], the driving voltage can be further reduced to 35V, to achieve maximum diffraction efficiency for the first order.

In conclusion, we have demonstrated a tunable phase grating with a polymer-stabilized blue phase liquid crystal composite. It is scattering free and does not need any alignment layer. High diffraction efficiency and submillisecond response time has been achieved at the expense of high driving voltage. With new materials and new device structures, the voltage could be greatly reduced. Based on our work, other types of tunable gratings with blue phase liquid crystals are also proposed [95,96]. The tunable gratings exhibit great potential for photonic and display applications, such as optical interconnects, beam steering, and projection displays.
CHAPTER 5  SUMMARY

In this dissertation, we investigated blue phase liquid crystal materials and their electro-optical properties for display and photonic applications.

A PS-BPLC precursor consists of nematic LC host, chiral dopant, and monomers. Each component plays an important role while interacting with each other. In Chapter 2, we analyzed the role and the desired physical property of each material component in a PS-BPLC mixture as well as the UV curing process. A liquid crystal with high $\Delta n$, large $\Delta \varepsilon$ and high clearing temperature $T_c$ is desirable in terms of enlarging the Kerr constant and reducing the driving voltage. Low viscosity LC is preferred in terms of response time. However, large $\Delta \varepsilon$ LC typically has high viscosity. Therefore, we need to balance $\Delta \varepsilon$ and viscosity of the nematic LC. Chiral dopant induces twist in blue phases. The desired property for chiral dopant is high twisting power, high melting point and good solubility. Regarding to monomers, a rigid polymer network is preferred to achieve wide temperature range and fast response time, but the downside is the driving voltage. Therefore, a delicate balance between different physical parameters needs to be taken in the material optimization.

In Chapter 3, we investigated the electro-optical performance of optically isotropic liquid crystals, including the measurement of electric field induced birefringence, dynamic response of a PS-BPLC, and the material optimization by defining a figure of merit. The major research achievements are summarized as follows:

1) The induced birefringence of polymer-stabilized blue phase under an electric field tends to saturate at high electric field region. An extended Kerr effect is proposed to explain the
saturation behavior in the high field region. It leads to a more accurate simulation of the
electro-optical properties of polymer stabilized optically isotropic LCs.

2) Different methods are proposed to measure the electrically-induced ordinary and
extraordinary refractive indices and induced birefringence of a VFS cell. These
measurement methods enable characterization of blue phase materials and on the other
hand, guide the optimization of materials and devices.

3) Dynamic relaxation of a PS-BPLC is investigated. It is found that the response time
becomes slower as the electric field exceeds the critical field, which is also the critical
field for hysteresis to occur. These results will guide the future device design for keeping
fast response time while suppressing hysteresis.

4) We define a figure of merit (FoM) to compare and optimize the overall performance of
BPLC materials. FoM is closely related to the properties of host LCs. Although
increasing $\Delta\varepsilon$ of a LC host enhances Kerr constant which is favorable for reducing
voltage, these strong polar materials also increase the viscosity and response time
dramatically. As a result, the overall FoM may not gain. The FoM provides a guideline
for developing high performance BPLC materials.

   In Chapter 4, the display applications of PS-BPLC are discussed, including transmissive
display and reflective display. Transmissive displays occupy the largest market in LCD industry.
There are two types of BPLC display mode for transmissive displays: IPS mode and VFS mode.
For the IPS mode, we proposed a method to reduce the driving voltage by $\sim35\%$ by red-shifting
the Bragg reflection of PS-BPLC composite and using circular polarizers. Submillisecond
response time and high contrast ratio are maintained. For the VFS mode, the major challenge is
the viewing angle. We proposed a turning film design to achieve wide-view VFS display. The viewing angle (FWHM) was widened to ± 80° in horizontal direction and ± 50° in vertical direction. Compared to transmissive display, reflective display has the advantages of good sunlight readability, low power consumption, and no need for a polarizer. For the first time, we demonstrated a reflective display using blue phase liquid crystals. It exhibits vivid-colors, narrow reflection bandwidth, submillisecond response time, and natural grayscales. It also shows potential for 3D applications. The proposed display opens a new gateway for reflective displays and will make significant impacts to display industry.

Photonic applications of PS-BPLC include tunable color devices, tunable lenses, lasing, etc. In Chapter 5, we demonstrated a tunable phase grating with a high diffraction efficiency of 40% and submillisecond response time.

This work covers PS-BPLC material and device development and advances in the recent years and will continue making a significant impact on the material development and related display and photonic applications.
CHAPTER 6   MAJOR ACCOMPLISHMENTS IN THIS DISSERTATION

The major accomplishments in this dissertation are summarized as follows:

1) An extended Kerr effect model is proposed, which explains the inadequacy of conventional Kerr effect and correctly predicts the saturation phenomena of induced birefringence. It fits well with experimental data. This model has been widely embedded in commercial simulation software like LCD Master and TechWiz.

2) Proposed a method to directly measure the electric field-induced ordinary and extraordinary refractive indices for the first time. Based on this approach, a vertical field switching mode (VFS) is invented. We evaluated the performance of VFS mode experimentally, predicted optimal cell gap for achieving low driving voltage both numerically and analytically, and proposed a new turning film design to achieve wide viewing angle. This mode shows several advantages and will have great impact on transmissive BPLC displays. Two patents have been filed.

3) A reflective display using PS-BPLC is demonstrated. The most challenging problems for reflective displays are unsaturated colors and slow response time. Our proposed reflective display exhibits vivid colors, narrow reflection bandwidth, submillisecond response time, and natural grayscales. The proposed display opens a new gateway for reflective displays.

4) A tunable phase grating based on BPLC is demonstrated with 40% diffraction efficiency and submillisecond response time. A few groups worldwide are following our original work to demonstrate 2D tunable phase gratings.
APPENDIX: LIST OF PUBLICATIONS
Journal publications:


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