Fast-response Liquid Crystal Displays

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FAST-RESPONSE LIQUID CRYSTAL DISPLAYS

by

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ABSTRACT

After about five decades of extensive material research and device development, followed by massive investment in manufacturing technology, thin-film-transistor liquid-crystal-display (TFT-LCD) has finally become the dominant flat panel display technology. Nowadays, LCD performances, such as viewing angle, contrast ratio, and resolution, have reached acceptable levels. The remaining major technical challenges are response time, light efficiency, and sunlight readability. Fast response time is desired to reduce motion blur and to enable field sequential color displays using red (R), green (G), and blue (B) LEDs (light emitting diodes) without noticeable color breakup. Sequential RGB colors would eliminate the commonly used spatial color filters which in turn enhances light efficiency and resolution density by ~ 3X. In this dissertation, several new approaches for achieving fast-response LCDs are explored.

From material viewpoint, the most straightforward approach for achieving fast response time is to employ a thin cell gap with high birefringence and low viscosity liquid crystal (LC). We investigated the thin cell approach theoretically and experimentally. Voltage shielding effect and anchoring energy effect of alignment layers are found to play important roles on operating voltage and response time. Simulations are carried out to understand the underlying physics and confirm the experimental results quantitatively.

Another approach to realize fast response time is to explore novel device configuration. Here, we proposed a dual fringing-field switching (DFFS) mode in which small LC domains are
formed following the distribution of fringing fields. Therefore, it exhibits submillisecond response time without using thin cell or overdrive/undershoot voltage method. The response time of the DFFS mode is ~20X faster than a conventional vertical aligned LCD. In addition, high optical efficiency is achieved from the complementary top and bottom active LC domains. Two transmissive and one transflective LCDs using DFFS mode are conceived and their electro-optical properties investigated.

A shortcoming of DFFS LCDs is their fabrication complexity. To keep the advantages of this fast-response mode while avoiding the requirement of double-TFTs and pixel registration, we modified the device structure to transflective LCD which uses a single TFT in each pixel and vertical aligned positive dielectric anisotropy LC. Two types of electrodes are considered: fringing-field switching (FFS) and in-plane switching (IPS). Besides fast response time and high transmittance, such a transflective LCD shows good sunlight readability.

As nematic LC is gradually approaching to its limit in term of response time, polymer-stabilized blue phase (PSBP) LCD is emerging. It has potential to become next-generation display because of following revolutionary features: submillisecond response time, no need for alignment layer, good dark state and symmetric viewing angle, and cell gap insensitivity if IPS electrode is employed. In this dissertation, we studied the material-property correlation of Kerr effect-induced birefringence in nano-structured PSBP LC composites. Furthermore, a new device configuration of BP LCD with corrugated electrodes is proposed to solve two critical technical issues: high driving voltage and relatively low transmittance. The on-state voltage can be reduced from ~35 $V_{\text{rms}}$ to ~10 $V_{\text{rms}}$ which will enable TFT addressing, and the transmittance is improved from ~65% to ~85%. This new device configuration will accelerate the emergence of
PSBP LCD.

Wide view is another important requirement for a high-end display. Several new LCD configurations with negative A-plate and biaxial plate as phase compensation films are proposed to achieve wide view and broadband operation. The underlying working principles are studied and detailed display performances are included in this dissertation.
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CHAPTER 1: INTRODUCTION

1.1 Background of Liquid Crystal Displays

Liquid crystal (LC) was first discovered by an Austrian botanist and chemist Friedrich Reinitzer during his experiment with cholesteryl benzoate and later named by a German physicist Otto Lehmann. LC is a phase of matter between isotropic liquid and crystalline solid. It can flow like a liquid but also has properties like some crystalline material, such as dielectric and optical anisotropies. These properties make LC a promising candidate for variable phase modulation with an external voltage, and further make it useful for display applications, in which LC functions as an intensity modulator between a pair of polarizers.

Nowadays, liquid crystals especially nematic phase LCs, have been widely used in display applications. Liquid crystal display (LCD) has become the mainstream technology in flat panel displays. Its application spans from cell phones, portable video players, car navigations, all the way to large size displays such as computer monitors, TVs, and data projectors. The major advantages of LCDs are slim and flat screen, lightweight, high definition, low driving voltages, and low power consumption, just to list a few. [1-2] LCD industry is growing rapidly and the market is estimated to exceed $100 billion in 2010s.
Generally speaking, a LCD panel consists of a two dimensional array of pixels. Each pixel can be driven independently by a thin film transistor (TFT). Taking a transmissive LCD as an example, Figure 1.1 shows the basic structure of a color pixel. Since LCD is non-emissive, a backlight unit is embedded behind the panel. In order to make the backlight uniform and efficient, several optical components, such as light guide plate, diffusive reflector, diffusers, brightness enhancement films and reflective polarizers, are usually laminated in sequence in the backlight unit. Following the backlight unit is the LC cell, which is sandwiched between two crossed linear polarizers. Usually on the bottom substrate, a TFT array is formed to provide independent switch for each pixel. A transparent electrode such as indium tin oxide (ITO) is deposited at either TFT substrate or both substrates, depending on which LCD mode is employed. With different voltages
applied to ITO, the LC molecules are reoriented by the exerted electric field and different gray levels can be generated. On the other side, color filters are fabricated on the top substrate. One pixel usually contains red (R), green (G) and blue (B) three sub-pixels. Combining RGB colors with varied transmittance in each pixel, a full-color display can be obtained. For wide-view applications, optical phase compensation films are required. These films are laminated between LC cell and polarizers. [2]

LCD is a non-emissive display comprising of several layers and each layer has its unique functionality. As a result, each layer can be optimized separately to realize its best performance. However, some shortcomings are associated with such non-emissive layered structure, such as limited viewing angle, low light efficiency and non-saturated colors. In the past decade LCD’s viewing angle has been greatly improved through advanced operation modes such as in-plane switching (IPS) [5-7], fringe-field-switching (FFS) [8], and multi-domain vertical aligned mode (MVA) [9, 10], as well as phase compensation. Color gamut has been expanded from 75% NTSC to 120% NTSC by replacing CCFL (cold cathode florescence light) backlight with RGB LED backlight. However, the response time is still slow (~5-10 ms) and overall panel’s light efficiency remains low (~7%).

There are two reasons for the urgent need of fast response time. One is to reduce motion image blurs, i.e., ghost images in a slow LCD when displaying fast-moving pictures. Nowadays, video are not only shown in TVs, but also in monitors and mobile devices. Therefore, response time is an important issue for most display applications. The other reason is that fast response will enable color sequential displays. [11] Color sequential display shows RGB colors in time sequential so that it does not need color filters to mix colors in space. With RGB color filters
eliminated, both light efficiency and image resolution density can be improved by approximately ~3X. Fast response is a critically desired property for next generation displays.

### 1.2 Literature Review of Fast-Response LCDs

The response time of LC directors can be described by two simplified equations, which are derived from Erickson-Leslie equation, when the backflow and inertial effects are ignored, [12, 13] and small angle approximation [14] is assumed. As shown below, the rise time and decay time are expressed in Eq. (1.1) and Eq. (1.2) respectively:

\[
\tau_{\text{rise}} = \frac{\gamma_1 d^2 / K \pi^2}{(V / V_{\text{th}})^2 - 1},
\]

\[
\tau_{\text{decay}} = \gamma_1 d^2 / K \pi^2,
\]

where \(\gamma_1\) is the rotational viscosity, \(K\) is the corresponding elastic constant, \(d\) is the cell gap, \(V\) is the applied voltage, and \(V_{\text{th}}\) is the threshold voltage.

These equations correlate LC response time with LC material, cell parameters, and operating conditions. From these equations, we find that in order to achieve fast response time, the visco-elastic coefficient \((\gamma_1/K)\) of the LC material and cell gap \(d\) need to be reduced. Also, a high voltage helps to shorten the rise time. This approach is known as overdrive voltage method. It has been widely used in LCD industry. In the following paragraphs, we will briefly describe each approach.

From material viewpoint, low viscosity LC mixtures help to reduce the response time. As shown in equations (1.1) and (1.2), a smaller \(\gamma_1/K\) leads to a shorter response time. Moreover,
high birefringence ($\Delta n$) LC materials are preferred in order to achieve enough phase retardation with a thin cell. Several low viscosity LC materials have been developed. [15, 16] However, there are always tradeoffs between dielectric anisotropy, birefringence, and viscosity. For instance, from molecular structure viewpoint a large $\Delta \varepsilon$ and high $\Delta n$ material tends to increase viscosity. To optimize LC compound structures and physical properties for display applications is a continuous effort but is not in the scope of this dissertation.

From device standpoint, the most straightforward way to improve response time is to employ a thin LC layer. As seen from equations (1.1) and (1.2), both rise time and decay time are proportional to $d^2$. Thus, the thinner the LC layer, the faster the response times. However, to keep the total phase retardation unchanged with a reduced cell gap requires a higher $\Delta n$ LC material [16]. There is no doubt that device performance is closely related to the material employed.

The LC behaviors in a thin cell were explored more than two decades ago. [17] It is found that when a cell gap is thinner than 3 $\mu$m, the effective $\Delta n$ of the LC is no longer the same as that in a thick cell. Because of the roughness or defects of the alignment layers, the boundary layers of a LC cell have a lower order parameter than that of the bulk layers. The effective $\Delta n$ will be strongly affected by these boundary layers in a thin cell. More recently, surface anchoring energy is also found to play an important role affecting the relationship between response time and cell gap. [18] The response time of LC directors is proportional to cell gap $d$ as $\tau_0 \sim d^x$, where the exponent $x$ can vary between 1 and 2, depending on the surface anchoring energy. As in Eqs. (1.1) and (1.2), the case of $x=2$ corresponds to strong anchoring. In present LCD industry, a typical cell gap is ~3.5 $\mu$m and the trend is to go thinner. With a thinner cell gap, the influences from surface alignment layers and their anchoring energy require detailed studies.
Beside cell gap, the response time of a LC device is also highly dependent on the driving voltage. Here we will explain the working principle of overdrive and undershoot driving method [19, 20]. With a higher voltage pulse than needed during rise process and a lower (zero) voltage pulse during decay process, both rise and decay times can be greatly shortened. Recently, more approaches using electric field to accelerate LC decay process have been demonstrated. A LC device configuration with three electrodes has been proposed for both hybrid alignment mode and vertical alignment mode, using fringing field to turn-on and vertical field to turn-off the LC modulator. [21, 22] Similarly, in another fast-response FFS mode, a pair of FFS driving electrodes is added on top substrate to speed up the relaxation process. With optimized electrodes parameters and driving scheme, decay time can be shortened to half of that without top electrodes. [23] However, these approaches require more complicated driving circuits which in turn lead to increased cost.

Another important factor affecting LC response time is LC cell configuration. Two research groups have developed optically compensated bend (OCB) mode, in which the back-flow effect which slows down LC’s response time does not exist. [24, 25] In an OCB cell, the pretilt angles on top and bottom substrates are in opposite directions. As the applied voltage is below a critical voltage \( V_c \), the LC directors favor splay mode. As \( V > V_c \), splay mode transitions to bend mode due to a smaller energy density as compared to the initial splay state. Working under bend mode, OCB cell exhibits an average gray-to-gray response time less than 3 ms benefiting from LC flow effect. However, the transition time from splay to bend state is relatively long (few seconds). Moreover, a bias voltage is required in order to keep in the bend state. [26] Studies show that if the pretilt angle exceeds \(~46^\circ\) then the cell is in the bend mode
without any bias voltage. [27, 28] However, the maximum transmittance of such a bend cell is decreased to ~70% because the high molecular tilt dramatically reduces the phase retardation.

Several other methods have also been investigated to reduce LC response time. For example, the polymer sustained alignment in MVA cell helps to improve the rise time by ~2X. [29, 30] Doping nanoparticles into LC mixtures tends to lower the viscosity and increase the elastic constant, which are also helpful to reduce response time. [31, 32] However, long term stability of these novel approaches remains to be tested.

Overall speaking, in the past decades, the nematic LC’s response time has been reduced from ~30 ms to ~5 ms. This will greatly help with motion blur reduction. However, the trend is to go to submillisecond response in order to realize color sequential display without noticeable color breakup.

Recently, polymer-stabilized blue-phase liquid crystal (PS-BPLC) [33-35] is emerging with strong potential to become next-generation LCD due to its revolutionary features: 1) less than 1 ms response time; 2) no need for alignment layer; 3) optically isotropic dark state and wide view; and 4) insensitivity to the cell gap if IPS electrodes are used. However, two major technical challenges: high operating voltage (~50 \( V_{rms} \)) [36] and relatively low transmittance (~65%) need to be overcome before widespread applications can be realized.

Several approaches have been proposed to lower the operating voltage of BPLC. For instance, a BPLC material with a large Kerr constant (\( K \sim 12.7 \text{ nm/V}^2 \)) [36] has been recently developed to reduce the driving voltage from over 100 \( V_{rms} \) to ~50 \( V_{rms} \). By optimizing the IPS electrode width and gap [37, 38], the operating voltage is further reduced to ~35 \( V_{rms} \). However, these voltages are still far beyond the acceptable range of mainstream amorphous-silicon TFTs.
Although some structures such as wall-shaped [39] and protrusion electrodes [40] show very positive trend to lower the driving voltage to 10 \( V_{rms} \), the transmittance is sacrificed and moreover the device fabrication becomes complicated. Therefore, there is an urgent need to develop approaches for not only lowering the operation voltage but also keeping a high transmittance.

In this dissertation, several fast-response LCD modes with both nematic LC and PS-BPLC are studied. In the conventional nematic LCD part, we have studied the alignment layer’s effects in thin cell, proposed a submillisecond LCD mode with vertical alignment and FFS driving electrodes, and also designed several configurations originating from this mode for both transmissive and transflective displays. When conventional nematic LC is gradually reaching its limit in term of response time, PS-BPLC stands out as a promising candidate to push the response time to much less than 1 ms. In this dissertation, studies on PS-BPLC are also carried out, on both physical properties and new device configurations. Our proposed device shows a relatively low operating voltage (<10V) while keeping a high transmittance (85%). Another chapter introducing our work on wide view compensation schemes is also included in this dissertation. Our approaches open a new door for next-generation LCDs to achieve fast response, high resolution, wide view, and low power consumption.
CHAPTER 2: FAST-RESPONSE LCDS WITH NEMATIC LIQUID CRYSTALS

Nematic, cholesteric, and ferroelectric liquid crystals (LCs) have been used in display devices, while the majority is nematic because of its natural grayscale capability. In early days, nematic LCs suffer from slow response time. After decades of extensive material research and device development, the performances of nematic LCDs have been significantly improved. Therefore, in this Chapter we begin discussion with nematic LCs and operation modes, and propose new approaches to achieve fast response.

2.1 Thin Cell Approach

Thin cell gap \(d\) is a most straightforward approach to obtain fast response time, since response time is proportional to \(d^2\). However, as the LC cell gap is reduced, several factors such as alignment layer thickness and surface roughness become much more important than those in a thick LC cell. A typical polyimide (PI) alignment layer is about 80-nm thick and there are two such layers in a LC cell. The dielectric property of these PI layers would shield a portion of the applied electric field in a thin cell, which results in an increased threshold voltage and on-state voltage. The anchoring energy of these alignment layers would affect the dynamics of the LC response. Moreover, the surface roughness of these alignment layers would reduce the effective birefringence of the LC layer. [17]
In this part of the dissertation, we analyze the factors affecting the performances of thin LC cells in both transmissive mode and reflective mode. [41] To demonstrate the impact, we use a vertical alignment (VA) cell as an example. We focus our analyses on the alignment layer’s dielectric and anchoring effects on the operating voltage and response time. In experiment, the voltage-dependent reflectance of three thin VA Liquid-Crystal-On-Silicon (LCoS) cells was measured. Parameters including thickness of alignment layer, pretilt angle, [42, 43] anchoring energy, and effective $\Delta n$ were extracted. The experimental results agree pretty well with theoretical analysis.

### 2.1.1 Theoretical Analysis and Simulations

In an active-matrix addressed LCD, each pixel can be independently driven by a TFT and the voltage on each pixel is hold by the LC layer which works as a capacitor. As shown in Figure 2.1 (a), by scanning the scan line sequentially, the TFTs can be switched on and off line by line. For each pixel, when the TFT is switched on, the voltage on the data line can be charged to the ITO electrodes. After charging, the TFT is switched off and the charges are kept by the LC capacitor. A storage capacitor is usually connected with LC capacitor in parallel to compensate any current leakage, because LC itself is not a perfect capacitor.
Figure 2.1 (a) Capacitor model of one LCD pixel; and (b) capacitor model of the LC layer and alignment layers in a LC cell.

On each inner surface of an LCD substrate, there is an alignment layer which is usually made of PI or silicon oxide, with a thickness of ~80 nm. Part of the applied voltage can be shielded by these alignment layers, due to their dielectric properties. The shielded voltage is very a small portion in a thick LC cell so that it is often negligible. In a thin cell, the capacitance of the alignment layers has to be taken into consideration. To analyze this, we develop a simple capacitor model. Two alignment layers and one LC layer can be treated as three capacitors in series, [44] as shown in Figure 2.1 (b). The relationship between the effective voltage on the LC layer ($V_{LC}$) and the applied voltage ($V_{applied}$) on the LC cell can be derived as follows:

$$V_{LC} = V_{applied} \left(1 + \frac{2 \varepsilon_{LC} d_{align}}{\varepsilon_{align} d_{LC}}\right),$$

(2.1)

where $\varepsilon_{LC}$ is the effective dielectric constant of the LC layer at a given voltage, $\varepsilon_{align}$ is the dielectric constant of the alignment layer, $d_{align}$ and $d_{LC}$ are the thickness of alignment layer and LC layer, respectively. Equation (2.1) indicates that $V_{LC}$ is smaller than $V_{applied}$ because of the
voltage shielding effect of the alignment layers. For a thick cell where $d_{LC} \gg d_{align}$, Equation (2.1) is reduced to $V_{LC} \sim V_{applied}$, which means the dielectric shielding effect is negligible. However, for a thin cell the dielectric shielding effect would be apparent.

Figure 2.2 Cell gap dependent VT (a) and VR (b) curves. Reference curves are without considering the voltage shielding effects of the LC alignment layers. Other curves are for different thickness cells taking voltage shielding effect into account.

Simulations are carried out to address this issue in quantities. A VA cell is used as an
example, both in transmissive mode and reflective mode. Figures 2.2 (a) and (b) show the calculated voltage-dependent transmittance (VT) and reflectance (VR) curves of a thin VA cell at wavelength $\lambda = 550$ nm and room temperature. Here, we assume the anchoring is strong and pretilt angle is 2°. For the transmissive cell, we assume the alignment layers are polyimide with a thickness $d_{\text{align}} \sim 80$ nm and dielectric constant $\varepsilon_{\text{align}} = 3.4$. And for the reflective cell, we assume the alignment layers are SiO$_2$ with a thickness $\sim 120$ nm and dielectric constant 3.9. To keep the on-state voltage below $\sim 6 V_{\text{rms}}$ for low power consumption, we choose $d_{\text{LC}\Delta n} = 360$ nm for the transmissive mode and $d_{\text{LC}\Delta n} = 180$ nm for the reflective mode. All the other physical properties of LC material are taken the same as Merck MLC-6608. The reference curves in Figure 2.2 represent the cells without considering the alignment layer effect. From Figure 2.2, the voltage shielding effect remains small for thick cells but gradually becomes evident when the cell gap is below $\sim 2 \mu$m. If we take $\sim 50\%$ transmittance or reflectance as an example, for the 2-µm transmissive cell, there is a $\sim 0.4 V_{\text{rms}}$ voltage drop across the PI layers; while for the 1-µm reflective cell, the shielded voltage by the SiO$_2$ layers is increased to $\sim 1.1 V_{\text{rms}}$. In a reflective cell, the cell gap is thinner so that the voltage shielding effect is more evident.

As the voltage exceeds a threshold, the LC directors are reoriented by the electric fields. Taking a VA cell as an example, the value of $\varepsilon_{\text{LC}}$ gradually increases from $\varepsilon_{//}$ to $\varepsilon_{\perp}$ as the applied voltage increases. Accordingly, the shielded voltage keeps on increasing. Such a voltage shift increases power consumption but has no benefit to response time, because the increased portion of voltage is wasted on the alignment layers. To minimize the voltage shielding effect, a thin alignment layer such as photo-alignment whose alignment layer is only a few nanometers, [45, 46] is particularly attractive for thin cell applications.
Figure 2.3 VT curves of a 4-µm cell and a 2-µm cell (but with the same $d\Delta n$) under strong anchoring ($W \sim \infty$) and medium anchoring ($W = 10^{-4}$ J/m$^2$).

It is commonly known that LC directors are much easier to be reoriented by an electric field under a weaker anchoring. As the anchoring energy decreases, both threshold voltage and on-state voltage decrease. This phenomenon manifests further in thin cells. Figure 2.3 shows the VT curves for a 4 µm cell and a 2 µm cell under strong ($W \sim \infty$) and medium ($W = 10^{-4}$ J/m$^2$) anchoring conditions. The alignment layers and LC material properties are the same as those in Fig. 2.2 (a). With anchoring energy changing from strong to medium, for the 4 µm cell the ~50% transmittance voltage is decreased by ~0.5 $V_{rms}$. However, for the 2 µm cell this ~50% transmittance voltage is reduced by ~0.9 $V_{rms}$. That is to say, the anchoring energy effect is more sensitive to thin cells than thick cells.
Figure 2.4 Simulated LC tilt angle distribution under medium anchoring energy $W = 10^{-4}$ J/m$^2$. (a) $d = 4 \mu$m and (b) $d = 2 \mu$m. In both cases, $d\Delta n = 360$ nm.

The physical mechanism of this phenomenon is investigated. Figures 2.4 (a) and (b) show the simulated LC tilt angle distributions of a 4 $\mu$m cell and a 2 $\mu$m cell with anchoring energy $W = 10^{-4}$ J/m$^2$. Under the same medium anchoring and same voltage, the LC directors at the
boundary layers of thin cells tilt more heavily than those of thick cells. The distribution of LCs is a result of the balance between the elastic energy, electric energy, and surface energy. Let us divide the LC layer into two boundary layers and one bulk layer in between. For the bulk layer in a thin cell, under the same voltage the electric field is stronger due to the smaller cell gap, but the anchoring effect is also stronger because the bulk layer is closer to the alignment layers. As a result, the middle layer’s tilt angle is more or less the same between the thin and thick cells. Indeed, this is the case shown in Figs. 2.4 (a) and (b). However for the two boundary layers, the corresponding electric field is stronger in a thin cell than a thick cell under the same applied voltage but their anchoring strength remains almost the same. Therefore, the LC tilt angle near the surface boundaries is larger in a thin cell than a thick cell, as shown in Fig. 2.4. In other words, it takes a lower voltage for a thinner cell to achieve the same transmittance than a thicker cell, as shown in Fig. 2.3. Please note, the $d_{LC\Delta n}$ of the cells remains the same; i.e., a thinner cell would require a higher $\Delta n$.

Anchoring energy effect on the LC director’s response time can be described as follows:

$$\tau_0 = \frac{\gamma_1}{K\pi^2} (d^2 + \frac{4dK}{W} + \frac{4K^2}{W^2})$$

(2.2)

$$\tau_{\text{rise}} = \frac{\tau_0}{(V/V_{th})^2 - 1}$$

(2.3)

where $\gamma_1$ is the rotational viscosity, $K$ is the corresponding elastic constant, $d$ is the cell gap, $V$ is the applied voltage, $V_{th}$ is the threshold voltage and $W$ is the anchoring energy.
Figure 2.5 Comparison of the response time of a 2 µm cell under different anchoring energies. The voltage is applied between 0 and that the transmittance-peak voltage shown in Figure 2.3.

From Equation 2.2, for a given LC material and cell gap, the decay time $\tau_0$ becomes longer for a weaker anchoring energy. On the other side, as in Equation 2.3, the rise time $\tau_{\text{rise}}$ not only depends on the anchoring energy but also depends on the voltage switching ratio, defined as $V/V_{\text{th}}$. Although a weaker energy lowers the threshold voltage, it also lowers the on-state voltage. Thus, its overall effect depends on the operating conditions. Figure 2.5 shows the response time for the 2-µm cell mentioned above under different anchoring energies. The voltage is applied from 0 to a value corresponding to the transmission peak shown in Fig. 2.3, i.e., $V = 6.6$ $V_{\text{rms}}$ for strong anchoring ($W \sim \infty$) and $V = 3.9$ $V_{\text{rms}}$ for medium anchoring ($W = 10^{-4}$ J/m$^2$). As the anchoring energy is decreased from strong to medium, the rise time and decay time are increased from ~1.2 ms, ~3.8 ms to ~3.9 ms, ~5.0 ms, respectively. The total response time (rise time + decay time) is increased by ~78%. From Equation 2.2, the longer decay time results from the
weaker restoring force, but from Equation 2.3, the longer rise time results also from a smaller voltage switching ratio. Although the threshold voltage is decreased under weak anchoring, the on-state voltage decreases even further. This effect is also more evident with reduced cell gap. Thus, to achieve fast response time using a thin cell, a strong anchoring is preferred.

### 2.1.2 Experimental Validation

The electro-optic properties of three LCoS cells are measured. The cell gap is ~2.4 µm. The LC employed is MLC-6608 whose physical properties are listed as follows: $K_{11} = 16.7$ pN, $K_{33} = 18.1$ pN, $\varepsilon_{//} = 3.6$, $\varepsilon_{\perp} = 7.8$, $\gamma_1 = 0.186$ Pa s, $n_o = 1.475$ and $n_e = 1.558$. All the data were measured at 25 °C and $\lambda = 633$ nm.

![Experimental setup for measuring the reflectance of a 2.4-µm LC cell under different driving voltages.](image)

To accumulate enough phase retardation, we placed the LCoS cell in reflective mode. The experimental setup is shown in Figure 2.6. The LCoS cell is attached on a reflector. The LC cell together with the reflector was arranged between a pair of crossed polarizers, and the on-state LC director at 45° with respect to the transmission or absorption axis of polarizer. We intentionally made a very small deviation angle between the incident and reflected beams, so that the reflected
beam can be separated from the incident one and thus the reflectance can be measured. The deviation angle is so small (< 10°) that we still treat it as normal incidence, since the phase retardation difference of LC cell between these two cases is small enough to be neglected. Reflectance are measured and recorded at different voltages.

Figure 2.7 Experimental data (dots) and fitting curves of three LCOS cells. Fitting curve 1 includes the voltage shielding effect and the extracted parameters are listed in Table 1.1. Fitting curve 2 does not consider the voltage shielding effect.

Figure 2.7 shows the experimental data and fitting curves. The measured data from three LCoS thin cells are consistent with each other quite well. We fitted these measured data with and without considering the voltage shielding effect of alignment layers. The black solid curve is the one with voltage shielding effect. It agrees very well with the experimental data. Without voltage shielding effect, as the dashed line, there is an obvious deviation between experimental data and simulated curve. With voltage shielding effect, the extracted parameters are listed as follows: alignment layer (SiOₓ) thickness ~(200 ± 20) nm, pretilt angle ~5 ± 1°, anchoring energy W ~(1.8 ± 0.3) × 10⁻⁴ J/m², and effective ∆n ~0.063 ± 0.02. The effective ∆n is lowered
by ~24% of the original value because of the defects and surface roughness of the alignment layers. Comparing the difference between the solid line and dashed lines, which represent the theoretical calculations with and without considering the voltage shielding effect respectively, we can easily see that our theory agrees well with experiment.

Table 2.1 Extracted parameters of three thin LCoS cells

<table>
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<tr>
<th>Parameter</th>
<th>Extracted value</th>
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<td>Alignment layer</td>
<td>(200±20) nm</td>
</tr>
<tr>
<td>Pretilt angle</td>
<td>5±1°</td>
</tr>
<tr>
<td>Anchoring energy</td>
<td>(1.8±0.3)×10^-4 J/m^2</td>
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<tr>
<td>Effective Δn</td>
<td>0.063±0.02</td>
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</table>

2.2 Dual Fringing Field Switching Mode

The analysis in Sec. 2.1 shows that due to the voltage shielding effect and anchoring energy effect of alignment layers, the electro-optic performance of a thin cell is likely to deviate from expectation. Moreover, cell gap uniformity and fabrication of thin cells are also concerns. In this part, we propose a dual fringe field switching (DFFS) mode, [47] which shows fast response without depending on thin cell gap.

2.2.1 Structure of DFFS Mode

Figure 2.8 shows the basic device structure of proposed DFFS mode. Fig. 2.8 (a) illustrates voltage-off state and (b) shows LC distribution with applied voltage. Because LC layer itself is a phase modulator, to achieve intensity modulation two crossed polarizers are attached
on top and bottom sides of the LC cell, respectively. The electrode structure on each substrate is the same as a conventional fringe field switching (FFS) LCD which has a planar common electrode and slit pixel electrodes separated by a layer of dielectric material. In the DFFS mode, the electrode width (W) and electrode gap (G) is around 2-5 \( \mu m \), and the LC cell gap is around 10 \( \mu m \), depending on the LC material employed. The purpose of using such a large cell gap is to form two separated active LC layers on top and bottom automatically. The top and bottom pixel electrodes are intentionally shifted by half a pixel electrode width in order to form complementary domains on two boundary layers for enhancing the optical efficiency.

When there is no voltage applied, as shown in Figure 2.8 (a), all the LC directors are aligned vertically to the substrate. Therefore, the light passing through the LC layer experiences no phase retardation and is blocked by the crossed analyzer, resulting in an excellent dark state. On the other hand, when the applied voltage exceeds a threshold (\( V_{th} \)), the LC directors are tilted by the fringing fields and the phase retardation effect takes place. As shown in Figure 2.8 (b), fringing fields between pixel electrodes and common electrode can be formed periodically. LC employed here has a positive dielectric anisotropy, so the LC molecules will be redistributed with long axis following electric field directions. At the center of both pixel electrodes and slits in between, LCs keep vertical because the electric field at those locations are either vertical or too weak to reorient the LCs. In this way, periodical sub-domains can be formed as shown in Fig. 2.8 (b). These active sub-domains are effective to induce phase retardation and therefore change light transmittance. Transmittance at other locations especially at the center lines keeps at a low level, which we call them dead zones. Fortunately there is another layer of active domains on top as we intentionally designed, and therefore the phase retardations from bottom and top active
layers can be compensated by each other. These dead zones should be eliminated in order to achieve high transmittance.

![Diagram of Device Structure](image)

(a)

![Diagram of Device Structure](image)

(b)

Figure 2.8 Device structure of DFFS mode. (a) shows the off-state without any driving voltage; (b) shows the on-state with a driving voltage applied corresponding to the maximum transmittance.
2.2.2 Mechanism of Fast Response

Three factors contribute to the fast response time in DFFS mode. Firstly, as shown in Figure 2.9, there is a middle layer where LC molecules keep vertical all the time formed between top and bottom active LC layers. We call these three layers as standing layer and effective layers respectively. These three layers are formed due to a limited penetration depth of fringing electric fields. Solving from Poisson equation, the smaller the dimension of pixel electrodes and slits in between, the shallower the fringing fields penetrate. In this DFFS mode, in order to achieve fast response time, we designed the pixel electrodes and slits at a small dimension scale, for example, 3 μm. Therefore the fringing fields from such driving electrodes are concentrated close to a thin boundary layer. We used a thick LC cell, thus even at on-state, the electric field in the middle of the cell is too weak to rotate the LC directors. In other words, although the LC cell gap is pretty large in our design, the effective LC layer is very thin. Since response time is a quadratic function of cell gap, the involved thin effective LC layers will lead to a fast response.

Secondly, domain walls are formed between every two neighboring LC domains, as shown in Fig. 2.9. The locations of these domain walls are on top of the center of pixel electrodes and gaps in between. As explained earlier, the electric field direction is perpendicular to substrate, so that the LCs remain at vertical direction. Although the transmittance in the dead zones originates exactly from these walls, these walls do make significant positive contribution to fast response. These walls provide a restoring force during decay process and help LCs at active domains relax back very quickly.
Figure 2.9 Simplified LC cell of DFFS mode showing the mechanism of fast response.

Moreover, the on-state LC profile between two horizontal walls is similar to an optically compensated bend (OCB) cell, [25] where the LC flow effect in DFFS helps LC directors switch even faster. So we expect there is no back flows to slow down LCs relax process. In our simulation, we neglected flow in LC layer.

These three factors work together and achieve fast switching speed. In one word, the proposed DFFS mode is a fast response mode due to periodical small active LC domains.

### 2.2.3 Simulations and Results

The proposed DFFS mode can have both fast response and high transmittance for the reasons discussed before. Its electro-optic properties vary with different electrodes dimensions and LC material. The requirement of minimum cell gap to achieve fast response is also dependent on these factors. To find out the appropriate values for different applications, we used a three-dimensional (3D) LC simulator (TECHWIZ developed by Sanayi) to simulate and optimize the DFFS LC cell structure. The electric field and LC redistribution are calculated by
finite element method [48] and optical calculation is based on the extended $2 \times 2$ Jones matrix methods [49].

Figure 2.10 Simulated VT curves for the proposed cells. Curve 1 is for Cell 1 with E7-like LC: $d = 14 \, \mu\text{m}$, $W = 3 \, \mu\text{m}$, and $G = 3 \, \mu\text{m}$; Curve 2 is for Cell 2 with high $\Delta n$ LC material: $d = 11 \, \mu\text{m}$, $W = 2 \, \mu\text{m}$, and $G = 2 \, \mu\text{m}$; Curve 3 is a comparison curve is for a cell with E7-like LC: $d = 14 \, \mu\text{m}$, $W = 3 \, \mu\text{m}$, and $G = 3 \, \mu\text{m}$.

For display applications, fast response, high transmittance, and wide view are highly desirable. Here Cell 1 is an example designed for display applications; its device parameters are listed as follows: cell gap $d = 14 \, \mu\text{m}$, electrode width $W = 3 \, \mu\text{m}$, and electrode gap $G = 3 \, \mu\text{m}$. The LC material used in simulations is very similar to those of Merck E7: $K_{11} = 11.7 \, \text{pN}$, $K_{22} = 8.8 \, \text{pN}$, $K_{33} = 19.5 \, \text{pN}$, $\Delta n = 0.223$, $\Delta \varepsilon = 14.4$, and $\gamma_1 = 150 \, \text{mPas}$. For comparison, the rotational viscosity of E7 is ~250 mPas at room temperature. Some LC mixtures with similar birefringence but with a lower viscosity ($\gamma_1 \sim 80 \, \text{mPas}$) are commercially available. A lower viscosity leads to a
faster response time.

The VT curve of Cell 1 is shown as curve 1 in Figure 2.10. The threshold voltage is $V_{th} \sim 2.5 \, V_{rms}$, on-state voltage $V_{on} \sim 13 \, V_{rms}$. Its maximum transmittance is $T_{max} \sim 91.8\%$ which is normalized to the maximum transmittance of two parallel linear polarizers. For comparison, the transmittance of conventional multi-domain vertical alignment (MVA) mode is $\sim 80\%$. So the light efficiency of DFFS mode is much higher than the conventional MVA mode, which in turn will save the power consumption of backlight.

Meanwhile, many phase modulation-based photonics devices also demand a fast response. Such modulators are usually operated at normal incident angle, therefore, wide view is not absolutely necessary. We used Cell 2 as an example to illustrate the application of DFFS mode in this field. The device parameters are listed as follows: $d = 11 \, \mu m$, $W = 2 \, \mu m$, and $G = 2 \, \mu m$. With decreased electrode width and gap, the tilted LC layer shrinks closer to the substrate, which means a thinner LC layer contribute to the phase retardation effect. Therefore, a higher birefringence LC material is required to obtain a sufficient phase change. Curve 3 in Fig. 2.10 represents the VT curve for Cell 2 using the same material as in Cell 1. Clearly, its phase retardation is insufficient to reach $1\pi$ at $15 \, V_{rms}$. Increasing cell gap does not lower the operating voltage much because it only thickens the middle standing layer which makes no contribution to the overall phase retardation. A more effective way is to employ a high birefringence LC mixture. The parameters for the high birefringence LC material (UCF-2 type) [50, 51] used in calculation are listed as follows: $K_{11} = 17.3 \, pN$, $K_{22} = 10.4 \, pN$, $K_{33} = 38.3 \, pN$, $\Delta n = 0.416$, $\Delta \varepsilon = 18.27$, and $\gamma_1 = 200 \, mPas$. The VT curve for Cell 2 filled with UCF-2 is shown as curve 2 in Fig. 2.10, with a threshold voltage $\sim 3 \, V_{rms}$ and a maximum transmittance $\sim 93\%$ at on-state voltage $\sim 13 \, V_{rms}$. The
high transmittance implies to a high optical efficiency.

Table 2.2 Calculated gray-to-gray scale response times (ms) of DFFS cell 1.

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Table 2.3 Calculated gray-to-gray scale response times (ms) of DFFS Cell 2.

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The gray-to-gray (GTG) response times of Cell 1 and Cell 2 were simulated and results are summarized in Table 2.2 and Table 2.3, respectively. During calculations, we divided the transmittance uniformly into 8 gray levels (1-8). Each pair of the GTG response time was calculated. Here, the response time is defined as 10% to 90% transmittance change. The cell gaps of the two cells are optimized to achieve a fast response time. If the cells are too thin, the middle LC layers will rotate slightly with a slower speed which, in turn, leads to a slower GTG response time. On the other hand if the gap is too thick, some problems such as narrow viewing angle and strong cross-talks between the neighboring pixels would occur. The optimized cell gaps also depend on the LC material employed. They are 14 µm and 11 µm for Cell 1 and Cell 2, respectively. With these optimized parameters, the response times are calculated. The average GTG rise time for Cell 1 is \(~1.88\) ms and average GTG decay time is \(~1.68\) ms. Such fast response can help realize color sequential displays. To further shorten response time, a lower viscosity LC or overdrive and undershoot voltage method can be employed. By combining these two effects, the response time is expected to be reduced by additional \(~3-5X\). For Cell 2, the average GTG rise time is \(~0.91\) ms and decay time is \(~0.68\) ms at room temperature. In comparison, a VA cell with 4.64 µm cell gap and MLC-6608 has an average GTG rise time \(~38.8\) ms and decay time \(~42.1\) ms. [52] In comparison, the response time of our DFFS mode is \(~20\) X faster.

Cell 1 is an example for display applications, so wide view is a requirement. To obtain wide viewing angle, we use a positive A-plate and a negative C-plate on each side of the cell for phase compensation. It is a common configuration for wide-view MVA display devices. The optic axis of the positive A-plate is parallel to the transmission axis of the polarizer on the same
side. The parameters of the compensation films are optimized by minimizing light leakage at dark state. The parameters used in our simulation are listed as follows: for positive A-plate refractive index $n_e = 1.5590$, $n_o = 1.5866$, and thickness $d \sim 25.65 \, \mu m$; and for negative C-plate refractive index $n_e = 1.50$, $n_o = 1.65$, and thickness $d \sim 8.02 \, \mu m$. [53]

![Diagram of phase compensation films](image)

Figure 2.11 The configuration of DFFS mode with A-plate and C-plate as phase compensation films.

With such a phase compensation configuration, wide view can be achieved. Figure 2.12 shows the isocontrast contour plots of film-compensated Cell 1. The 100:1 isocontrast contour line extends beyond the $70^\circ$ viewing cone. This is adequate for most display applications, including TVs, monitors, and mobile devices. However, it is quite difficult to achieve a good dark state for Cell 2 because its $d\Delta n$ is too large to be compensated precisely. With the employed large $d\Delta n$, the accumulated phase retardation is quite large even under a very small pretilt angle resulting in a non-negligible light leakage. Thus, Cell 2 is more suitable for laser beam steering
and adaptive optics where the incident laser beam is nearly normal to the LC cell. The incident laser polarization should be set parallel to the LC reorientation axis (horizontal direction in Fig. 2.8) in order to obtain phase-only modulation. For such applications, the required phase change is $2\pi$. This can be achieved by using reflective mode where the incident light traverses the LC layer twice or by increasing the birefringence of LC material.

Figure 2.12 Isocontrast contour plot of Cell 1. The parameters of the compensation films are listed as follows: for A+ plate $n_e = 1.5590$, $n_o = 1.5866$, and $d = 25.65 \, \mu m$; and for C plate $n_e = 1.50$, $n_o = 1.65$, and $d = 8.02 \, \mu m$.

### 2.2.4 Transflective LCD using DFFS mode

Based on the fast-response DFFS structure, we further implement it to transflective LCDs (TR-LCDs) for mobile device applications. [54]
Figure 2.13 Schematic structure of the single cell gap transreflective LCD using DFFS mode.

Figure 2.13 shows a cross-section of the schematic structure of the proposed TR-LCD using DFFS mode. On each side of the LC cell, a broadband quarter wave plate [55] together with a linear polarizer works as a circular polarizer. Additionally, one negative C-plate is adopted to compensate the phase retardation from the VA LC cell. Each display pixel is divided into two sub-pixels: a transmissive (T) region and a reflective (R) region. Each region is a DFFS structure introduced before. The difference between T and R parts is the electrode width and electrode gap. We intentionally designed the dimensions of pixel electrodes and gaps at R regions smaller than those at T regions. Therefore, the penetration depth of electric fields in the R region is weaker than that in the T region so that the phase difference at voltage-on state can be matched. By optimizing the parameters, similar VT and VR curves are obtained.

When no voltage is applied, all the LC directors are perpendicular to the substrate. Therefore, the light passing through the LC layer experiences no phase retardation so that its
polarization state is preserved. As a result, a dark state is achieved for both T region and R region. On the other hand, the LC directors are tilted with external electric field applied, resulting in phase retardation effect. Ideally, at the same on-state voltage, the phase retardation of the LC layer should be $\sim \lambda/2$ for the T region and $\sim \lambda/4$ for the R region in order to get a maximum transmittance and reflectance.

The LC material used in simulation is Merck E7 with parameters as follows: $K_{11} = 11.7$ pN, $K_{22} = 8.8$ pN, $K_{33} = 19.5$ pN, $\Delta n = 0.223$, $\Delta \varepsilon = 14.4$, and $\gamma_1 = 150$ mPas. Merck E7 is used here as an example to show the optical performances of the proposed TR LCD. In our calculations, the cell gap is $d = 14$ μm, electrode width $W = 3.2$ μm and electrode gap $G = 3.2$ μm for the T region. For R region, $W = 2$ μm and $G = 2$ μm.

![Figure 2.14 Equal-potential line distribution in the LC cell for a sample section with 11 V\textsubscript{rms} applied to pixel electrode. Cell gap $d = 14$ μm; T part: electrode width $W = 3.2$ μm, electrode gap $G = 3.2$ μm; R part: $W = 2$ μm and $G = 2$ μm.](image)

Figure 2.14 shows the calculated equal-potential line distribution when the same pixel...
voltage $11 \ V_{\text{rms}}$ is applied to both T region and R region. The potential difference between two neighboring potential lines is $0.5 \ V_{\text{rms}}$. The strong fringing field is mainly confined to the electrode surfaces, so only the boundary LC layers directors are perturbed by the strong horizontal fields there and the middle LC layer remains standing. The electrode width and electrode gap in the R region are narrower than those in the T region. Thus, the strong fringing fields penetrate to a thinner LC layer in the R region, resulting in smaller phase retardation than the T region. This is desirable because the incident light passes through R part twice while only once through T part. Nearly equal phase retardation is achieved by optimizing the electrode dimensions for the T part and the R part. In other words, we can realize a dark state, a white state and reasonably matched gray levels simultaneously for T part and R part with a single cell gap which eases device fabrication.

![Figure 2.15 VT and VR curves for the proposed TR-LCD. The insert shows the normalized results.](image)

Figure 2.15 VT and VR curves for the proposed TR-LCD. The insert shows the normalized results.
The VT and VR curves are shown in Figure 2.15. Here the maximum transmittance from two parallel linear polarizers in our simulation is ~37%. And the effective peak transmittance and reflectance of the proposed TR-LCD reach ~95.4% and ~93.8%, respectively. From the normalized VT and VR curves, T region and R region share a same on-state voltage ~12 \( V_{\text{rms}} \) and a very close threshold voltage ~2.5 \( V_{\text{rms}} \). The VT and VR curves overlap reasonably well for single gamma driving. Here the driving voltages are still a little bit too high, new LC materials with a higher \( \Delta \varepsilon \) can be employed to lower the driving voltages without sacrificing other optical performances, such as (3,5) difluoro NCS-biphenyl LC mixture. The NCS-biphenyl compounds exhibit a high birefringence, large dielectric anisotropy (\( \Delta \varepsilon \sim 12 \)), and relatively low viscosity, however, their resistivity is not high enough for thin film transistor (TFT) LCD applications. The (3,5) fluoro groups not only increase dielectric anisotropy to \( \Delta \varepsilon \sim 20 \) but also dramatically boost resistivity [16]. High resistivity is important for TFT LCD devices in order to avoid image flickering.

![Figure 2.16 Response time for the proposed TR-LCD at 12 \( V_{\text{rms}} \) (black) and 4.5 \( V_{\text{rms}} \) (red) for T part (a) and R part (b).](image-url)
The response times (10% - 90% transmittance change) of the DFFS TR-LCD are calculated as plotted in Figure 2.16 (a) for T part and Figure 2.16 (b) for R part. The rise time and decay time for T part are ~1.3 ms and ~1.8 ms, while for R part ~0.9 ms and ~0.9 ms, respectively. Furthermore, the response time at a low gray level $V = 4.5 V_{rms}$ is calculated and also plotted in Fig. 2.16 to illustrate the GTG response. The GTG response times at $4.5 V_{rms}$ are ~6.5 ms during rising process and ~1.3 ms during decaying process respectively for T part, and ~3.2 ms and ~0.8 ms for R part. Such a fast response time makes this transflective display attractive for reducing motion blurs.

The DFFS cell does not require any rubbing process. The LC directors form two domains on both LC boundary layers due to the fringing field effect. If zigzag electrodes are employed, then a four-domain structure is produced which helps to expand the viewing angle. As shown in Figure 2.13, on each side of the LC cell, together with a linear polarizer, positive A-plate and negative A-plate are used alternately as half wave plate (HWP) and quarter wave plate (QWP) to form a self-compensated wide-view and broadband circular polarizer [55]. An additional negative C-plate is used to compensate the viewing angle properties of the TR-LCD under circular polarizer system. These compensation films are optimized at green light $\lambda = 550$ nm and the parameters used in our simulation are listed as follows: For positive A-plate, $n_e = 1.65, n_o = 1.55$; for negative A-plate, $n_e = 1.55, n_o = 1.65$; for negative C-plate, $n_e = 1.55, n_o = 1.65$ and its thickness $d = 29.26 \mu m$. The thicknesses of the HWP and QWP are 2.75 $\mu m$ and 1.375 $\mu m$, respectively. With the transmission axis of polarizer and analyzer orientated at - 45° and 45° respectively, the optic axis of HWP and QWP are orientated at - 120° and 30° on each side of the LC cell.
Figure 2.17 Isocontrast contour plot of the proposed DFFS TR-LCD with compensation films.

Figure 2.17 shows the isocontrast contour after phase compensation. T part shows a
contrast ratio 10:1 over ~70° viewing cone and R part over ~40°. These viewing angles are adequate for most mobile displays, since a handheld LCD is usually viewed by only one person.

### 2.3 Sunlight Readable LCDs with Reflectors under Dead Zones

DFFS mode is advantageous in term of response time, but there are some shortcomings which may limit its mass production with current fabrication lines, such as 1) two TFTs needed 2) low tolerance in alignment accuracy between top and bottom patterned electrodes, and 3) relatively high driving voltage. In this part, we try to solve this problem by modifying DFFS structure into two new LCD modes with sunlight readability.

#### 2.3.1 Sunlight Readable VA-FFS mode

To ease the fabrication problem, we should pattern the FFS electrodes only on one substrate [55]. However, the biggest problem of this single-side VA-FFS mode is low transmittance (~50%); the exact value varies depending on the electrodes dimension. Figure 2.18 illustrates the simulated LC director distribution and transmittance profile of VA-FFS mode in a voltage-on state. The low transmittance occurs in the regions above pixel electrodes and spacing centers due to weak horizontal electric fields there.
In order to solve the problem of low light efficiency, we proposed a new LCD structure as shown in Figure 2.19. [57] It shows a cross-section of the schematic structure. LC cell is sandwiched between two crossed circular polarizers. The employed LC has positive $\Delta\varepsilon$ and is vertically aligned. So a normally black state is obtained under crossed circular polarizers. The driving electrodes are single-side FFS electrodes, with patterned pixel electrodes and a plane common electrode located below. In a voltage-on state, fringing fields are generated between pixel electrodes and common electrode. The LC directors are reoriented as shown in Fig. 2.19. The horizontal field is the strongest near the edges of pixel electrodes where effective domains are formed. While at the centers of electrodes and gaps, LC remains vertical because the horizontal electric field component there is too weak to reorient the LC directors. Therefore, the
phase retardation is not enough for T-mode and leads to low transmittance or dead zones. Here we imbedded patterned bumpy reflectors in these areas. In R-mode, light passes through the LC layer twice, so the optical phase retardation is doubled. Under such a circumstance, these transmittance inefficient areas in T mode would perform better in reflective mode. At the same time, transmittance in T regions is enhanced because the inefficient areas are excluded.

Figure 2.19 Device structure of proposed sunlight readable LCD with FFS driving electrodes and vertically aligned positive LCs.

In order to obtain fast response time, narrow electrode width and gap are preferred. With smaller electrode dimension, 1) the generated electric field is stronger, and 2) smaller effective sub domains can be formed. Both factors help reduce the response time. But on the other hand, to fabricate narrow electrodes (<5 μm) arrays would require high precision photolithography. Balancing both sides, we used electrode width \( W = 3 \) μm and gap \( G = 4 \) μm. The penetration depth of fringing field into LC cell is quite shallow with such electrode dimension. In this case, high birefringence LC material is needed in order to accumulate sufficient phase retardation. We
used a UCF-2 type LC mixture whose parameters are given in Sec. 2.2.3.

![Graph](image)

**Figure 2.20** Normalized VT and VR curves of the proposed device structure shown in Figure 2.19.

Figure 2.20 depicts the normalized VT and VR curves of the proposed sunlight readable FFS LCD at $\lambda = 550$ nm. Since T part and R part use different light sources: backlight for T part and ambient light for R part, so we should compare the normalized VT and VR curves instead of the absolute values. We optimized the values of cell gap and reflector width to obtain matched VT and VR curves. Here cell gap $d$ is 4 $\mu$m and reflector width $W_r$ is 1.6 $\mu$m locating at the pixel electrodes center and gap center. From Fig. 2.20, VT and VR curves of the proposed TR-LCD with FFS electrodes match with each other very well so that single gamma curve can be used to drive it. Transmittance reaches its peak at $V_{on} = 8 \ V_{rms}$, where the transmittance is $\sim 89\%$ normalized to that of two paralleled linear polarizers (37%). Reflectance is $\sim 46\%$ at $8 \ V_{rms}$. The relatively low reflectance originates from dead zones at the center of reflectors. However, the readability is dependent on R part only when the device is used under strong ambient light. In
this case, the luminance in R part is still quite high due to strong ambient light source. Together with anti-reflection film, good sunlight readability can still be achieved.

Table 2.4 Calculated GTG response time (ms) for the T part shown in Fig. 2.19

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Table 2.5 Calculated GTG response time (ms) for the R part shown in Fig. 2.19

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This sunlight readable VA-FFS mode exhibits fast response, following similar mechanism as that of DFFS mode. What’s different from DFFS mode is that the middle standing layer is not necessary in this mode, so a thin cell gap can be used. The 4-μm cell gap is compatible to current LCD industry and thus is easy to fabricate with high yield. Similar to DFFS mode, the domain walls are also formed which divide the active LC layers into small domains. As a result, the nice feature of fast response is preserved. To calculate GTG response time, we divided the VT curve uniformly into eight gray levels (1-8) and response times (10% - 90% transmittance change) between gray levels are calculated. Tables 2.4 and 2.5 summarize the calculated GTG response time of the structure shown in Fig. 2.19 for T and R parts, respectively. The averaged response time is ~ 2.08 ms for T part and ~ 3.10 ms for R part. The fast response time makes this TR-LCD attractive for mobile devices with video applications.

### 2.3.2 Sunlight Readable VA-IPS mode

Following the same working principle of sunlight readable VA-FFS mode in Chapter 2.3.1, we further propose a VA mode with IPS driving electrodes, as shown in Figure 2.21. Different from FFS electrodes, pixel electrodes and common electrodes in IPS cell are both patterned and located alternatively to each other. In this case, the inefficient regions are formed coincident with driving electrodes locations. At the center of electrode gap, there can still be a transmittance inefficient region, but the region is so narrow that its contribution to low transmittance can be neglected. So instead of inserting an extra layer of patterned reflectors, we use reflective electrodes in the reflective regions. As we substitute former ITO electrodes by aluminum reflective electrodes, we combine two functions into one component. These driving electrodes also function as reflectors. In this way, both sunlight readability and higher
transmittance are achieved. Moreover, its fabrication becomes much easier than the mode discussed in Sec. 2.3.1. By eliminating the layer of bottom common electrodes and the layer of patterned reflectors, at least two photomask processes can be eliminated.

![Schematic structure of the sunlight readable TR-LCDs using positive \( \Delta \varepsilon \) LC driven by horizontal electric field generated by IPS electrodes.](image)

Figure 2.21 Schematic structure of the sunlight readable TR-LCDs using positive \( \Delta \varepsilon \) LC driven by horizontal electric field generated by IPS electrodes.

In our simulation, we assume electrode width is 3 \( \mu m \) and electrode gap is 4 \( \mu m \), which are typical dimensions in present LCD industry. The LC material parameters are as follows: \( K_{11} = 12 \) pN, \( K_{22} = 9 \) pN, \( K_{33} = 20 \) pN, birefringence \( \Delta n = 0.2 \), dielectric anisotropy \( \Delta \varepsilon = 11 \), and rotational viscosity \( \gamma_1 = 250 \) mPa·s. Since reflective electrodes are used in this cell instead of extra reflectors, reflector width is determined by the driving electrodes width. Therefore only cell gap can be optimized to match VT and VR curves. With an optimized value \( d = 3 \) \( \mu m \), VT and VR curves of the proposed TR-LCD with IPS electrodes are shown in Figure 2.22. Although VT and VR curves are not matched with each other so well as in the sunlight readable VA-FFS mode in Sec. 2.4.1, it is still fairly good for single gamma driving. Transmittance reaches \( \sim 85\% \) at on-state voltage \( V_{on} = 7V \) and reflectance \( \sim 40\% \) at the same on-state voltage.
Figure 2.22 Normalized VT and VR curves of the proposed sunlight readable TR-LCDs with a) FFS electrodes and b) IPS electrodes at $\lambda = 550$ nm.

Response time of the proposed VA-IPS mode is sacrificed slightly because 1) we keep the electrode dimension relatively wide in order to make it feasible in present fabrication line; 2) the walls where LCs remain vertically aligned are formed at the center of each electrode, thus the sub-domain dimension is twice as that in VA-FFS mode. In short, the active LC domains in VA-IPS mode is not small enough to achieve as fast response time as in other modes mentioned in previous sections. But still, the response time can be considered fast if compared with current MVA LCD mode. This proposed sunlight readable VA-IPS mode shows a rise time ~5.99 ms and a decay time ~8.39 ms for T part, and a rise time ~5.58 ms and a decay time ~6.46 ms for R part, as shown in Fig. 2.23. For comparison, the response time of other LCD modes used in current mobile devices is much slower. For instance, response time of some FFS mode used in cell phones or other portable devices is ~30 ms. Our proposed LCD mode is more than 3X better and is especially applicable for mobile displays with fast response requirement, so that motion blur
can be reduced.

Figure 2.23 Simulated response time of T and R parts respectively of the proposed sunlight readable LCD with IPS driving electrodes.

2.4 Summary

In this chapter, we studied the thin cell approach of fast response LCDs. Especially the alignment layer effects are analyzed in details. Both voltage shielding effect and anchoring energy effect of the alignment layers are more evident in a thin cell than that in a thick cell. Further, DFFS mode is proposed and optimized to achieve submillisecond response time. The underlying mechanism is that the thin effective layer leads to a fast response and the periodic boundary walls supply a restoring force during decay process. In addition of fast response time, high transmittance, high contrast and wide view are achieved in this mode. It also shows good sunlight readability and easy fabrication capability with further modification.
CHAPTER 3: BLUE PHASE LIQUID CRYSTAL DISPLAYS

Recently, a new generation LCD with blue phase LCs is emerging with some revolutionary features, such as no need for alignment layer and submillisecond response time. The latter is due to its self-assembled nanoscaled periodic structures. However, some technical challenges in high operating voltage and relatively low transmittance remain to be overcome before wide-spread applications can be realized. In this chapter, we will investigate the properties of polymer-stabilized blue phase LCs (PS-BPLCs) and its potential applications for displays. A new driving concept is proposed to solve the two technical bottle necks: high driving voltage and low transmittance.

3.1 Introduction of Blue Phase Liquid Crystal

Blue phase liquid crystal exists in a fairly narrow temperature range, usually ~1-2 K below the isotropic state. [58-60] Early in Reinitzer’s report published in 1888, which marks the discovery of LC, there is a description about blue phase. Reinitzer observed that his sample turned blue between changing from clear to cloudy states during temperature cooling process. That’s why it is named as blue phase. Nowadays we know that this phenomenon is due to Bragg reflection from periodical structures in blue phase LC. The color varies upon different pitch length of the periodical structure, thus the reflected color is not necessarily blue, nor in the visible region. But still the name blue phase refers to all liquid crystalline phases with this kind
of specific LC structure regardless of the reflected colors.

Figure 3.1 Blue phase LC structure at the microscopic level: (a) double twist alignment of LC molecules; (b) double twist cylinder; (c) lattice cubic formed by double twist cylinders and (d) disclination lines.

Figure 3.1 shows how LC molecules are arranged in a blue phase LC. [59] As in Fig. 3.1 (a), LC directors form a double twist alignment. Similar to a chiral nematic, the LC directors are rotated in a helical structure. However, instead of a single helical axis there are many helical axes formed by the rotated LC directors and all of these axes are perpendicular to a center line. Although in reality an unlimited number of such helical axes could be present, we just use two of them to illustrate the molecular orientation and name it double twist structure. This double twist
structure is only extended to a small distance, with the boundary molecules aligned at 45° to the middle line, as shown in Fig. 3.1 (a). The double twist structure extends and forms a cylinder as Fig. 3.1 (b) shows. The helical lines drawn on the surface of the cylinder represent the LCs on boundary. The diameter of such double twist cylinder, which is related to the pitch length of the twisted LC structure, usually is ~100 nm. Such double twist cylinders are arranged in three directions perpendicular to each other and form a symmetric cubic structure, like a lattice structure, as shown in Fig. 3.1 (c). Here we describe the LC structure in a microscopic view. Since LC directors are aligned in various directions in a lattice structure, so macroscopically blue phase LC is an optically isotropic material.

Defects occur at the contact areas of three perpendicular cylinders. In these areas, LC directors are not aligned in order but randomly. Disclination lines formed by such defects also form a lattice structure, as shown in Fig. 3.1 (d). The lattice dimension depends on the pitch length and arrangement order of the double twist cylinders, usually around several hundred nanometers. Bragg reflection occurs in a certain wavelength range due to the periodic lattice structure of defects, and that is why BPLC appears color.

The LC state with such double twist lattice structure only exists in a small temperature range, as mentioned above. As the temperature is decreased, it will turn to chiral nematic phase, which has no defect lines and are more stable over a wider temperature range. Because of the narrow temperature range, blue phase LC is not suitable for display applications Polymer stabilization [33-36] widens the blue-phase range to over 60 K including room temperature. The function of polymer is like a long rope tangled together to fix the defects. In this way, the lattice structure is stabilized by polymers and become stable over a large temperature range. Polymer-
stabilized blue phase LC becomes a promising candidate to realize fast response time.

![Diagram of LC cells](image)

Figure 3.2 Comparison between nematic LC cell and blue phase LC to show the mechanism of the fast response of blue phase LC.

Blue phase LC exhibits submillisecond response time. The mechanism can be understood from Figure 3.2. As we have mentioned in Chapter 1, the response time of LC [14] depends on the cell gap as follows:

\[
\tau_n = \frac{\gamma_1 d^2}{K_{ii} \pi^2},
\]

(3.1)

where \(\gamma_1\) is the rotational viscosity, \(K_{ii}\) is the corresponding elastic constant and \(d\) is the cell gap. It is obvious from the equation that a thin cell plays an important role for achieving fast response.

Following similar methods, the response time equation can be extended to blue phase. Instead of depending on cell gap, the response time of a blue phase LC [61] depends on the pitch length of the periodical structure. As shown in Fig. 3.2, the whole blue phase LC bulk is comprised of many periodical domains. The boundaries are disclination lines instead of two
substrates. The distance between them is approximately half of the pitch length of the twisted structure. Neglecting the effect of different anchoring, the decay time of blue phase LC is expressed as:

\[ \tau_b = \frac{\gamma_1 P_o^2}{4k \pi^2}, \]  

(3.2)

where \( \gamma_1 \) is the rotational viscosity of the BPLC, \( P_o \) is the pitch length, and \( k \) is the effective elastic constant of the BPLC.

From these two equations, it can be easily seen that the response time of a blue phase LC could be significantly faster than that of nematic LC. For the convenience of discussion, let us assume the LC parameters of the BPLC and nematic are roughly the same. The cell gap of a nematic LC cell is usually \(~3.5\ \mu m\), while the pitch length of a blue phase LC is only \(~350\ \text{nm}\). Although the rotational viscosity and elastic constant of blue phase LC will both differ from those in nematic LC, it can still be estimated from equations 3.1 and 3.2 that the response time of a blue phase LC is about two orders of magnitude faster than that of nematic. Considering a typical response time of a nematic LC cell is \(~30\ \text{ms}\), the BPLC response time will be less than 1 ms. This prediction has been validated by several experiments. Some polymer-stabilized BPLC has shown a response time in the order of 100 \(\mu s\). Figure 3.3 shows the measured response time of a blue phase LC cell (the preparation process will be introduced later) driven between 200 \(V_{\text{rms}}\) and 0 \(V_{\text{rms}}\) at 40 \(^\circ\text{C}\), which is the approximate temperature of LCD panel due to backlight heating. Both rise and decay times are less than 200 \(\mu s\). Such a fast response time is very attractive for realizing color sequential displays, which can almost triple the light transmittance and image resolution density.
Figure 3.3 Measured response time of a blue phase LC when driven between 200 \( V_{\text{rms}} \) and 0 \( V_{\text{rms}} \) at 40 °C. Signal 1 is the applied voltage and signal 2 is the transmittance change which implies the fast response time.

In summary, polymer-stabilized blue phase LC is an optically isotropic material. It exhibits a fast response and has a fairly wide temperature range. Because of the optical isotropy in the voltage-off state, blue phase LCD exhibits a good dark state and wide viewing angle. The structure of blue phase LC is self-assembled and pinned by polymers, so it does not need any alignment layer or any rubbing process, thus its fabrication process is greatly simplified and the cost is reduced. Its response time is in submillisecond range which is ~100X faster than a conventional nematic LC. It is a strong contender for color sequential display without noticeable color breakup. All these revolutionary features make BPLC a potential candidate for next-generation display.
3.2 Electro-optical Property of Blue Phase Liquid Crystal

3.2.1 Kerr Effect of Blue Phase Liquid Crystal

Different from nematic LC, whose LC directors are rotated by externally applied electric field, the underlying physical mechanism of blue phase LC is electric-field-induced birefringence, which is known as Kerr effect. [62, 63] Kerr effect is a type of quadratic electro-optic effect caused by an electric-field induced ordering of polar molecules in an optically isotropic medium. It usually exists in crystals with centro-symmetric point groups. Macroscopically, the induced birefringence of blue phase LC follows Kerr effect, while microscopically the birefringence is still realized through LC molecules’ redistribution by an external electric field. Therefore the maximum induced birefringence of a blue phase LC cannot exceed the birefringence of the LC composite.

According to Kerr effect, the induced birefringence is proportional to the quadratic electric field as described in the following equation:

$$\Delta n = K\lambda E^2,$$

(3.3)

where $K$ is the Kerr constant, $\lambda$ is the wavelength and $E$ is the applied electric field.

An equation as follows can be used to represent the refractive index ellipsoid of a medium in the presence of an electric field:

$$\left(\frac{1}{n^2}\right)_1 x^2 + \left(\frac{1}{n^2}\right)_2 y^2 + \left(\frac{1}{n^2}\right)_3 z^2 + 2\left(\frac{1}{n^2}\right)_4 yz + 2\left(\frac{1}{n^2}\right)_5 xz + 2\left(\frac{1}{n^2}\right)_6 xy = 1$$

(3.4)

where,
The first term in equation 3.5 is related to initial refractive indices of the medium at three primary directions, \(n_x, n_y, n_z\). The second term refers to linear electro-optic effect, which is known as Pockels effect, and the third term refers to quadratic electro-optic effect, which is known as Kerr effect. \(r_{ij}\) and \(s_{ij}\) are electro-optic tensor for linear and quadratic electro-optic effect, respectively. Kerr effect is small as compared to linear effect, so it is usually neglected in the presence of linear effect. However in crystals with centrosymmetric point groups, the linear effect vanishes and then Kerr effect becomes dominant. \[63\]

Blue phase is an optically isotropic liquid when the external electric field is absent, therefore the refractive index at any direction is equivalent, say \(n_i\). Therefore we assume the applied electric field is along \(z\) direction in a Cartesian coordinate system, as shown in Figure 3.4.
Figure 3.4 A coordinate showing the refractive index ellipsoid and the direction of applied electric field.

Under such a circumstance, the electric field components at $x$ and $y$ directions are both zeros:

$$
\begin{bmatrix}
E_1^2 \\
E_2^2 \\
E_3^2 \\
E_{xy}E_{xy} \\
E_{xz}E_{xz} \\
E_{yz}E_{yz}
\end{bmatrix}
\Rightarrow
\begin{bmatrix}
0 \\
0 \\
E_{zz}^2 \\
0 \\
0 \\
0
\end{bmatrix}
$$

(3.6)

In equations 3.5, the term of linear electro-optic effect vanishes and only the Kerr effect term survives. The electro-optic tensor for Kerr effect varies with different molecular structure. For an isotropic liquid, its quadratic electro-optic effect coefficients can be represented in the following matrix:
Substituting matrix 3.6 and 3.7 into equation 3.5, we can get the refractive index ellipsoid of blue phase LC under electric field as follows:

\[
\begin{bmatrix}
    s_{11} & s_{12} & s_{12} & 0 & 0 & 0 \\
    s_{12} & s_{11} & s_{12} & 0 & 0 & 0 \\
    s_{12} & s_{12} & s_{11} & 0 & 0 & 0 \\
    0 & 0 & 0 & \frac{1}{2}(s_{11} - s_{12}) & 0 & 0 \\
    0 & 0 & 0 & 0 & \frac{1}{2}(s_{11} - s_{12}) & 0 \\
    0 & 0 & 0 & 0 & 0 & \frac{1}{2}(s_{11} - s_{12}) \\
\end{bmatrix}
\]

(3.7)

From equation 3.8, we can tell that the ordinary refractive index is along \( x \) and \( y \) directions and the extraordinary refractive index is along \( z \) direction.

\[
n_o = \left( \frac{1}{n_i^2} + s_{12}E_z^2 \right)^{-1/2} \approx n_i - \frac{1}{2} n_i^3 s_{12} E_z^2
\]

(3.9)

\[
n_e = \left( \frac{1}{n_i^2} + s_{11}E_z^2 \right)^{-1/2} \approx n_i - \frac{1}{2} n_i^3 s_{11} E_z^2
\]

(3.10)

\[
\Delta n = n_e - n_o \approx \frac{1}{2} n_i^3 (s_{12} - s_{11}) E_z^2
\]

(3.11)

Equation 3.3 and equation 3.11 can both represent the induced birefringence of a blue phase LC, the former using Kerr constant and the latter using its quadratic electro-optic coefficients. Comparing these two equations, we can see Kerr constant \( K \) is also dependent on the wavelength. It is a constant only at a given wavelength and temperature.
3.2.2 Dispersion of Induced Birefringence

As discussed before, Kerr-effect-induced birefringence varies with wavelength. However such a relationship is not explicit in Eq. 3.3 because Kerr constant $K$ is also wavelength dependent. Although the dispersion property of the Kerr-effect-induced birefringence of blue phase LCs has been predicted to follow the normal dispersion trend, [37, 38] few experimental results have been reported to understand the underlying physics and to validate the physical model. On the other hand, the refractive index dispersion is important and should be considered for full-color displays. It will further affect the gamma curves for RGB sub-pixels, or RGB sub-frames in color sequential displays. In this part of the dissertation, we report the dispersion property of blue phase LCs with experimental results. [64]

![Experimental setup](image)

Figure 3.5 Experimental setup for measuring the VT curves of a blue phase LC cell at different wavelengths.

To study the dispersion relation of blue phase LCs, we carry out an experiment measuring the electro-optic properties of blue phase LC under different wavelengths. Figure 3.5 shows the experimental setup. A narrow band interference color filter is placed after a white light source to select a wavelength for measurements. In our experiment, interference filters with transmission peaks at 450 nm, 500 nm, 550 nm, 633 nm and 660 nm and a bandwidth ~5 nm are used and the
electro-optical properties under these five wavelengths are measured. Since the white light source has an evident divergence angle, a group of lenses is used to collimate the light. In Fig. 3.5, we use one collimating lens to illustrate this function group. A collimated light can travel a long distance without much divergence. Finally a focusing lens is used to focus the transmitted light into a photodiode detector. The blue phase LC cell is sandwiched between two crossed polarizers with striped electrodes towards 45° with respect to the transmission axis of polarizer. The blue phase LC used in this experiment is a UV cured mixture consisting of 56 wt% nematic LC host MLC14200, 29 wt% chiral dopant and 15 wt% monomers. The LC cell uses periodical striped electrodes with slits in between. The optical working principle of blue phase LCD with such electrodes will be explained later. The electrode width and gap are both ~10 μm and cell gap is ~7.5 μm. Voltages are applied to the LC cell and transmittance under different driving voltages are measured. The operating temperature is at room temperature (~23°C).

Figure 3.6 shows the measured VT curves of our BPLC sample at five wavelengths. The transmittance at each wavelength is normalized to its own peak value. The operating voltage is lower at a shorter wavelength for two reasons: 1) phase retardation is inversely proportional to wavelength, thus a shorter wavelength will lead to a larger phase retardation under the same driving voltage; 2) birefringence decreases with wavelength in a normal dispersion medium, while the phase retardation is proportional to birefringence so the phase retardation is larger at a shorter wavelength. Considering these two factors, the required operating voltage is lower to reach the same phase retardation at a shorter wavelength than that at a longer wavelength.
Figure 3.6 Measured (dots) and fitted (curves) VT curves of a blue phase LC cell at different wavelengths.

In order to study the detailed dispersion trend of a blue phase LC, we used the extended Kerr effect model [65] to fit the experimental data:

$$\Delta n = \Delta n_{sat} \left(1 - \exp\left[-\left(\frac{E}{E_s}\right)^2\right]\right)$$  \hspace{1cm} (3.12)

where $E$ is the applied electric field, $E_s$ is the saturated electric field and $\Delta n_{sat}$ is the saturated induced birefringence. The extended Kerr effect model is proposed in order to describe the electro-optic property of a blue phase LC more accurately, in which the induced birefringence is linearly proportional to $E^2$ at low electric field and gradually saturate with increased electric field. [65]
The fitting results based on equation 3.12 are shown in Figure 3.6. The dots are experimental data and the curves are fitting results. They overlap with each other very well at each wavelength. There are two fitting parameters: saturated electric field $E_s$ and saturated induced birefringence $\Delta n_{sat}$. The fitting results at different wavelengths are list in Table 3.1.

Table 3.1 Fitting results of the saturated birefringence, saturated electric field, and the corresponding Kerr constant of the blue phase LC at different wavelengths.

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>$\Delta n_{sat}$</th>
<th>$E_s(10^6$ V/m)</th>
<th>$K(10^{-9}$ m/V$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>0.0730</td>
<td>6.8</td>
<td>3.51</td>
</tr>
<tr>
<td>500</td>
<td>0.0695</td>
<td>6.8</td>
<td>3.01</td>
</tr>
<tr>
<td>550</td>
<td>0.0670</td>
<td>6.8</td>
<td>2.63</td>
</tr>
<tr>
<td>633</td>
<td>0.0635</td>
<td>6.8</td>
<td>2.17</td>
</tr>
<tr>
<td>660</td>
<td>0.0630</td>
<td>6.8</td>
<td>2.06</td>
</tr>
</tbody>
</table>

It is interesting to note that the fitting results of saturated electric field $E_s$ keep the same for all wavelengths, which means the term $E_s$ mainly governs the electric behavior of a blue phase LC. At a given temperature and applied voltage, the LC directors are reoriented and a distribution of LC directors is formed determined by the balanced elastic energy and electrostatic energy. This distribution will not be affected by the employed wavelength. Therefore, the term $E_s$ keeps the same.

The optical dispersion of a blue phase LC is represented by the saturated induced birefringence $\Delta n_{sat}$. As we can see from Table 3.1, it decreases with wavelength following a normal dispersion trend.
Figure 3.7 Dispersion relations of the saturated induced birefringence of the BPLC (red) and LC host MLC-14200 (blue). Solid lines are fitting curves.

Figure 3.7 shows the wavelength dependent saturated induced birefringence $\Delta n_{sat}$ (dots), and the solid line represents the fitting curve based on the single-band model [66]:

$$\Delta n_{sat} = G \frac{\lambda^2 \lambda^*}{\lambda^2 - \lambda^*} \rightarrow G \lambda^*$$  \hspace{1cm} (3.13)

where $\lambda^*$ is the resonant wavelength of the LC composite and $G$ is a proportionality constant. As Fig. 3.7 shows, similar to nematic LCs the dispersion of blue phase also follows the single band dispersion model quite well. With two fitting parameters: $\lambda^* \sim 216$ nm and $G \sim 1.205 \times 10^{-6}$ nm$^{-2}$ the agreement between experimental data and curve fitting is quite good. The obtained average resonance wavelength ($\lambda^* \sim 216$ nm) is expected by judging from the birefringence ($\sim 0.17$) of the LC host MLC14200. For a higher birefringence LC host, $\lambda^*$ will
increase because of the elongated $\pi \rightarrow \pi^*$ electronic transition wavelengths.

To better illustrate this, we further measured the birefringence of LC host MLC14200 using Abbe refractometer. The measured data are included in Fig. 3.7 and the solid blue line is the fitting curve based on Eq. 3.13 with $\lambda^* \sim 218$ nm and $G \sim 3.047 \times 10^{-6}$ nm$^{-2}$. Comparing the fitting results of the blue phase LC and its host LC MLC14200, we find the saturated induced birefringence of blue phase LC follows the same dispersion as its host LC with a similar $\lambda^*$. The proportionality constant $G$ is changed due to the polymer and chiral dopant in polymer-stabilized blue phase LC. Thus the saturated induced birefringence of blue phase LC is smaller than the original birefringence of its host LC.

The saturated birefringence of blue phase LC decreases as wavelength increases. When the wavelength is much longer than the resonant wavelength $\lambda^*$, the induced birefringence gradually saturates to a constant $G\lambda^*$ as shown in Eq. 3.13. When blue phase LC is used in the infrared region, for instance $\lambda > 1 \ \mu m$, the induced birefringence will reach a saturation level.

In the low electric field region, the extended Kerr effect model is reduced to conventional Kerr effect model, with a relationship between the parameters as follows:

$$ K = \frac{\Delta n_{\text{sat}}}{\lambda E_i^2} $$

(3.14)

Kerr constants obtained following equation 3.14 are also listed in Table 3.1. It also decreases with wavelength. From equations 3.13 and 3.14, we can get the wavelength dependency of Kerr constant:

$$ K = \frac{G\lambda\lambda^2}{E_i^2(\lambda^2 - \lambda^*^2)} = \frac{A\lambda\lambda^2}{\lambda^2 - \lambda^*^2} $$

(3.15)
where $A$ is a proportionality constant.

Figure 3.8 Calculated Kerr constant at different wavelengths and the fitting results of the dispersion of Kerr constant of the blue phase LC.

We fitted the Kerr constant data with equation 3.15. The fitting result is shown in Figure 3.8, in which the resonant wavelength is $\lambda^* \sim 216$ nm and proportionality constant $A \sim 2.62 \times 10^{-2}$ nm$^{-1}$. The well fitted data clearly demonstrate the wavelength dependency of Kerr constant $K$. It decreases with an increasing wavelength following Eq. 3.15. In Kerr effect, $\lambda K$ is used as a coefficient to calculate the induced birefringence under certain electric field. The term $\lambda K$ follows the same dispersion as the saturate electric field $\Delta n_{sat}$ with a saturation trend when wavelength is much larger than the resonant wavelength. Correspondingly, the Kerr-effect-induced birefringence also decreases with wavelength and gradually saturate at long wavelength region.

In conclusion, the wavelength and electric field dependency of induced birefringence of
blue phase LC can be expressed as follows:

\[
\Delta n = \frac{G^2 \lambda^2}{\lambda^2 - \lambda^2_s} \left[1 - \exp \left(-\left(\frac{E}{E_s}\right)^2\right)\right].
\]  

(3.16)

In this equation, saturation electric field \(E_s\) governs the electric behavior of blue phase LC while saturated induced birefringence determines the optical behavior and thus the optical dispersion of blue phase in mainly represented by this term. It still follows the normal dispersion trend and agrees very well with the single-band model.

### 3.3 Modeling of Blue Phase LCD

To accurately calculate the detailed molecular distribution of blue phase LC in response to external fields, both Landau free energy and electric energy need to be considered, [58, 60] which is rather complicated. However, at macroscopic scale the electro-optical properties can be calculated by a simple model based on Kerr effect. Without electric fields, each small blue phase unit can be viewed as an optically isotropic material, having refractive indices identical in its principle coordinates. When a strong electric field \(E\) is applied, birefringence is induced and the refractive ellipsoid has its optic axis along the \(E\) vector. The induced birefringence is linearly proportional to \(E^2\), but this is valid only when the electric field is well below the saturation electric field \(E_s\).

As the electric field keeps increasing, the induced birefringence will gradually saturate but it cannot exceed the intrinsic birefringence of the LC/polymer composite when all the LC directors are eventually reoriented by the external field. Both extended Kerr effect and
conventional Kerr effect model are used to carry out the electro-optical calculation of blue phase LC. When using conventional Kerr effect model, a maximum birefringence is set for any electric field stronger than the saturation electric field. Although it is a rough approximation, this approach has been tested and proven to be accurate enough to predict the electro-optical properties of blue phase LCs. In the following paragraph, we outline our simulation method base on conventional Kerr effect. The simulation based on extended Kerr effect follows the same pattern but just with a different equation of the induced birefringence under external electric fields.

In our numerical modeling, we assume the blue phase LC initially behaves like an isotropic substance. As shown in Figure 3.9, we first compute the potential distribution from solving the Poisson equation $\nabla(\nabla \cdot \Phi) = 0$ and then the distribution of electric field $E$ in the medium. Based on the obtained electric fields, we further calculate the induced birefringence distribution from Eq. (3.3) and assign the optic axis direction of each unit from the $E$ vector. After obtaining the birefringence and optic axis profiles, we adopt the extended Jones matrix to compute the related EO properties.
To validate our simulation, we prepared two fringing field switching (FFS) cells. One filled with sample I having a host LC material, monomers, and chiral dopants, which was cured at an isotropic state, and the other filled with sample II having the same mixture but cured in the blue phase temperature range. The host LC material used here has a large dielectric anisotropy ($\Delta \varepsilon \approx 32$) and high birefringence ($\approx 0.30$). The monomers employed are RM-257 and EHA (ethylhexyl acrylate). LC host material is mixed with monomers at the ratio which enables BP stabilization at room temperature. The FFS cell used in Figure 3.10 has a cell gap $d = 10 \, \mu\text{m}$, electrode width $w = 4 \, \mu\text{m}$, and electrode gap $g = 6 \, \mu\text{m}$. 

Figure 3.9 Flowchart of polymer stabilized blue phase LCD modeling based on Kerr effect. Insert plot depicts the induced birefringence.
In an FFS cell, strong horizontal electric fields exist near the patterned stripe electrode edges; thus high transmittance occurs only near those electrode edges where induced ellipsoid is more horizontally oriented. The photo in Fig. 3.10 shows an image of the FFS cell filled with sample II, placed between two crossed polarizers, and operated at 90 $V_{rms}$. The black area on the right side of the photo represents the dark state.

![Graph showing VT curves](image)

Figure 3.10 VT curves of FFS cells filled with LC sample I (cured at an isotropic phase) and II (cured at a blue phase) at $\lambda = 632.8$ nm. Cell gap $d = 10 \, \mu m$, electrode width $w = 4 \, \mu m$, and electrode gap $g = 6 \, \mu m$. The photo shows the experimental results of the FFS addressed blue phase LC at 90 $V_{rms}$.

Figure 3.10 shows the normalized VT curves for FFS cells filled with samples I and II. Dots are experimental data and lines are fitting curves with Kerr constant as the only adjustable parameter. A reasonably good agreement between our simple model and experiment is obtained. Therefore our model can work fairly well although it is only a rough model.
Through fittings, we found the Kerr constant for samples I (cured at an isotropic state) and II (cured at blue phase) is \(K \sim 0.47 \text{ nm/V}^2\) and \(\sim 1.03 \text{ nm/V}^2\), respectively, at \(\lambda = 632.8 \text{ nm}\). The Kerr constant of sample II is \(\sim 2.2X\) larger than that of sample I. Clearly, a larger Kerr constant causes a higher induced birefringence which in turn leads to a lower operating voltage.

In our experiment, the measured rise time of the FFS cell using sample II is \(\sim 300 \mu s\) at \(\sim 23 \degree C\).

Later, we further modified our simulation following extended Kerr effect as shown in equation 3.12. This model has been validated with directly measured data of induced birefringence of blue phase LC in a homogenous LC cell with in-plane driving electrodes. [67] Compared with our rough model at first stage, the modified simulation with extended Kerr effect agrees much better with experimental data in an in-plane switching (IPS) cell. So our simulation became more accurate by adopting extended Kerr effect.

### 3.4 Device Concepts of Blue Phase LCDs

To successfully drive blue phase LCs to realize different grayscales, a strong electric field along horizontal direction is desired. Therefore, the most effective driving electrodes currently available should be IPS switching electrodes. Besides, newly designed driving electrodes with a large horizontal electric field component and good uniformity across the horizontal direction is suitable for blue phase LCDs to reduce driving voltage and improve light transmittance.

#### 3.4.1 Blue Phase LCDs with IPS Electrodes

As discussed in Section 3.2, the induced birefringence of blue phase LC under an external
electric field follows Kerr effect. Therefore the induced birefringence occurs where electric field exists and its optic axis follows the direction of the electric field. To achieve effective phase retardation, we need the birefringence to be induced in a plane parallel to LC cell substrates instead of vertical; therefore horizontal electric field is desired. Among driving electrodes used in present LCD modes, IPS electrodes are most effective to generate horizontal electric field. That’s why most of blue phase LCD devices at present are using IPS driving electrodes.

Figure 3.11 Device structure and the working principle of blue phase LC driven by IPS electrodes. The right photo shows the top view of a group of IPS electrodes with 10 µm electrode width and 10 µm electrode gap.

Figure 3.11 illustrates the working principle of a blue phase LC cell with conventional IPS electrodes in a cross section view. The blue phase LC is filled in an IPS cell with patterned pixel electrodes and common electrodes located in the same plane but alternatively to each other. The photo in the right side shows the top view of an IPS cell (employed in our experiment) with 10 µm electrode width and 10 µm electrode gap. The LC cell works under a pair of crossed linear polarizers, bottom one called polarizer and top one called analyzer.
In Fig. 3.1, the left part shows the voltage-off state and right part shows the voltage-on state. Without voltage, the blue phase LC is optically isotropic from macroscopic view. Therefore its refractive index ellipsoid is like a sphere, as shown in Fig. 3.1. The polarization state of the incident light will not be changed because there is no phase retardation generated by the LC layer, therefore the outgoing light will be blocked by the analyzer. Since blue phase LC is like an isotropic medium at V=0, the dark state is very good and this will further leads to a high contrast. When a voltage is applied, as the right side of the figure shows, induced birefringence will be generated in blue phase LC following the electric field direction. The striped electrodes are placed at 45° to the transmission axis of polarizer, so that the induced birefringence will be generated along 45° to this axis, which is the most effective direction to accumulate phase retardation. In a voltage-on state, blue phase LC layer will work as a half-wave plate thus the linearly polarized light after polarizer will be rotated by 90° and pass through the analyzer. In this way, a white state is achieved.

Figure 3.12 depicts the simulated VT curves of different IPS cells at various electrode width \( w \) and gap \( l \) combinations (here IPS: 5–10 denotes \( w = 5 \ \mu m \) and \( l = 10 \ \mu m \)). For comparison purpose, the results of the FFS cell are also included. The Kerr constant used in the simulations is 1.03 nm/V\(^2\) at \( \lambda = 632.8 \) nm. As expected, smaller electrode spacing generally leads to a lower operating voltage. Moreover, a larger \( l/w \) ratio increases the area ratio having horizontal fields and improves the transmittance. Besides, for the same electrode spacing, a larger electrode width enables the horizontal fields to penetrate deeper into the vertical direction which is helpful for lowering the operating voltage, because more phase retardation can be accumulated in a thicker effective layer. Similarly, the FFS cell exhibits a lower transmittance.
than the IPS one due to a much shallower penetration depth of the electric fields. On one hand, a smaller electrode width $w$ and spacing $l$ generates larger electric fields near the surface at a lower voltage; on the other hand, the effective layer with evident induced birefringence is also reduced as compared to that with a larger electrode dimension. As a result, when the electrode dimension shrinks, the decrease in operating voltage in IPS cells is balanced by the increased electric field intensity and the thinner effective layer in the longitudinal direction. Therefore adjusting the electrodes dimension of IPS cell is helpful for reaching a balanced performance, but there is a limitation to push further.

![Simulated VT curves of blue phase LC in an IPS cell with different dimensions of electrodes and slit. In addition, a VT curve with a Kerr constant 100X larger is shown here to illustrate the future possibility and a VT curve of blue phase LC in a FFS cell is also shown here for comparison.](image)

Figure 3.12 Simulated VT curves of blue phase LC in an IPS cell with different dimensions of electrodes and slit. In addition, a VT curve with a Kerr constant 100X larger is shown here to illustrate the future possibility and a VT curve of blue phase LC in a FFS cell is also shown here for comparison.
Therefore, to lower the driving voltage, a larger Kerr constant is critically important. In Fig. 3.12, the same IPS cell with \( w = 2 \mu m \) and \( l = 4 \mu m \) was calculated by increasing the Kerr constant by 100X. The operating voltage is reduced by 10X to \(~15 V_{rms}\) which roughly follows the relation of \( V_1/V_2 \sim (K_2/K_1)^{1/2} \). In 2009, it was reported that a blue phase LC with Kerr constant at the order of 10 nm/V\(^2\) has been developed, [36] which is \(~10X\) improvement compared to the one used in our simulation. Correspondingly, the on-state driving voltage can be reduced to \(~50 V_{rms}\) in an IPS cell with 5-\( \mu m \) electrode and 10-\( \mu m \) space in between.

Figure 3.13 Calculated isocontrast contour of a blue phase LCD driven by IPS electrodes with a layer of biaxial film compensation.

Blue phase LCD shows a big advantage in term of viewing angle because of its isotropic dark state. Without any phase compensation film, blue phase LCD can achieve a wide view with contrast 10:1 over 70° viewing cone. For a large-panel LCD TV which demands wide view,
compensation films can be used to expand the viewing angle of blue phase LCDs. Fig. 3.13 plots the iso-contrast contour of a blue phase LC in an IPS cell compensated by a half-wave biaxial plate: \( n_x = 1.5110, \; n_y = 1.5095, \) and \( N_z = 0.5 \). The biaxial plate is placed with its optic axis parallel to that of polarizers. The 100:1 contrast ratio can be extended to 70° viewing cone with one layer of biaxial film compensation.

### 3.4.2 BPLCD with corrugated electrodes

To solve the high driving voltage and low transmittance problems of blue phase LCDs in IPS cells, we propose a device structure consisting of periodic corrugated electrodes [68] which generates a strong horizontal electric field component and more importantly this field penetrates deeply into the LC medium. These two factors jointly contribute to reduce the operation voltage to below 10 volts. Meanwhile, the electric field generated by such a structure is uniformly distributed across the entire pixel area and this plays a crucial role for obtaining high transmittance (~ 85%).

Figure 3.14 depicts the device structure of our proposed electrode configuration. The LC cell is sandwiched between two crossed polarizers, thus, it is a normally black display. Both top and bottom substrates are fabricated with periodic corrugated structures. As compared to typical dimensions of patterned IPS electrodes, the electrode period \( W \) in our structure is quite large. As an example, in our simulations we choose electrode width \( W = 40 \, \mu m \) and the inclination angle of the corrugations \( \alpha = 60^\circ \). These dimensions are similar to those of backlight films such as brightness enhancement films or turning films, [69] and can be fabricated fairly easily by mold-pressing method or printing method. In each pixel, the common electrodes are coated over the
entire top substrate without patterning and the pixel electrodes coated on bottom substrate. In practice, all turning edges drawn in Fig. 3.14 can be round and smooth to make fabrication easier. In our simulation, for simplicity we assume the corrugation has triangular shape. Performance will not be affected much because these edges happen to be dead zones with almost no transmittance. A blue phase LC with Kerr constant $K \sim 12.7 \text{ nm/V}^2$ at $\lambda=550 \text{ nm}$ is assumed. The cell gap is $3.5 \mu\text{m}$, but since the cell is tilted in vertical zigzags, the effective distance for normal incident light passing through the LC layer is $d/\cos(\alpha)$, which is $7 \mu\text{m}$ in our example.

![Diagram](image.png)

Figure 3.14 Cross-section view of proposed polymer stabilized blue phase LCD structure with corrugated driving electrodes.

Figure 3.15 depicts the simulated transmittance ($\lambda = 550 \text{ nm}$) of the BPLC cell at a cross-section along horizontal ($x$-axis) direction and some indicated voltages. The transmittance is normalized to that of two parallel polarizers (~35%). Although the induced birefringence below $10 \ V_{\text{rms}}$ is still small and the optic axis is not completely orientated in the desired horizontal direction, its horizontal component is reasonably large. Furthermore, the induced birefringence is
uniformly distributed inside the whole cell (z-axis) except at the turning edge areas, so the phase retardation can be accumulated along the entire travelling distance inside the LC layer. As a result, the on-state voltage is substantially reduced. As shown in Fig. 3.15, some transmission dead zones are found at every turning edge area. This is because the induced birefringence is along the vertical direction so that it makes no contribution to phase retardation. However, our electrodes are quite wide, thus the area ratio of these dead zones is relatively small. We could reduce this area ratio further by using a wider electrode. In comparison to IPS or wall-shaped electrodes [39], our design exhibits a higher transmittance.

Figure 3.15 Simulated transmittance profile across an electrode period area at different driving voltages. Here the electrode period is 40 μm and λ = 550 nm.
Figure 3.16 Normalized VT curves at $\lambda = 550$ nm of the proposed PS-BPLCD under normal incidence (black curve). The other curves are VT curves with varied horizontal shift of electrodes misalignment, from 0.25 $\mu$m shift all the way to 1 $\mu$m shift.

Figure 3.16 shows the normalized VT curves of our device at $\lambda = 550$ nm, as the black curve shows. With the parameters mentioned before, the on-state voltage occurs at $V_{on} \approx 9.9\ V_{rms}$ and the peak transmittance reaches $\approx 85.6\%$. The distance between the top and bottom electrodes, i.e., the LC cell gap is controlled by spacers, so its assembly error with current fabrication technology is small, usually below 0.3 $\mu$m. The horizontal alignment accuracy between top and bottom electrodes of our structure is also determined by spacers, so the assembly error is expected to be as small as cell gap variation. Here we plot in Fig. 3.16 are VT curves with varied shift in horizontal direction between the top and bottom electrodes. It shows that our structure is reasonably tolerant to assembly errors. With 0.25 $\mu$m misalignment, the shift in VT curve is
almost unnoticeable. As misalignment increases to 0.50 µm, \( V_{on} \) drops to 9.7 \( V_{rms} \) and transmittance to 82.4%. From Fig. 3.15, the VT curves overlap with each other very well when \( V < 8 \ V_{rms} \) even with an alignment error as large as 1 µm. Therefore this device is insensitive to horizontal shift if the device is driven below 8 \( V_{rms} \) where the transmittance maintains at \(~75\%\).

Table 3.2 On-state driving voltage (\( V_{on} \)) and corresponding transmittance (T) of the proposed PS-BPLCD with different electrode inclination angles (\( \alpha \)) and LC cell gaps (d).

<table>
<thead>
<tr>
<th>( \alpha ) (°)</th>
<th>d (µm)</th>
<th>( V_{on} ) (( V_{rms} ))</th>
<th>T (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>3.5</td>
<td>14.9</td>
<td>86.3</td>
</tr>
<tr>
<td>75</td>
<td>3.5</td>
<td>6.2</td>
<td>84.7</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>7.5</td>
<td>93.4</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
<td>12.1</td>
<td>80.5</td>
</tr>
</tbody>
</table>

Varying the device dimension will undoubtedly alter the electro-optical performance. Generally speaking, increasing the inclination angle of the corrugated electrodes helps to reduce the operation voltage. With a larger inclination angle, the horizontal component of the induced birefringence is enhanced and the effective path length of incident light inside LC medium is increased, so that the required phase retardation can be achieved with a lower voltage. A thinner cell gap is also helpful to reduce operation voltage. As the cell gap decreases, on one hand the optical path length \( d_{opl} \) is decreased; but on the other hand the induced birefringence \( \Delta n_{ind} \) increases in quadratic manner due to the stronger electric field. So overall speaking, since phase retardation is proportional to \( d_{opl}\Delta n_{ind} \), a lower driving voltage can result in the same phase
retardation in a thinner cell gap. Moreover, the dead zones become narrower in a thinner cell and thus transmittance will be improved. We summarize in Table 3.2 the driving voltage and transmittance in several examples with different inclination angles and cell gaps; here the electrode width is kept at 40 µm in all these examples. We monitor the induced birefringence during these calculations. The induced birefringence at effective areas is far below the saturation value, thus the Kerr effect is valid. From material viewpoint, a blue phase LC with a larger Kerr constant is always helpful for lowering the operation voltage.

Figure 3.17 Iso-contrast contour (a) and on-state transmittance contour (b) of the proposed corrugated blue phase LCD with a biaxial compensation film.

As mentioned before, wide view is another advantage of blue phase LCD. Macroscopically, blue phase is optically isotropic in the voltage-off state. Under such a circumstance, the light leakage at dark state is only from the crossed linear polarizers. Thus, the
contrast ratio is expected to be high and viewing angle should be wide. Our structure has a zigzag shape in vertical direction, so two domains are automatically formed in the voltage-on state and this will further result in a symmetric viewing angle. Figure 3.17 shows the isocontrast contour of our device structure at $\lambda = 550$ nm using one biaxial film to compensate the light leakage at oblique angles. A half-wave biaxial film with the same parameters as in IPS cell in Sec. 3.4.1 can effectively compensate this mode and achieve a wide view. A contrast ratio larger than 100:1 can be obtained over $70^\circ$ viewing cone.

### 3.5 Summary

In this chapter, we have discussed the physical properties of blue phase LCs and the driving concepts of blue phase LCDs. The induced birefringence of blue phase LCs follows Kerr effect and its dispersion still follows the single-band model. For display applications, IPS electrode turns out to be the simplest. Some big advantages of blue phase LCDs are submillisecond response time, wide view, and cell gap insensitivity. But the driving voltage is still a challenge for displays using TFTs, and the transmittance is still relatively low. Our novel corrugated electrodes help to significantly reduce the operating voltage from $\sim 50$ $V_{rms}$ to below $10$ $V_{rms}$ and to improve the transmittance from $\sim 65\%$ to $\sim 85\%$, while preserving the major advantages in fast response and wide view. With an on-state voltage below 10 volts, it will enable the TFT addressing which will accelerate the emergence of blue-phase LCDs.
CHAPTER 4: BROADBAND WIDE VIEW LIQUID CRYSTAL DISPLAYS WITH PHASE COMPENSATION

Beside fast response, wide view and high contrast are also very important requirements for high-end LCDs. Since a group of people may view a large panel LCD TV together from different angles, and users are likely to view a portable device in portrait and landscape formats, wide viewing angle is a critical requirement for most display applications. Therefore, in our design of fast-response LCDs, we always pay attention to their viewing angle property as mentioned in previous chapters. Especially, no matter for nematic LCDs or blue phase LCDs, we have been using phase compensation films to compensate the off-axis light leakage and to guarantee a wide view. Here a separate chapter of viewing angle compensation is included in this dissertation to illustrate the operating principles and approaches for realizing broadband and wide view LCDs with phase compensation.

4.1 Introduction of Viewing Angle Compensation

The viewing angle has been a problem of LCDs when tracing back to its history. LCD is a non-emissive display consisting of multiple layers, and LC layer itself works as a phase modulator. Therefore, when viewed from an off-axis angle, there are two factors contributing to the light leakage at dark state. First factor is the light leakage from crossed polarizers, since the two polarizers are no longer perpendicular to each other when viewed from off-axis. Another
light leakage is the unwanted phase retardation from LC layer at dark state when viewed from an oblique angle. In this case, the readability at oblique viewing angles is significantly degraded. Moreover, because the effective refractive index is different at different viewing angle several problems can occur, such as color shift, gray scale inversion and so on.

In last century, twisted nematic (TN) \[70\] dominated the LCD products. However, its viewing angle is narrow, nonsymmetrical and requires sophisticated films to compensate. Therefore, TN LCDs are mainly used in panel sizes smaller than ~26 inches. For larger panels, some advanced LCD modes, such as multi-domain vertical alignment (MVA) \[9, 10\] and in-plane switching (IPS) \[5-7\], have been developed to replace TN. These modes have wider and more symmetric viewing angles. To be specific, the contrast ratio of MVA at normal viewing direction is quite high because the LC directors are vertically aligned at \(V=0\) so that no phase retardation will be experienced by the incident light and its on-axis light leakage is minimal. However, without phase compensation film, the viewing angle of MVA is still very narrow, because the vertically aligned LCs will show evident phase retardation at an oblique angle. Therefore, phase compensation films are necessary for almost any wide-view LC devices. Since MVA has multi-domains which can compensate each other and average the difference at different viewing angles, so it can achieve wide and symmetrical viewing angle with film compensation. On the other hand, LCD modes with homogenous alignment and transversal fields, such as IPS and FFS modes, the on-axis contrast is slightly inferior to that of MVA, but the off-axis viewing angle can be much better than MVA without film compensation. This is because the LC directors are reoriented in plane and thus the unwanted phase retardation at oblique viewing angle is not as large as vertically aligned LCs. IPS and FFS modes can get a 10:1 contrast over 60° viewing
cone without compensation films. This is good for small panel displays which are mostly viewed by one person at one time. However, to realize viewing angle wide enough for large LCD panels, such as LCD TVs, phase compensation is indispensable. With proper phase compensation, both MVA and IPS modes can achieve contrast 100:1 over 80° viewing cone at the optimized wavelength, which is usually green light.

Contrast ratio is defined as the ratio of transmitted light in the bright and dark states. The most effective way to improve contrast is to reduce the light leakage at dark state. Therefore the basic principle of phase compensation is to use a group of compensation films with specially designed phase retardation to compensate the light leakage at dark state. Here we use one compensation configuration for MVA mode as an example to explain the compensation principle in details. [71]

Figure 4.1 (a) shows a typical compensation configuration for MVA mode. It uses two layers of phase compensation films, one negative C-film and one positive A-film. Optic axis of C-film is perpendicular to its surface while the optic axis of A-film is located in plane. Both are uniaxial films. Later, we will introduce biaxial films, whose refractive indices at three primary axes are all different. Positive films mean that the extraordinary refractive index is larger than the ordinary one while negative films mean the opposite.

Fig. 4.1 (b) shows the working principle of the compensation configuration by a Poincaré sphere. The Poincaré sphere is a graphical view in real three-dimensional space that allows convenient description of the polarization state of a light beam. Any state of polarization can be uniquely represented by a point on the surface of the Poincaré sphere. The coordinate corresponding to certain polarization state is determined by its three normalized Stokes
parameters. Poincaré sphere is a very convenient and useful in analyzing the polarization state change as the light traveling through different layers of LCDs.

![Diagram of LCD structure with Poincaré sphere](image.png)

Figure 4.1 (a) A conventional compensation configuration and (b) its working principle illustrated by Poincaré sphere for MVA mode with a positive A-film and a negative C-film.

The maximum light leakage of a MVA cell occurs when viewed from the bisector direction of the crossed polarizers. If the light leakage at all bisectors can be suppressed, then the viewing angle of the LCD can be significantly enhanced. [53] Therefore, we optimized the
compensation films by suppressing the light leakage at $\theta = 70^\circ$ and $\phi = 45^\circ$, where $\theta$ is polar angle and $\phi$ is azimuthal angle. The polarization state of the light traveling through all optical layers is traced on Poincaré sphere, as shown in Fig. 4.1(b).

The MVA LC cell is sandwiched between two crossed linear polarizers. When viewed from an oblique angle, the absorption axes of the polarizer and analyzer are no longer perpendicular to each other resulting in a deviation between the transmission axis of the polarizer and the absorption axis of the analyzer, represented by point T and point A in Fig. 4.1(b). After the backlight passing through polarizer, it is converted to linearly polarized light, with its polarization state located at point T. After the LC layer, the polarization state is moved from point T to point B. Then negative C-film moves the polarization state back to point C. The LC and negative C-plate together behave like an effective positive C-plate. Finally, positive A-film converts the polarization state from point C to point A, which is the absorption axis of the analyzer. Here the positive A-film should be approximately a quarter-wave plate and the optic axis should be the same as the absorption axis of the bottom polarizer.

Without compensation films, the viewing angle of MVA is very narrow. The contrast 100:1 is limited to $20^\circ$ viewing cone. With A-plate and C-plate compensation, the viewing angle of MVA is significantly enhanced. The contrast 100:1 can be widened to $80^\circ$ viewing cone.

However, the compensation example is only optimized at a single wavelength. The light leakages at other wavelengths are ignored. While in a full color display, three primary colors are used to generate different colors therefore it is important to get wide view over a large range of wavelengths. In this chapter we will introduce several of our achromatic wide view LCDs with phase compensation configuration.
4.2 Negative A-plate and its Application in Phase Compensation

A-plate, whose optic axis is located in the plane parallel to film surface, has been widely used in wide-view LCDs. Although positive and negative A-plates are usually equivalent to each other, in some applications negative A-plate has its unique functions. For instance, a negative A-plate together with a positive A-plate can reduce the phase mismatch at oblique viewing angle and thereby improve the off-axis image quality. Besides, the adoption of negative A-plate makes it easier to achieve wide view and broad bandwidth. Negative A-plates have found emerging applications in transmissive and transflective LCDs.

4.2.1 Fabrication and Molecular Modeling of Negative A-plate

For large LCD panels, the compensation films are commonly made by stretching or compressing polymers at their glassy states. The stretching method offers good uniformity, low cost, and high yield. While the fabrication technique for C-plates and positive A-plates is relatively mature, negative A-plates have not been well explored. So far, several approaches have been proposed, such as photo-induced polymerization [72] and self-assembled lyotropic liquid crystal films using coating or printing method. [73, 74] Both approaches are effective for obtaining a large negative in-plane birefringence but neither is ready for widespread applications.

We fabricated negative A-plates by stretching polystyrene (PSt) around its glass-transition temperature. We also developed a molecular model to explain why the stretched polystyrene exhibits a negative birefringence. [75]

Negative A-plates can be obtained by stretching negative birefringence materials, such as PSt. The molecular structure of PSt is shown as follows:
We have modeled a core structure of PSt using HYPERCHEM molecular modeling software. A semi-empirical method of modified neglect of diatomic overlap was used with Polak–Ribiere geometry optimization algorithm. As a result, a single molecular core with side phenyl units was calculated “in vacuo” to its possibly lowest energy gradient, which suggests most possible configuration of the molecule. Figure 4.2 shows molecular configuration of PSt optimized to total energy gradient of $10^{-5}$ kcal/ (mol Å) calculated as a root mean square value. The energy gradient is the rate of change (first derivative) of total energy with respect to displacement of each atom in the $x$, $y$, and $z$ directions. Here, the mechanical stretching occurs along $x$-axis.

As shown in Fig. 4.2 (a), an imaginary long molecular axis is formed along $x$-axis with all the backbone carbon atoms surrounding it. The side phenyl ring is connected to every other carbon, with a $\sim 75^\circ$ angle phenyl ring plane and the imaginary long axis. The birefringence of PSt mainly originates from the conjugated electrons of side phenyl rings. Since $45^\circ < 75^\circ < 90^\circ$, after projection the refractive index along the long molecular axis ($n_x$) is smaller than the perpendicular components ($n_y$ and $n_z$). Moreover, the model reveals that the distribution of side phenyl rings is very uniform. Figure 4.2 (b) depicts the Newman projection of the PSt molecule. For simplicity, the hydrogen atoms are neglected in the drawing. The angle between each pair of neighboring phenyl rings is $96^\circ$, which means that every 15 side-chain phenyl rings complete a cycle. Within each cycle, the phenyl rings are evenly separated. Therefore, the refractive indices
in y-z plane are the same at all directions, i.e., $n_y = n_z$. This is the definition of a negative A-plate whose refractive indices satisfy following order: $n_x < n_y = n_z$.

![Figure 4.2 Molecular conformation of stretched polystyrene: (a) Front view and (b) side view](image)

Figure 4.2 Molecular conformation of stretched polystyrene: (a) Front view and (b) side view

The above description of molecular modeling unfolds the local property of a PSt molecule. At a glassy state, the molecules are randomly oriented and thereby the material is isotropic. By stretching the PSt in the x-axis, the molecules tend to align with their long molecular axis along $x$ direction. In this way, a negative A-plate with $n_x < n_y = n_z$ is obtained. Based on the above model, the basic criteria for obtaining a negative A-plate are twofold: (1) to have side chains that contribute more to the refractive index at the direction perpendicular to the long molecular axis and (2) to have a better orientation of the long molecular axis along the
stretching direction.

We fabricated negative A-plates by stretching PST films around its glass-transition temperature \( T_g \sim 100 \, ^\circ \text{C} \). Its physical properties are measured and introduced in the following chapter.

4.2.2 Physical Properties of the Negative A-plate

The refractive indices were measured by an ellipsometry to be \( n_x = 1.5805 \) and \( n_y = n_z = 1.5812 \) at \( \lambda \sim 590 \, \text{nm} \). Meanwhile, the transmittance of a setup with negative A-plate orientated at 45° with respect to the optic axes of the crossed polarizers was measured using a spectrophotometer. The wavelength dependent birefringence was obtained through the normalized transmittance.

![Figure 4.3 Experimental setup of the spectrum measurement of the transmittance of the stretched A-film under crossed polarizers.](image)

Figure 4.3 shows the measurement setup. It is set based on a spectrometer. In the middle, two crossed polarizers are added, with one’s optic axis at 0° and the other’s at 90°. The negative A-plate is inserted in between at the bisector direction of the two polarizers, 45° to the transmission axis of polarizers. The light source covers the visible light spectrum. Since the set-
up is based on a spectrometer, so the transmittance over the visible spectrum can be measured, as shown in Fig. 4.4.

Figure 4.4 Measured transmittance spectrum of the stretched negative A-plate under crossed linear polarizers. The transmittance is normalized to the peak value.

In such a setup, the normalized transmittance $T$ follows the equation below:

$$T = \sin^2\left(\frac{\pi d \Delta n}{\lambda}\right)$$  \hspace{1cm} (4.1)

where $d$ is the thickness of the negative A-plate, $\Delta n$ is the birefringence of the negative A-plate, and $\lambda$ is the corresponding wavelength.

With the measured transmittance spectrum, the birefringence of negative A-plate can be calculated at each wavelength.
Figure 4.5 Wavelength dependent birefringence of the stretched A-plate: black curve stands for the experimental data and red curve for the fitting results.

Figure 4.5 depicts the birefringence dispersion of the negative A-plate. Black curve is the measured data and the red denotes the fitting curve based on the birefringence dispersion equation [66, 76]:

\[
\Delta n = \frac{G \lambda^2 \lambda'^2}{\lambda^2 - \lambda'^2}
\]  

where \( G \) is a proportionality constant and \( \lambda^* \) is the mean resonance wavelength. The fitting curve with \( \lambda^* \sim 177.7 \) nm and \( G \sim 1.775 \times 10^{-5} \) nm\(^{-2}\) agrees very well with the experimental results. For the PST negative A-plate, \( \lambda^* \) represents the resonance wavelength of the conjugated electrons of the side phenyl rings. A shorter \( \lambda^* \) leads to a weaker dispersion in the visible spectral region.

**4.2.3 Applications of Negative A-plate in Broadband Wide-View LCDs**

Negative A-plates have many applications in transmissive LCDs [77], wide-view and broadband circular polarizers [55], and simple compensation scheme of transflective LCDs [78].
Here, we propose a simple compensation configuration using our negative A-plate to achieve a broadband wide-view MVA LCD.

![Diagram of compensation configuration](image)

Figure 4.6 The proposed compensation configuration to achieve a broadband and wide view MVA mode with a negative A-plate added to the conventional MVA compensation configuration.

Figure 4.6 shows the proposed compensation scheme. The LCD works under a crossed linear polarizers system. The transmission axes of polarizer and analyzer are at -45° and 45°, respectively. Three compensation films, a negative C-plate, a negative A-plate, and a positive A-plate, are laminated successively on top of the LC cell. The optic axes of the two A-plates are both parallel to the transmission axis of the analyzer. The conventional compensation scheme with a negative C-plate and a positive A-plate is commonly used for MVA LCD, as introduced in Sec. 4.1 shown in Fig. 4.1. It offers wide view for an optimized wavelength but not for the whole visible spectral region. With only one negative A-plate added, our compensation is able to suppress the light leakage over the whole visible spectrum and lead to a wide view under white light. C-plate usually has a weaker dispersion than LC, so we intentionally designed the C-plate
to have a larger phase retardation $d\Delta n$. In this way, LCs phase retardation change under different wavelengths can be compensated by the phase retardation change of the negative C-plate. Overall speaking, the LC and negative C-plate work together as an effective dispersion-free negative C-plate. Likewise, the dispersions of the negative and positive A-plates are canceled by each other. The dispersion of our PSt negative A-plate is relatively weak. Positive A-plates with stronger dispersion characteristic can be easily obtained from polycarbonate or polysulfone films. With optimized film thicknesses, the two A-plates together behave as a dispersion-free negative A-plate. Theoretically, a perfect dark state can be obtained with this compensation configuration.

We calculate the LC director’s distribution by finite element method and optical properties by extended 2×2 Jones matrix methods. [79] The LC used in calculation is MLC-6608 with parameters as follows: $K_{11} = 16.7$ pN, $K_{22} = 7.3$ pN, $K_{33} = 18.1$ pN, birefringence $\Delta n = 0.0836$ at $\lambda = 550$ nm, dielectric anisotropy $\Delta \varepsilon = -4.2$, and rotational viscosity $\gamma_1 = 186$ mPa s. The LC cell gap is 4 μm. The phase retardation $d\Delta n$ at $\lambda = 550$ nm is 370, 491.4, and 355 nm for negative C-plate, negative A-plate, and positive A-plate, respectively. The dispersion of negative A-plate is based on the experimental data of our PSt negative A-plate. The dispersions of other layers are all based on data from commercially available products.
Figure 4.7 Comparison of the maximum light leakage over 85° viewing cone between the conventional (red curve) and the proposed (blue curve) compensation schemes for a MVA LCD.

Figure 4.7 compares the maximum light leakage over 85° viewing cone of the conventional and proposed compensation configurations. Red curve stands for the abovementioned conventional compensation scheme while the blue for the proposed one. The light leakage is suppressed significantly over the entire visible spectra. This would lead to a broadband and wide-view LCD with good color saturation.

4.3 Broadband Wide View LCDs with Biaxial Film Compensation

As mentioned in Sec. 4.1, different from uniaxial plates such as A-plate or C-plate, biaxial film is an optical plate with different refractive indices along three primary axes. Compared with uniaxial plate, biaxial film has one more dimension for optimization. Therefore, applying biaxial film in LCD phase compensation configuration helps to achieve better viewing
angle properties. In this section, we will introduce biaxial film compensation for MVA mode and IPS/FFS mode. Both broadband and wide view can be achieved in these configurations.

4.3.1 Optical Calculation of Biaxial Film

The biaxial films used in LCD compensation are usually fabricated by mechanically stretching or compressing method. The optic axis is perpendicular or parallel to the stretching or compressing direction. Therefore, the $z$-axis of the principal coordinates $(x', y', z')$ of the biaxial medium is still perpendicular to the film surface. Without losing the generality, we choose a coordinate system $(x, y, z)$ that the incident light is located in $x$-$z$ plane. The refractive index ellipsoid and the incident beam can be illustrated in Fig. 4.8. Here, $x'$, $y'$ and $z'$ are three principal coordinates of the biaxial film. The $x$-$y$ plane is parallel to the biaxial film surface. The $z$-axis is coincident with $z'$. In this case, the dielectric tensor of biaxial film can be obtained by doing the Eulerian angle transformation from principal coordinates system to the coordinate system.

![Figure 4.8 Refractive index ellipsoid and propagation direction in principal coordinate system and local coordinate system](image)
\[ \bar{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \]

\[
\bar{\varepsilon} = \begin{bmatrix} \cos \phi & -\sin \phi & 0 \\ \sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} n_x^2 & 0 & 0 \\ 0 & n_y^2 & 0 \\ 0 & 0 & n_z^2 \end{bmatrix} \begin{bmatrix} \cos \phi & \sin \phi & 0 \\ -\sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]

(4.3)

where

\[
\varepsilon_{xx} = n_x^2 \cos^2 \phi + n_y^2 \sin^2 \phi,
\]

\[
\varepsilon_{yy} = n_x^2 \sin^2 \phi + n_y^2 \cos^2 \phi,
\]

\[
\varepsilon_{zz} = n_z^2,
\]

\[
\varepsilon_{xy} = \varepsilon_{yx} = (n_x^2 - n_y^2) \sin \phi \cos \phi,
\]

\[
\varepsilon_{xz} = \varepsilon_{zx} = 0,
\]

\[
\varepsilon_{yz} = \varepsilon_{zy} = 0.
\]

(4.4)

Once the dielectric tensor of biaxial film is obtained, the optical properties can be calculated using the extended \(2 \times 2\) matrix method.

From Maxwell’s equation, a matrix representation of electric field and magnetic field of the propagating light can be derived.

\[
\frac{\partial}{\partial z} \begin{bmatrix} E_x \\ E_y \\ \hat{H}_x \\ \hat{H}_y \end{bmatrix} = i k_0 Q \begin{bmatrix} E_x \\ E_y \\ \hat{H}_x \\ \hat{H}_y \end{bmatrix},
\]

(4.5)

where

\[
\hat{H} = \left( \frac{\mu_0}{\varepsilon_0} \right)^{1/2} H,
\]

(4.6)
and

\[
Q = \begin{bmatrix}
\frac{-\varepsilon_{xx}}{\varepsilon_{zz}} \sin \theta & \frac{-\varepsilon_{yy}}{\varepsilon_{zz}} \sin \theta & 0 & 1 - \frac{1}{\varepsilon_{zz}} \sin^2 \theta \\
0 & 0 & -1 & 0 \\
-\varepsilon_{yx} + \varepsilon_{xy} \frac{\varepsilon_{xx}}{\varepsilon_{zz}} & -\varepsilon_{yx} + \varepsilon_{xy} \frac{\varepsilon_{yy}}{\varepsilon_{zz}} & 0 & \frac{\varepsilon_{zz}}{\varepsilon_{yy}} \sin \theta \\
\varepsilon_{xx} - \varepsilon_{zz} \frac{\varepsilon_{xx}}{\varepsilon_{zz}} & \varepsilon_{xy} - \varepsilon_{xx} \frac{\varepsilon_{yy}}{\varepsilon_{zz}} & 0 & -\frac{\varepsilon_{zz}}{\varepsilon_{yy}} \sin \theta
\end{bmatrix}
\]  (4.7)

Implementing dielectric tensor values of biaxial film as in equation 4.3 into the Q matrix in equation 4.7, we can extend the same method developed for uniaxial films to calculating the optical properties for biaxial films. Our calculations follow the backward-eigenwave method. Detailed derivation and formulation of backward-eigenwave method can be found in Ref. 79.

4.3.2 Broadband Wide View MVA LCD with Biaxial Film

To suppress the light leakage over a broadband spectrum, we use a biaxial plate to substitute the positive A-plate in the conventional configuration as shown in Fig. 4.1. The new compensation configuration with biaxial plate is shown in Fig. 4.9. In this compensation scheme, LC cell still works under crossed linear polarizers. The absorption axes of polarizer and analyzer are 0° and 90°, respectively. A layer of negative C-plate is located right above the MVA LC cell to compensate the phase retardation from LC at oblique viewing angle. Then a biaxial film is adopted mainly to reduce the light leakage from the crossed polarizers. It works approximately like a half wave plate. For the biaxial film employed here, \( n_x > n_y > n_z \), we use \( n_x \) direction to represent its orientation. It can be either parallel or perpendicular to the absorption axis of the...
bottom polarizer. The orientation can be selected according to the dispersion properties of the compensation films in order to obtain wide view over a broad spectral range. In our example, the dispersions of compensation films are much smaller than that of LC. So the biaxial film orientation is chosen to be 90°.

![Diagram of compensation configuration](image)

Figure 4.9 MVA LC cell compensation configuration with one negative C-plate and one biaxial film.

Figure 4.10 illustrates the compensation principle for obtaining a broadband dark state. Fig. 4.10 (a) shows the polarization tracing on Poincaré sphere at \( \lambda = 550 \) nm. After passing through the polarizer, LC layer, and negative C-plate, the backlight polarization is changed from point T to B and then to C. Here, the thickness of C-plate is optimized to make LC layer and negative C-plate work together as a thin positive C-plate. When the \( N_z \) factor of biaxial film changing from 0 to 1, in our configuration, the rotation axis on Poincaré sphere changes from point T to A. The arc length is dependent on its in-plane phase retardation value \( d(n_x-n_y) \), where \( d \) is the thickness and \( (n_x-n_y) \) is the in-plane birefringence of the biaxial film. These parameters in our configuration are designed to ensure the polarization be moved from point C to A, which is
coincident to the absorption axis of the analyzer. In this way, a good dark state at \( \lambda = 550 \) nm can be achieved.

Moreover, the light leakage at other wavelengths can also be suppressed significantly with small dispersion films. Let us take \( \lambda = 450 \) nm as an example as Fig. 4.10 (b) shows, since C-plate has a weaker dispersion than LC layer, these two layers work as a positive C-plate with a larger phase retardation value at \( \lambda = 450 \) nm than at 550 nm. Compared to the Poincaré sphere tracing at \( \lambda = 550 \) nm, the point C now is lower and further away from point T. At the same time, the phase retardation of the consequent biaxial film is also larger. With a slightly smaller \( N_z \) factor, the biaxial film can move the polarization from point C to D which is very close to point A, as shown in Fig. 4.10 (b). Similarly, the polarization can also be moved to a point close to the polarization absorption axis of a longer wavelength, as shown in Fig. 4.10 (d). The light leakage at \( \lambda = 450 \) nm and 650 nm after compensation is shown in Fig. 4.10 (d) and (e), respectively. Compared with the conventional positive A and negative C compensation configuration, our configuration suppresses the light leakage significantly at blue and red light.
Figure 4.10 Polarization state tracing on Poincaré sphere for the compensation scheme shown in Fig. 4.9 at (a) $\lambda=550$ nm, (b) 450 nm, and (d) 650 nm. The angular dependent light leakage is plotted in (c) for 450 nm and (e) for 650 nm.
In our calculation, the LC distribution is calculated by the finite element method [48] and the optical properties are calculated based on extended 2×2 Jones matrix methods [49, 79]. In the configuration as shown in Fig. 4.9, the LC mode considered is 4-domain MVA with cell gap \( d = 4.5\, \mu m\). The LC used in our simulation is MLC6608 with the same parameters mentioned in Sec. 4.2.3. The parameters for negative C-plate are \( n_e = 1.4925 \) and \( n_o = 1.5024 \) at \( \lambda = 550\, nm \). Its thickness is intentionally designed at 34.5 \( \mu m \) so that the total effect of the LC cell and negative C-plate is like a thin positive C-plate. The parameters of the biaxial film at \( \lambda = 550\, nm \) are optimized as follows: the in-plane birefringence \( n_x - n_y = 0.01 \), \( \chi \) factor \( (n_x-n_z)/(n_x-n_y) = 0.49 \) and thickness 28.5 \( \mu m \). With the compensation films designed as above, the viewing cone at 550 nm is expanded significantly. Meanwhile, the light leakage at other wavelengths can also be suppressed by a proper film dispersion design, which will be discussed later.

Figure 4.11 Isocontrast contour of MVA-LCD at \( \lambda = 550\, nm \) with the compensation scheme shown in Fig. 4.9.

Figure 4.11 shows the isocontrast contour plot at \( \lambda = 550\, nm \) after compensation. The CR
≥ 100:1 is over the entire viewing cone and CR ≥ 200:1 is over 75° viewing cone.

To obtain wide viewing angle for a broadband backlight, the light leakage at red and blue should also be suppressed besides green. Thus, the dispersion properties of LC and compensation films need to be taken into consideration. Several polymeric films such as PVA exhibit a very weak dispersion characteristic because of the lacking of molecular conjugation [80]. Compensation films made from such a weak dispersive material would exhibit a much smaller dispersion than that of LC material consisting of a phenyl ring. Luckily we can take advantage of this dispersion difference to get self compensation for different wavelengths, which has been discussed before. Within the small dispersion range, we optimized the birefringence of the negative C-plate and biaxial film at 450 nm, 550 nm, and 650 nm to get the least light leakage at these wavelengths. Fig. 4.12 shows the optimized results.

![Figure 4.12 Optimized birefringence dispersion of the compensation films.](image)

In our calculation, we use the birefringence dispersion model in equation 4.2 to simulate
LC’s dispersion. For compounds with a single phenyl ring, their $\lambda^*$ is around 210 nm.

![Figure 4.13 Comparison of light leakages at bisectors between the conventional compensation scheme (Fig.4.1) and our proposed scheme (Fig. 4.9) at $\lambda$=450 nm, 550 nm, and 650 nm.](image)

With the above designed parameters, the light leakage in the proposed configuration is greatly reduced. Figure 4.13 shows the light leakage at the bisector direction of the two polarizers, where usually the maximum light leakage occurs so that the viewing angle is the worst. The solid lines represent the light leakage of the proposed compensation configuration with one negative C-plate and one biaxial film, while the dash lines are for the conventional configuration with one negative C-plate and positive A-plate. The light leakage values are normalized to the maximum transmittance of two parallel polarizers. At $\lambda$ = 550 nm, both configurations show a very small light leakage at all viewing angle. However, there is still light leakage at $\lambda$ = 450 nm and $\lambda$ = 650 nm in the conventional configuration. By contrast, the light
leakages at red and blue of our configuration are significantly reduced, which will lead to a much higher contrast ratio and wider viewing angle for a white light source employed.

Knowing the refractive index at the three optimized wavelengths, we can use the extended Cauchy equation [81] to obtain the refractive index in the entire visible spectra.

\[ n = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \]  

(4.8)

Figure 4.14 Comparison of maximum light leakage over the whole viewing cone between the conventional MVA compensation scheme shown in Fig. 4.1 (red) and the proposed broadband wide view compensation configuration in Fig. 4.9 (blue).

Once the refractive indices from ~ 400 nm to ~ 700 nm are obtained, we can calculate the light leakage for the entire visible spectra. The global maximum light leakage over the entire viewing cone for each wavelength is plotted in Fig. 4.14, where red and blue curves represent the maximum light leakage for the proposed configuration with biaxial film and conventional configuration with positive A-plate, respectively. For the improved compensation scheme, the
maximum light leakage is reduced by ~6X at $\lambda = 450$ nm and ~4X at $\lambda = 650$ nm. The light leakage over the whole visible spectra is greatly suppressed in the proposed configuration as compared to the conventional one. With better dark state, the contrast ratio and viewing angle of a full-color LCD will be further improved.

4.3.3 **Broadband Wide-View IPS/FFS LCD with Biaxial Compensation Films**

Figure 4.15 shows (a) the compensation configuration and (b) compensation principles represented by Poincaré sphere of our proposed compensation configuration for IPS/FFS mode with biaxial plate. [82] The LC cell works under a set of crossed linear polarizer system. Figure 4.15 (a) shows the absorption axes of the polarizer and analyzer at $45^\circ$ and $-45^\circ$, respectively. The optic axis of LC layer is parallel to the absorption axis of the bottom polarizer so that it will not change the polarization state after the polarizer no matter for normal or oblique viewing angles. The two biaxial films are parallel and perpendicular to the absorption axis of the polarizer so that the normal viewing angle image will not be disturbed by the compensation films. The $N_z$ factor, which is defined as $(n_z-n_y)/(n_x-n_y)$, is 0.5 for both films. The phase retardation difference between the first and the second biaxial films should be approximately a half-wave plate.
Figure 4.15 (a) Compensation configuration with two biaxial films. (b) Poincaré sphere representation of the broadband wide view compensation principle

Under the abovementioned conditions, the compensation principles are illustrated with Poincaré sphere in Fig. 4.15 (b). The maximum light leakage of a crossed linear polarizer system with a LC cell occurs when viewed from the bisector direction. If the light leakage at all bisectors can be suppressed, then the viewing angle of the LCD can be significantly enhanced. At this angle, the transmission axis of polarizer and absorption axis of analyzer are deviated from each other, represented by point T and point A on the Poincaré sphere. Point P&LC represent the optic axis of the polarizer and the LC layer. It is located on the extension line of OT, so the
polarization state stays at point T after LC layer. Let us take \( \lambda = 550 \text{ nm} \) green light as an example, on Poincaré sphere, the polarization state is rotated from point T to point G after the first biaxial film and then moved back to point A by the second biaxial film. As the \( N_z \) factors of both films are 0.5, the rotation axes are the same which is OD. The rotation directions however are opposite to each other due to different orientations of their optic axes. In this way, these two biaxial films can together change the polarization state from point T to point A, which is the absorption axis of analyzer. Therefore the light leakage is minimized at this viewing angle. Here we used two biaxial films in order to get a wide view for other wavelengths as well. For instance, for the blue light \( \lambda = 450 \text{ nm} \), the phase retardation values of both films are larger than that of green light for two reasons: 1) the shorter wavelength, and 2) the normal dispersion properties of the films. The second biaxial film has a larger dispersion than the first one. By adjusting the phase retardations of these two films, we can find a solution ensuring that the combination of these two films also works for blue light to change the polarization state from point T to point A, with a rotation path from point T to point B and then to point A on Poincaré sphere. Repeating the same procedure for red light (\( \lambda = 650 \text{ nm} \)) and balancing the performance for all wavelengths, we are able to suppress the light leakage at oblique angles for the entire visible spectrum.

The LC is homogenously aligned with cell gap \( d = 4 \mu \text{m} \). The LC parameters are listed as follows: \( K_{11} = 9.6 \text{ pN}, K_{22} = 5.3 \text{ pN}, K_{33} = 11.6 \text{ pN}, \) birefringence \( \Delta n = 0.0987 \) at \( \lambda = 550 \text{ nm} \), dielectric anisotropy \( \Delta \varepsilon = 8.2 \), and rotational viscosity \( \gamma_1 = 84 \text{ mPas} \). We still follow equation 4.2 to calculate LC’s dispersion with a resonant wavelength around 210 nm.
Figure 4.16 Dispersion properties of the two biaxial films used in the calculations, the red solid line is the fitting curve based on data of PS (triangle dots) and the blue dashed lines are the fitting curves based on data of PVA (square dots).

For the biaxial films considered here, we assume the mean resonance wavelength $\lambda^*$ is the same for both in-plane ($n_x-n_y$) and out-of-plane birefringence ($n_z-n_y$). Consequently they should follow the same dispersion curve. That also explains why the $N_z$ factor keeps almost the same over the entire visible spectrum.

We fitted the birefringence of PVA and PS based on equation 4.2, as shown in Fig. 4.16. The first biaxial film in our configuration has a very weak dispersion, so we chose PVA as an example, as the blue dashed lines show. While the second biaxial film has a strong dispersion and we chose polysulfone (the solid red line) as an example. The squares and triangles represent the measured data of these two materials. [80, 83] In this example, the optimized in-plane phase retardations for the two biaxial films are 740 nm and 460 nm for the first and second biaxial films at $\lambda = 550$ nm.
Figure 4.17 Maximum light leakage over the entire viewing cone of different IPS/FFS display configurations, (1) without any compensation films (black curve), (2) with one biaxial plate (blue curve), (3) with two biaxial films proposed in Ref. 84 (red curve) and (4) ours with two biaxial films (green curve).

To show the compensation performance, in Fig. 4.17 we plotted the maximum light leakage over the whole viewing cone within the visible spectrum. The results are compared with three prior approaches. Curve 1 represents the dark state light leakage of an IPS or FFS display without any compensation film. There is strong off-axis light leakage at any wavelength. With one biaxial film compensated, as curve 2 shows, the light leakage is significantly reduced at the optimized wavelength but still remains relatively severe at other wavelengths. This will further degrade the contrast and the color uniformity. Curve 3 shows the light leakage of compensation configuration with two biaxial films proposed in Ref. 84. In this configuration, each biaxial film contributes to half of the phase needed. We used the dispersion curve of PVA in Fig. 4.16 to get an optimized result of their configuration. Curve 4 is for our compensation configuration with
two biaxial films. Both configurations with two films can reduce the light leakage significantly over the entire visible spectrum. This will result in high contrast over the whole viewing cone under white light. Moreover, the broadband weak light leakage will help to reduce the color shift of low gray level images.

Figure 4.18 Dark state color shift at the varied viewing angles from 0° to 60° of different display configurations, (a) without any compensation film, (b) with one biaxial plate, (c) with two biaxial films proposed in Ref. 84 and (d) ours with two biaxial films. Red spot represent the color at normal viewing angle.

Dark state colors at oblique viewing angles can vary from that at normal viewing angle,
depending on the ratio of the light leakage at different wavelengths. Fig. 4.18 compares the dark state color shift of four IPS/FFS configurations. The CIE 1976 uniform chromaticity scale diagram is used here to give a direct view of the color difference. The red dots are the \((u', v')\) coordinates at normal viewing angle and those black dots correspond to the \((u', v')\) values at viewing angles with \(\theta\) varied from 0° to 60° and \(\phi\) from 0° to 360°. The deviation between the red dots and black dots represent the color shift between normal and oblique viewing angles, as described in equation 4.9:

\[
\Delta u'v' = \sqrt{(u'_2 - u'_1)^2 + (v'_2 - v'_1)^2}
\]  

(4.9)

where \((u'_1, v'_1)\) is the coordinate at normal viewing angle and \((u'_2, v'_2)\) is that at an oblique viewing angle.

The maximum color shift \(\Delta u'v'\) is 0.051 for the configuration without compensation film, as Fig. 4.18 (a) shows. As in Fig. 4.18 (b), it increases to 0.206 in the configuration with one biaxial plate, due to the strong blue shift resulting from the strong light leakage at shorter wavelengths compared with longer wavelengths. The two biaxial films configuration proposed in Ref. 84 improves the color uniformity to a level similar to crossed polarizers, with a maximum color shift \(\Delta u'v' = 0.052\). For comparison, the dark state color shift of our configuration is reduced significantly to \(\Delta u'v' = 0.033\), as shown in Fig. 4.18 (d). With better material engineering of the two biaxial films, the color shift can be even further reduced in our configuration.

The proposed configuration can achieve achromatic dark state and good color uniformity at different viewing angles. The greatly suppressed light leakage over the entire visible spectrum can further help to reduce the color shift of low gray level images of IPS/FFS LCDs.
4.4 Summary

In this chapter, we demonstrate several broadband and wide view compensation configurations with new compensation films, such as negative A-plates and biaxial plates. The parameters of the compensation films are optimized with the help of Poincaré sphere and the compensation results are calculated by extended Jones matrix method. In most configurations, a 100:1 contrast contour can be achieved over all viewing cone for the optimized wavelength. Moreover, light leakage can be greatly suppressed over the whole visible spectrum. It can further leads to smaller color shift and better gray levels at off axis angles.
CHAPTER 5: SUMMARY

In this dissertation, we investigate fast-response LCDs based on both nematic LCs and blue phase LCs. Generally speaking, the LC response time is dependent on several factors, for instance, cell gap, LC rotational viscosity, LC elastic constant, driving voltage, and operating temperature. We analyze the response time issue mainly from the device point of view. Different approaches have been discussed and new fast-response modes proposed.

Thin cell is the most straightforward and widely used approach at present. In Chapter 2, we study thin cell effects both theoretically and experimentally. The alignment layer effects are found very important in thin LC cell. Especially, the voltage shielding effect of the alignment layer becomes so evident that the operating voltage can be evidently shifted. Moreover, different anchoring energy from alignment layer can significantly impact the response time of thin cell. These factors are validated through experiments and good agreements are achieved.

A fast-response nematic LCD mode named DFFS mode is proposed in Chapter 2. Due to its thin thickness of effective LC layer and the self-formed boundary line with small periods, DFFS mode achieves submillisecond response time. It shows a potential to respond faster with a better LC material design and a finer electrodes fabrication. Both transmissive and reflective LCDs based on DFFS modes are proposed and evaluated with detailed data. They both show high optical efficiency and wide view as well as fast response, which make them very promising candidates in display applications to significantly reduce motion blur.
To lower the burden of fabrication, we further modify DFFS mode with two TFTs into single-side structure with one TFT. At the same time of keeping fast response, sunlight readability is achieved by embedded periodical reflectors or reflective driving electrodes. The modified structures are feasible under current mass production capability and foreseeable to be applied in displays with fast-response and sunlight readability requirements.

When nematic LC is gradually approaching its limit in term of response time, blue phase LCDs are emerging with a response time less than 1 ms, as well as other revolutionary features such as isotropic dark state, no need for alignment layer, and so on. Blue phase LCDs are investigated in Chapter 3. The Kerr effect and its wavelength dispersion are studied theoretically and experimentally. It is found that the dispersion of Kerr effect induced birefringence can be well described by the conventional single-band model. Furthermore, a new driving concept using corrugated electrodes is proposed. It solves two major technical challenges of blue phase LCDs: high operating voltage and low light transmittance. With this structure, the on-state voltage is reduced from ~50 V_{rms} to below 10 V_{rms} and transmittance is improved from ~65% to ~86%. The former enables the TFT addressing which will speed up the emergence of this new display, while the latter helps to guarantee a high light efficiency which in turn saves the power consumption. Further research is undergoing to make this next generation LCD feasible in mass production.

Wide view LCDs using phase compensation are also studied and included in Chapter 4. With the application of negative A-plate and biaxial plate, light leakage can be greatly suppressed over the entire visible spectrum as well as realizing wide view for optimized wavelength. Our proposed phase compensation schemes will be helpful to realize wide view for full-color displays.
In conclusion, in this dissertation we have explored several new approaches for achieving fast response time. It includes conventional nematic LCDs and emerging polymer-stabilized blue phase LCDs. We believe this work will make an important impact to advancing the state-of-the-art in fast-response LCDs.
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