Enhancing the Contrast Ratio of Blue Phase LCDs

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Abstract

Experimental evidence proves that polymer-stabilized blue phase liquid crystal is not perfectly optically isotropic. The optical rotatory power (ORP) of double twist cylinders causes the polarization axis of the transmitted light to rotate a small angle, and leaks through the crossed polarizers. Rotating the analyzer by ~2° to correct this ORP can improve the contrast ratio by 3X.

Author Keywords

blue phase; optical rotatory power; contrast ratio

1. Introduction

A polymer-stabilized blue phase liquid crystal (PS-BPLC) exhibits submillisecond response time and does not require any surface alignment layer, thus it is emerging as next-generation display and photonic technology [1-4]. However, its limited contrast ratio (CR) remains to be overcome before widespread applications can be realized. Most nemetic LCDs can reach CR> 5000:1, but BPLC can barely reach ~1000:1 [4, 5]. There is an urgent need to understand the dark state light leakage mechanism in order to boost the contrast ratio.

Macroscopically, a PS-BPLC is commonly treated as an optically isotropic medium. If this is true, then the dark state light leakage should be very small between crossed polarizers. But according to Meiboom's model [6], BPLC is a three-dimensional structure consisting of double-twist cylinders. Inside each cylinder, LC molecules form double-twist structures. When the incident linearly polarized light traverses these cylinders, a small optical rotatory power (ORP) [7, 8] could be accumulated depending on the cylinder's orientation. As a result, the polarization state of the outgoing light could be rotated by a small angle, which in turn leaks through the crossed polarizer and degrades the CR significantly.

In this paper, we characterize the ORP of a dozen PS-BPLC samples with different pitch lengths, and fit the results with a modified De Vries equation. Simply rotating the analyzer in azimuthal direction by ~2° to correct the ORP can boost the device contrast ratio by 3-5X.

2. ORP measurement setup and process

Our BPLC precursors consist of four ingredients: 1) nematic LC host (HTG135200-100), 2) chiral dopant (R5011), 3) di-functional reactive monomer RM257, and 4) mono-functional reactive monomer C12A. The precursors were cured in the BP-I phase.

Fig. 1 depicts the experimental setup for characterizing the ORP of a BPLC cell at three laser wavelengths: R=633 nm, G=514 nm and B=457 nm. The transmission axis of the linear polarizer was fixed in the horizontal direction while the analyzer was crossed to the polarizer initially.

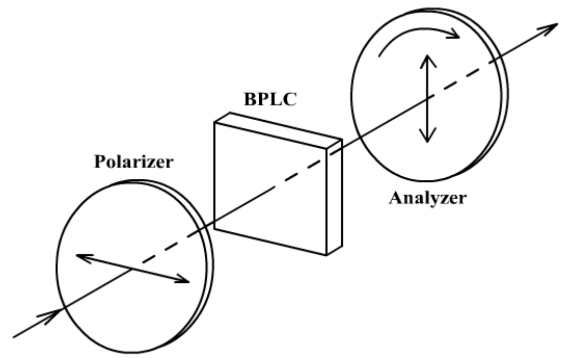

Figure 1. Experimental setup for measuring the ORP of a BPLC cell.

The BPLC sample was sandwiched between polarizer and analyzer, and the light leakage measured. Without a sample, the extinction ratio of the crossed polarizers exceeds 10^5:1. When the sample is placed, some light leakage was detected.

To rule out the refraction effect on the edge of ITO electrode and focus on the intrinsic BPLC material property, we compare the IPS and vertical-field switching (VFS) cells. The later was made of two planar ITO glass substrates [9]. The measured light leakage results of IPS and VFS samples with the same BPLC material at the RGB laser wavelengths are shown in Table I. When the analyzer was crossed, transmittance $T_\perp$ is still quite noticeable. But if we rotate the analyzer in azimuthal direction by a small angle $\propto$, a 5-10X smaller $T_\perp$' can be achieved for each wavelength, implying that the outgoing light still keeps a fairly good linear polarization, but its polarization axis is rotated by a small angle $\propto$. The $\propto$/d ratio is similar for IPS and VFS cells, proving that polarization rotation is primarily due to the BPLC material, not the refraction from ITO edges.

Table 1. Polarization rotation effect: IPS and VFS cells

λ (nm)	$T_\perp$ (%)	α (deg.)	α/d (deg./μm)	$T_\perp'$ (%)
IPS cell, cell gap d=7.4μm				
633	0.02	0.5	0.07	0.004
514	0.10	2.0	0.27	0.020
457	0.60	4.0	0.54	0.090
VFS cell, cell gap d=10μm				
633	0.02	0.5	0.05	0.004
514	0.20	2.5	0.25	0.020
457	1.0	5.5	0.55	0.080

Considering that the outgoing light still keeps a linear polarization, the polarization rotation angle caused by the BPLC cell is the same as the analyzer rotation angle ($\propto$). So, optical rotatory power (ORP) $\varphi \equiv \propto/d$ is defined as the polarization rotation angle divided by the cell gap. And as shown by Table I, this ORP is only related to material, but not the electrode design (IPS or VFS).

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In order to double confirm that this ORP is a parameter solely determined by the BPLC material and independent from cell gap, one kind of BPLC material is injected into several IPS and VFS cells of different cell gaps. The polarization rotation angles of these samples at three wavelengths aforementioned are sketched in Fig. 2 below, against their cell gaps.

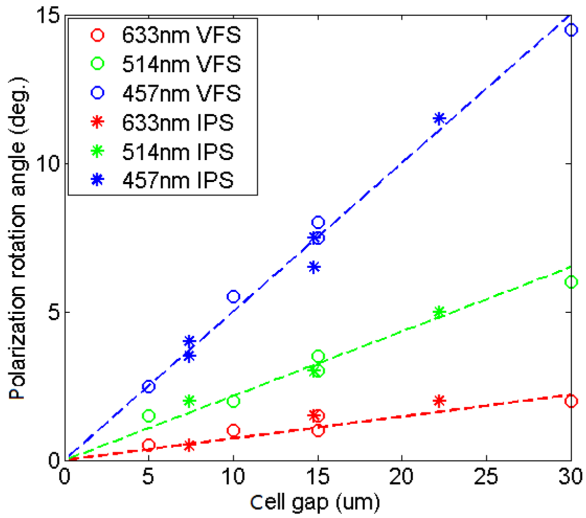

Figure 2. Polarization rotation angles vs. cell gaps.

In Fig. 2, red, green and blue points represent polarization rotation angle at 633nm, 514nm and 457nm wavelengths, respectively. Open circles come from VFS cells, while asterisks are from IPS cells. Dashed lines are straight lines from the origin point. All measured points are distributed along dashed lines, proving that polarization rotation angle is proportional to cell gap, and ORP is a material parameter, independent from cell gap.

3. ORP and contrast ratio

Temperature effect: In experiment, we first investigate how the temperature affects ORP. We prepared a BPLC sample, designated as HTG-23, using the above mentioned recipes. Its Bragg reflection wavelength is λ_B~410 nm and clearing point after UV curing is 78°C. We measured the ORP of HTG-23 at λ=514 nm and 457 nm between 30°C and 90°C, and results are plotted in Fig. 3(a) and Fig. 3(b), respectively. In Fig. 3, circles represent the measured ORP values of the sample. The BPLC sample was placed on a rotary mount whose scale is 2° per division, so the precision of our data is ±0.5° in azimuthal angle. Therefore, the data shown in Fig. 2 appear stepwise. A positive ORP implies that the polarization rotation is in the right-hand direction, as Fig. 1 depicts.

To understand the temperature dependent ORP data shown in Fig. 3, we measured the temperature dependent induced birefringence of the BPLC composite. In theory, the temperature dependent birefringence of PS-BPLC can be estimated from:

$$\Delta n_s = \Delta n_0 C(1 - T/T_c')^{\beta} \quad (1)$$

here Δn_s is the saturated birefringence of Kerr-effect-induced isotropic-to-anisotropic transition in the BPLC composite [10]. Δn_0 is the extrapolated birefringence of the LC host at T=0, C is the concentration (wt%) of the LC host in the BPLC composite, β is a material parameter, and T_c' is the clearing point of BPLC after UV curing. Using the measured data (not shown here), we obtained β =0.227, and Δn_0=0.296, 0.321, and 0.347 for λ=633 nm, 514 nm, and 457 nm, respectively. The dashed lines in Fig. 2 represent the temperature dependent $(\Delta n_s)^2$. Semi-empirically, we found that ORP correlates with $(\Delta n_s)^2$ reasonably well.

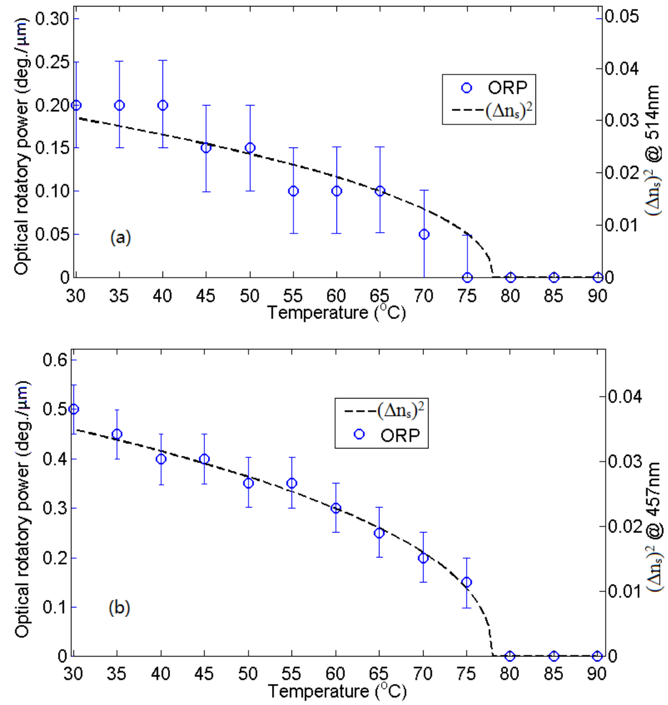

Figure 3. Temperature dependent ORP (left) and $(\Delta n_s)^2$ (right) of HTG-23.

Pitch length effect: In total we prepared 15 PS-BPLC samples with different Bragg reflection wavelength λ_B's, and measured their ORP at the specified RGB laser wavelengths. Results are plotted in Fig. 4. Here, red open circles, green solid circles, and blue triangles represent the measured ORP of BPLC samples at λ=633 nm, 514 nm, and 457 nm, respectively, while red solid line, green dashed lines and blue dotted lines are the corresponding fitting curves according to the modified De Vries equation:

$$\varphi = \varphi_o \frac{(\Delta n_s)^2}{\lambda^2/\lambda_B^2 - 1}. \quad (2)$$

In Eq. (2), φ_0 is a fitting parameter and Δn_s is the saturated birefringence of BPLC [10]. We use Eq. (2) to fit the measured ORP data for the RGB laser wavelengths, as Fig. 2 shows. With only one fitting parameter (φ_0=3.12deg./μm), good agreement between experiment and Eq. (2) is obtained for all three wavelengths.

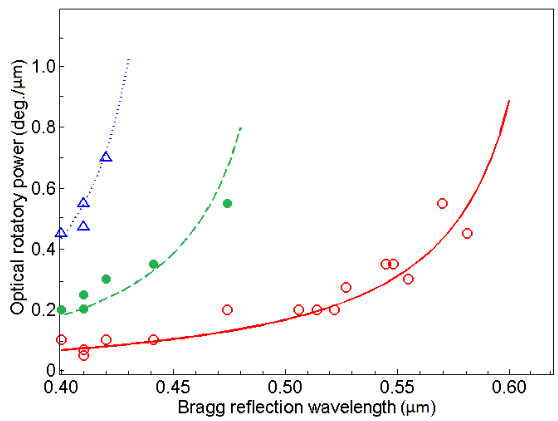

Figure 4. Bragg reflection wavelength vs. ORP.

Contrast ratio issue: Fig. 2 shows that the ORP of BPLC samples is in the 0.1°/μm to 0.7°/μm range. Since a typical BPLC cell gap is 5-10μm, the outgoing polarization rotates by 0.5° to 7° from the perfectly crossed position. To evaluate the impact of such rotation angle on contrast ratio, we measure the dark state light leakage of a BPLC sample with Bragg reflection wavelength λ_B~410 nm. Results are shown in Fig. 5. Here, 0° analyzer rotation angle means the analyzer is crossed with polarizer, and positive rotation angle represents rotation in right-hand direction [Fig. 1]. Red open circles are the measured light leakage at λ=633 nm, green filled circles at λ=514 nm, and blue triangles at λ=457 nm. Dashed lines are the overall leakage of white light, which includes 30% red, 60% green and 10% blue lights.

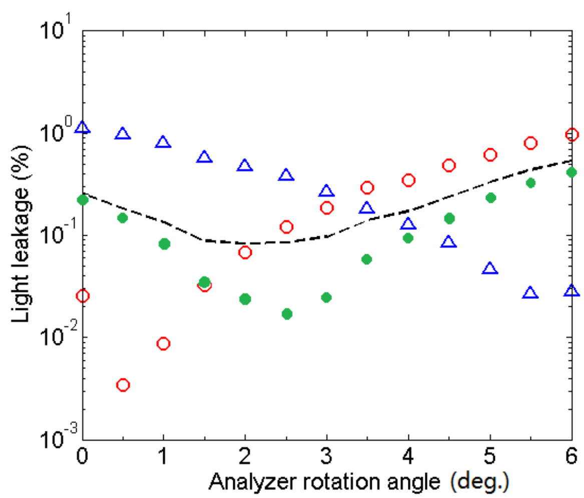

Figure 5. Light leakage vs. analyzer rotation angle for RGB wavelengths.

From Fig. 5, we observe that when the analyzer is crossed, white light leakage is ~0.25%, corresponding to CR~320:1, assuming the bright state transmittance is 80% (a typical value for IPS cell). If we rotate the analyzer by ~2°, the white light leakage drops to ~0.08%, and the CR is boosted to 1000:1. The white light leakage is still much higher than the leakage at each specific wavelength, because ORP varies with wavelength, and three wavelengths could not reach their own best dark state at the same time by simply rotating the analyzer to a certain direction. In order to further reduce light leakage, according to Eq. (2), λ_B may be decreased to 350nm (which is also a common practice to get clear BPLC), and this could potentially improve CR to 3000:1, which is comparable to the contrast of commercial LC display panels.

4. Mechanism of ORP

We try to explain the observed optical rotatory power by the thin TN (twisted nematic) model. It is known that in BP-I phase the LC molecules are arranged in double-twist cylinders, and these cylinders are stacked to form BCC structure, as sketched in Fig. 6.

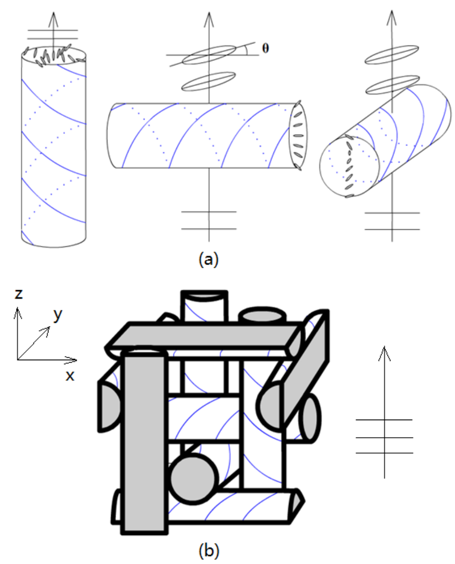

Figure 6. LC director configuration in BP-I phase: (a) Double-twist cylinders, and (b) BCC structure.

Let us assume the incident light is in the positive z direction, as the arrow shows in Fig. 6(b), the optical activity of each cylinder is illustrated in Fig. 6(a). Due to the random alignment of BCC domains, incident light could propagate along any direction into the cylinders. But for the simplicity of our discussion, we focus on the three basic configurations, when the incident wave vector is either parallel or perpendicular to the cylinder's axis. On the left side of Fig. 6(a), the incident light is propagating along the cylinder's axis. Because the LC molecules in the cylinder are aligned equally in all directions, the cylinder appears optically isotropic, which does not affect the polarization state of the incident light. However, for the other two cylinders in the middle and right, the light propagation directions are perpendicular to the cylinder's axis. Therefore, as the light travels from one side of the cylinder to the other it will interact with the 90° twisted LC directors. This twisted alignment will affect the outgoing polarization of the input linearly polarized light. Generally speaking, the outgoing light will be elliptically polarized, with the long axis of its ellipse rotated by a certain angle θ away from incident polarization direction, as shown in Fig. 6(a). This phenomenon is similar to the case when a linearly polarized light passes through a very thin TN cell. Thus, we simulate the optical activity of a thin TN cell by Jones matrix and see if we can find analogy between TN and BPLC cells.

Another thing to be remembered is that in our VFS cell there are multiple micro-domains of BPLC. Each domain is aligned in different direction. Besides, the BCC structure of BPLC has multiple layers of double- twist cylinders stacked together inside each domain. Therefore, in order to imitate the optical activity of BPLC precisely, we use a multi-domain, multi-layer LC cell as the thin TN model for BPLC, i.e., we divide a 5-μm-thick LC cell into multiple domains. Each domain is aligned in a random azimuthal angle, and further divided into multiple layers. Each layer is a 100-nm-thick TN cell with 90° twist angle in right hand direction. The LC birefringence is 0.2 and the wavelength is 550 nm. We first simulate the polarization of the light passing through each TN domain and then take the average of all domains. Results are depicted in Fig. 7. The outgoing light is elliptically polarized, but the eccentricity of this ellipse is close to unity, so it looks like a linear polarization with polarization direction rotated by -4.5°. So the ORP in the thin TN model is defined as the rotation angle of the ellipse's long axis divided by the cell gap. Based on our simulation result, this ORP is described by:

$$\varphi = \varphi_o \frac{(\Delta n)^2}{\lambda^2 / \lambda_B^2} \quad (3)$$

here φ_0 is a constant, Δn is the birefringence of the LC material, and λ_B is the Bragg reflection wavelength of such a multi-layer TN cell, which is determined by the refractive index and the thickness of each TN layer. Note that Eq. (3) is quite similar to Eq. (1) except for the denominator. Actually, Eq. (2) is reduced to Eq. (3) when $\lambda_B \ll \lambda$. The physical meaning of this approximation is that when the Bragg reflection wavelength is much shorter than the incident wavelength, Bragg reflection is negligible in the BPLC. Under this approximation, the optical activity of BPLC could be explained by the thin TN model, and Eq. (3) has similar form as Eq. (2).

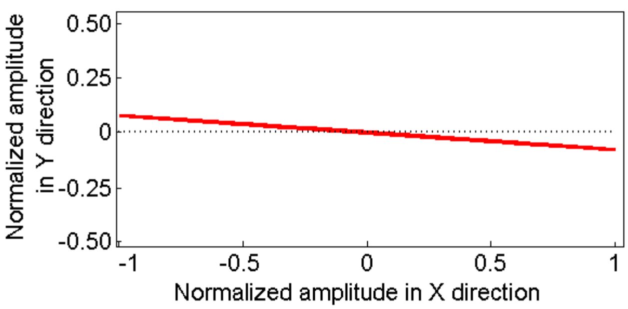

Figure 7. Polarization state change through a multi-domain multi-layer TN cell.

5. Conclusion

We have investigated the light leakage mechanisms of a dozen PS-BPLC samples and found a simple way to correct the problem. By correcting the ORP through rotating the analyzer's angle the device contrast ratio can be improved by at least 3X, to the level of ~1000:1.

6. Acknowledgement

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7. References

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