Viewing angle controllable displays with a blue-phase liquid crystal cell

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Abstract: We demonstrate a controllable viewing angle liquid crystal display (LCD) using an inserted blue-phase liquid crystal (BPLC) cell. The BPLC layer functions as a tunable positive C-film or a negative C-film, depending on whether the employed LC has a positive or negative dielectric anisotropy. Therefore, the viewing angle of the LCD panel can be controlled continuously by the applied voltage of the BPLC cell.

OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices

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1.Introduction

Liquid crystal displays (LCDs) are now widely used in cell phones, computer screens, TVs and so on. Wide viewing angle is a critical requirement for high-end LCDs. To realize wide-view, various LC modes such as in-plane switching (IPS) [1], fringe-field switching (FFS) [2], multi-domain vertical alignment (MVA) [3] and patterned vertical alignment (PVA) [4]

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have been developed. With proper phase compensation, the light leakage at oblique angles is dramatically suppressed, resulting in a wide viewing angle. In the meantime, the protection of privacy is becoming more important nowadays and thus an on-demand controllable viewing angle is highly desirable. Several approaches have already been proposed to control the viewing angle by using dual backlight system [5], or pixel division method [6].

In this paper, we propose a method using a blue phase liquid crystal (BPLC) layer to control the viewing angle. It is applicable to all the LCD modes without affecting the on-state transmittance. The viewing angle can be tuned continuously with a fast response time.

2. Device structure and operation mechanism

Blue phase is a type of liquid crystal that appears in a very narrow temperature range (~2 °C) between chiral nematic and isotropic phase [7] [8]. With polymer stabilization, the temperature range can be expanded to ~60°C including room temperature [9]. BPLCs are comprised of double-twist cylinders arranged in a cubic lattice with periods of several hundred nanometers. The coexistence with disclination lines stabilizes such three-dimensional periodic structures.

When there is no electric field applied, the symmetric cubic structure in a BPLC appears to be optically isotropic as shown in Fig. 1(a). When a strong field is applied, the anisotropy is induced along the electric field direction. Macroscopically it can be treated as Kerr effect, which is a type of quadratic electro-optic effect caused by an electric-field-induced ordering of polar molecules in an optically isotropic medium. The induced birefringence (δn) by the Kerr effect is directly proportional to the square of the electric field E as [10,11]:

$$\delta n = \lambda K E^2. \tag{1}$$

Here, λ is the wavelength and K is the Kerr constant. In Eq. (1), the induced birefringence follows the linear relationship to E^2 in the low field regime but will gradually saturate to the intrinsic birefringence $(\delta n)_o$ of the host LC composite as E increases. Consequently, the isotropic sphere will appear as an elongated (Fig. 1(b)) or a flattened (Fig. 1(c)) ellipsoid, depending on whether the host LC has a positive or negative dielectric anisotropy (Δε) [12].

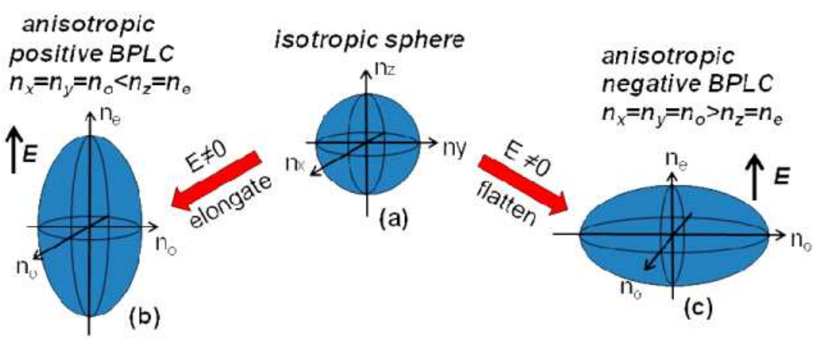

Fig. 1. Electro-optical effect on BPLC refractive index ellipsoid: (a) BPLC without an electric field, (b) positive Δε BPLC with an electric field, and (c) negative Δε BPLC with an electric field.

Therefore, we can use the BPLC cell to control the viewing angle of a LCD. The viewing angle can be tuned continuously by adjusting the applied voltage. Depicted in Fig. 2 is the proposed device structure for the viewing angle controllable display with a BPLC layer. In Fig. 2(a), the LCD panel is originally well-compensated and can be of any modes, such as IPS, and MVA, etc. The BPLC layer can be sandwiched above or below the initially wide-view LCD. When there is no external electric field, the BPLC cell is optically isotropic and will not affect the viewing angle of the display. With a voltage, the BPLC cell will act as an additional positive or negative C-film to disturb the well-compensated wide-view LCD. The actual viewing angle will depend on the applied voltage.

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Compared to other dual cell approaches, such as homogenous cell [13], the blue phase cell exhibits two major advantages: 1) simple fabrication: The blue-phase LC cell does not require any surface alignment layer and, moreover, the electric fields are in longitudinal direction. This can be achieved easily by planar ITO electrodes on both substrates. Such an electrode configuration is much simpler than that used in a blue-phase LCD, in which lateral fields are needed and the IPS electrodes are more complicated to fabricate [14]. 2) Blue-phase LC exhibits submillisecond gray-to-gray response time [15], which is at least 10X faster than the corresponding homogeneous cell.

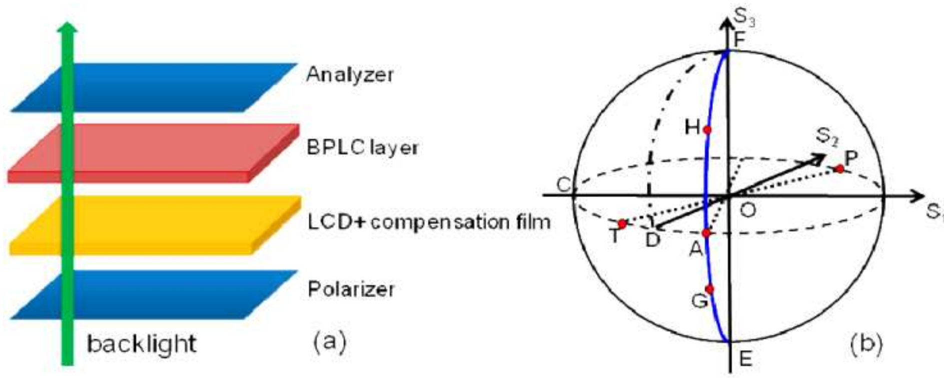

Fig. 2. (a) Device configuration for a viewing angle controllable LCD; (b) Poincaré sphere representation.

Poincaré sphere representation is an elegant geometrical means for solving problems involving the propagation of polarized light through birefringent and optically active media [16]. The mechanism of the proposed device can be explained by the Poincaré sphere depicted in Fig. 2(b). The unpolarized light from backlight unit passing through the bottom polarizer (point **P**) will become linearly polarized with its polarization state locating at point **T**. At oblique view, the absorption axes of polarizer (point **P**) and analyzer (point **A**) do not locate on the S_2 axis. For an uncompensated LCD panel, point **T** deviates from point **A,** but a well-compensated LC layer will then move the polarization state **T** to the absorption axis of the analyzer (point **A**), so a good dark state is achieved. When the light hits the BPLC layer whose $\Delta\varepsilon$ is positive, it will act like a positive C-film and rotate point **A** clockwise around the CO axis to point **G**. On the other hand, if the BPLC has a negative $\Delta\varepsilon$ it will act like a negative C-film and rotate point **A** counterclockwise around the CO axis to point **H**. As a result, point **G** or **H** deviates again from the absorption axis of the analyzer (point **A**). The well-compensated wide-view LCD can be switched gradually to be narrow-view according to the voltage applied. Because the BPLC layer is an isotropic medium at V=0, so the light remains in point **A** and the good dark state will not be affected. This method works equally well for all the display modes. In addition, BPLCs have a sub-millisecond response time that enables a rapid transition between wide view and narrow view. What is more, the fabrication of the BPLC cell is also simple because no alignment layer is needed [17].

3. Results and discussion

To prove concept, we conducted device simulations using a nematic IPS cell as an example. The cell parameters are listed as follows: cell gap d_{IPS}=4 µm, electrode width w=5 µm, electrode spacing l =10 µm, LC Δn=0.096 and wavelength λ=550 nm. The BPLC cell is comprised of plane ITO electrode on both substrates with a cell gap d_{BP}=5 µm. The electric field is in the longitudinal direction. The BPLC material we used has a Kerr constant K=12.68 nm/V^2 at λ=550 nm.

Figure 3(a) shows the isocontrast plot for an IPS cell without any compensation film. The viewing angle is relatively poor; the 10:1 contrast ratio (CR) only extends to ~65° polar angle. This is due to the large dark-state light leakage along the bisectors. Figure 3(b) is the

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isocontrast plot of a well-compensated IPS-LCD by a biaxial film with $d(n_x-n_y)=\lambda/2$, and Nz=0.5. The BPLC layer is optically isotropic at V=0. The CR of the well-compensated IPS-LCD is high. The display is in the wide-view mode. When the voltage is gradually increased from $0V_{rms}$ (Fig. 3(b)), $5V_{rms}$ (Fig. 3(c)), $8V_{rms}$ (Fig. 3(d)), $10V_{rms}$ (Fig. 3(e)), to $20V_{rms}$ (Fig. 3(f)), the viewing angle gets narrower. Comparing Fig. 3(b) with Fig. 3(f), we find that the viewing angle can go far below the original display without compensation film. However, as shown in Fig. 3(f), although the privacy protection is still imperfect along the horizontal and vertical directions, the region is getting smaller as the voltage increases.

Depicted in Fig. 4 are the isocontrast ratio plots for a viewing angle controllable display with a negative BPLC layer. This BPLC layer functions like a negative C-film. When the voltage is gradually increased from $5V_{rms}$ (Fig. 4(a)) to $8V_{rms}$ (Fig. 4(b)), $10V_{rms}$ (Fig. 4(c)) and $20V_{rms}$ (Fig. 4(d)), the polar angles for CR=100:1 decrease from 60° to 40°, 30° and then 15°. And for CR=10:1, in Figs. 4(b), 4(c) and 4(d), the polar angles are 60°, 50° and 25°. This again demonstrates the outstanding performance of the proposed viewing angle controllable displays. Besides, the symmetry of the contrast ratio contour is also remarkable.

According to Eq. (1), if we replace the electric field E with V_{BP} / d_{BP}, here V_{BP} is the applied voltage and d_{BP} is the thickness of the BPLC layer, we will have the following expression for the C-film like BPLC layer:

$$d_{BP}\delta n = d_{BP}\lambda KE^2 = d_{BP}\lambda K(\frac{V_{BP}}{d_{BP}})^2 = \lambda K\frac{{V_{BP}}^2}{d_{BP}}. \qquad (2)$$

On one hand, if we keep on increasing the voltage V_{BP}, the induced birefringence will be larger and the resulted viewing angle will become narrower. Although there is saturation on the induced the birefringence, new blue phase material can always be developed to match the design requirement. On the other hand, by adjusting the thickness of the BP layer d_{BP}, the operation voltage needed to change the viewing angles can be modified. That is, a thinner BPLC cell will experience a stronger vertical electric field and thus a lower voltage is needed. To further lower the operation voltage V_{BP}, we can use a blue phase material with a larger Kerr constant K.

From Eq. (2), the induced birefringence can be tuned continuously by the voltage. Therefore, to obtain a specific view angel for the display, we just need to find out the induced birefringence needed, and then simply apply the corresponding voltage. The induced birefringence here is uniformly distributed all over the BPLC cell, which adds to the accurateness of the control. Moreover, the overall transmittance of the original panel will not be affected by the uniform BPLC layer. A tradeoff is the increased panel thickness and weight.

Aside from the IPS example we discussed above, the proposed configuration in Fig. 2(a) works equally well for other display modes, such as FFS, MVA and PVA, in which different compensation schemes with uniaxial or biaxial films have been proposed [18]. Therefore, as long as the LCD is initially well-compensated, the viewing angle can always be controlled by the applied voltage of the inserted BPLC layer.

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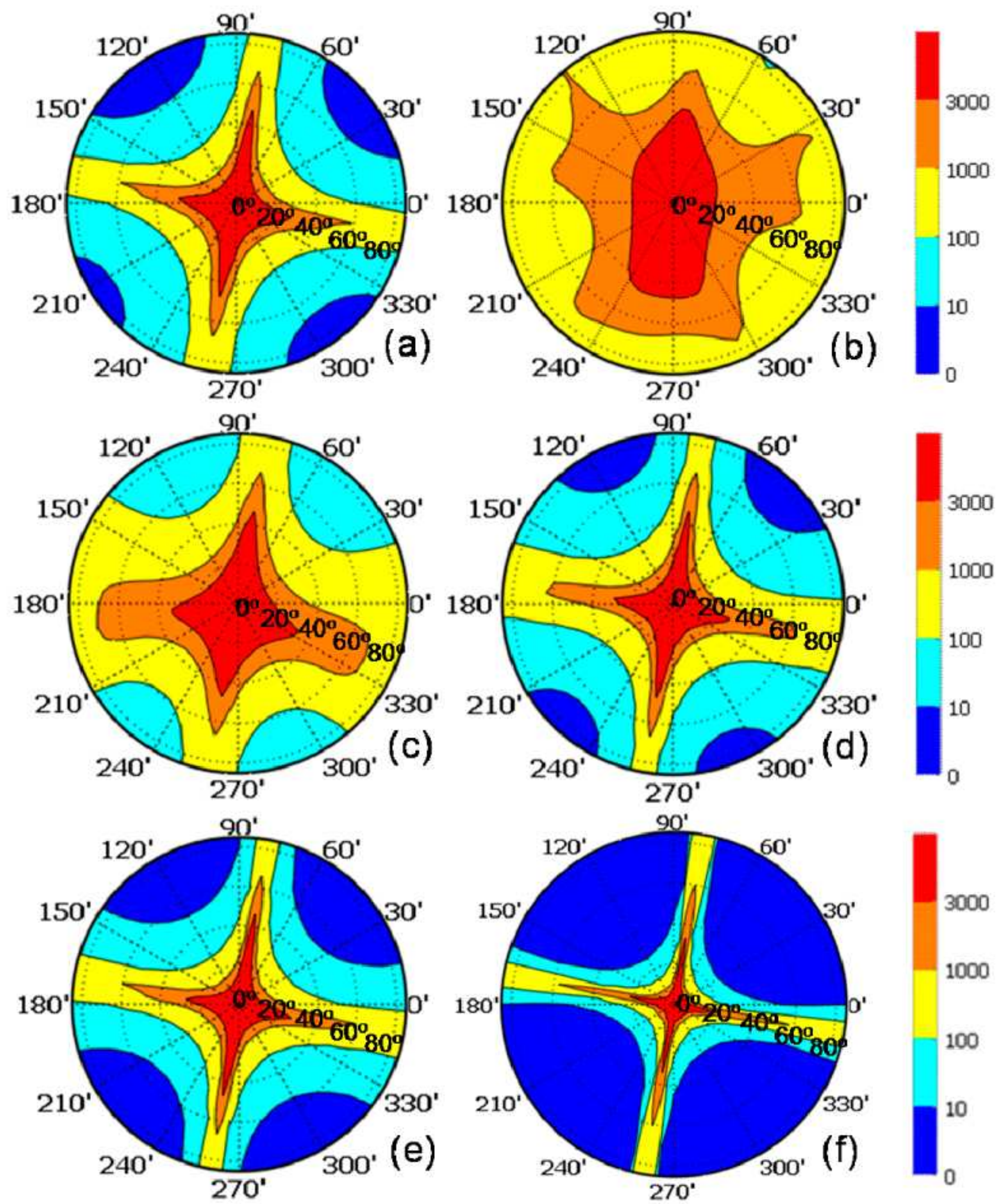

Fig. 3. Isocontrast plots of (a) an IPS-LCD without compensation film, and viewing angle controllable IPS with a biaxial film and a positive BPLC layer at (b) V=0, (c) $V=5V_{rms}$, (d) $V=8V_{rms}$, (e) $V=10V_{rms}$, and (f) $V=20V_{rms}$. λ=550nm.

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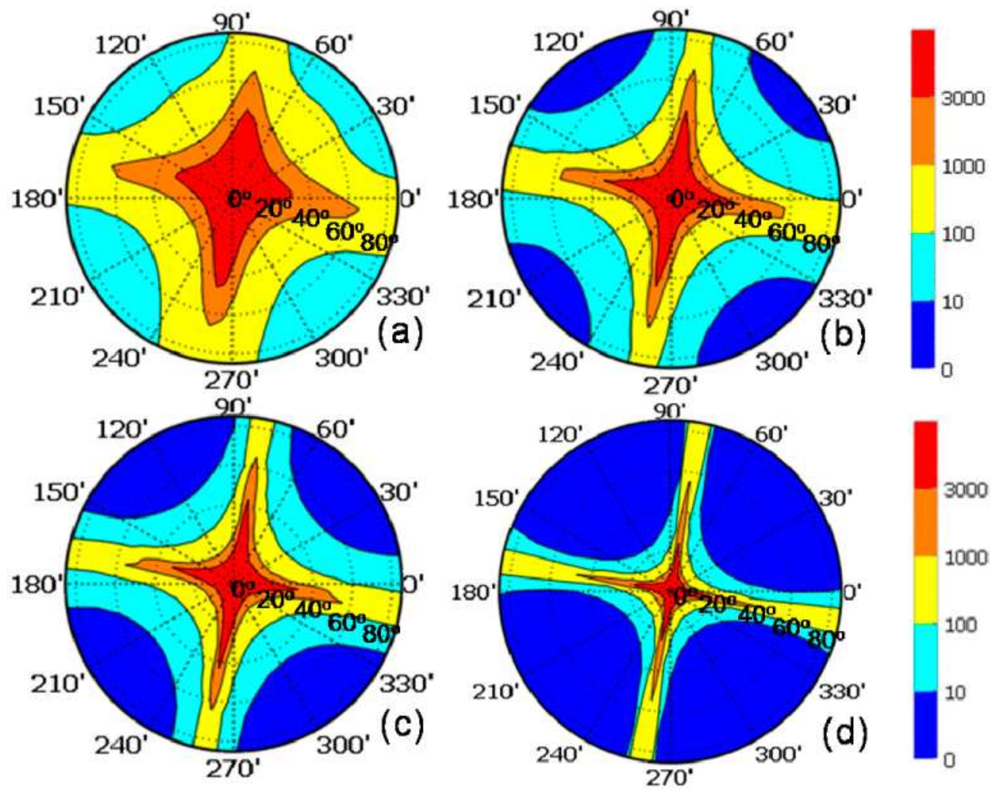

Fig. 4. Isocontrast plots of viewing angle controllable IPS cell with a negative BPLC layer at (a) V=5V_{rms}, (b) V=8V_{rms}, (c) V=10V_{rms}, and (d) V=20V_{rms}. λ=550 nm.

5. Conclusion

We have demonstrated a method to control the display viewing angles using an inserted blue phase liquid crystal cell. This method works well for all the LCD panels originally compensated by uniaxial or biaxial films. The viewing angle can be tuned continuously by electronically controlling the induced birefringence of the blue phase LC layer. Moreover, the BPLC layer has a simple fabrication process without alignment layer and submillisecond response time. The transmittance of the original LCD panel will not be affected by the BPLC cell. It is believed that this approach will have a strong potential for future display applications.

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