Display Technology Letters

Compensation Film Designs for High Contrast Wide-View Blue Phase Liquid Crystal Displays

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***Abstract*—The polarization rotation effect of blue phase liquid crystal (BPLC) composite causes light leakage in the dark state, which in turn degrades the contrast ratio. We propose three approaches to compensate the light leakage and thereby improve the contrast ratio and widen the viewing angle of a BPLC display. The merit and drawback of each design are also discussed.**

***Index Terms*—Blue phase, compensation film, contrast ratio, liquid crystal.**

I. Introduction

AFTER NEARLY one decade of extensive efforts, the major technical issues of polymer-stabilized blue phase liquid crystals (BPLCs) [1], [2] have been gradually overcome and working prototypes demonstrated [3], [4]. The operation voltage can be lowered to below 10 V by developing BPLC materials with a large Kerr constant [5], [6], and implementing new device structures to create deep and strong electric field [7]–[9]. Hysteresis and residual birefringence [10] can be suppressed by reducing the peak electric field [11], [12]. Finally, high transmittance (>80%) can be obtained by optimizing electrode designs [13].

In a transmissive BPLCD, Bragg reflection is usually shifted to UV region to avoid light scattering. Because of the self-organization process, surface alignment layer is not required. However, for some special applications such as reflective displays, in order to obtain vivid colors surface alignment layer is used for generating single-domain structures [14], [15].

Macroscopically, blue phase can be treated as an optically isotropic medium. As a result, BPLC is supposed to have a good dark state and high contrast ratio (CR) under crossed polarizers. However, most experimental results show that CR $\sim$ 1000 : 1 [3], [4], which is much lower than the commercial LCD panels. Several reasons may cause light leakage in dark state, and degrade CR in turn. One is refraction on the edge of protrusive electrodes [16]. Another reason is due to the polarization rotation effect of BPLC material [17], [18]. In the voltage-off state, the polarization direction of traversing light is rotated by the BPLC material, so the outgoing light would leak through the crossed analyzer. Experimental results indicate that the light leakage of a typical multi-domain BPLC cell is reduced by 5 $\sim$ 10$\times$ if the analyzer is rotated by a small angle to compensate the polarization rotation effect induced by the BPLC layer [18]. This evidence implies that polarization rotation effect, rather than scattering or other mechanisms, plays a major role affecting the dark state light leakage of a BPLC device. And it is possible to significantly reduce this light leakage by using some optical compensation films designed by the Poincaré Sphere method.

In this letter, we propose three compensation film designs to compensate the polarization rotation effect of BPLC in order to achieve high contrast in the normal viewing direction. Besides, the requirement for wide viewing angle is also taken into consideration in our designs.

II. Simulation

In the first step, we simulate the contrast of an In-Plane-Switching (IPS) BPLC cell sandwiched between two crossed polarizers and set it as our benchmark for comparison. Extended Kerr Model [19] is used to simulate the bright state transmittance of the BPLC cell. The saturation field of BPLC material we employed is 11.1 V/μm.

Table I lists the saturated birefringence (Δn_s) and optical rotatory power (ORP) of BPLC, and refractive indices of the polarizers at three primary wavelengths. For the BPLC materials analyzed in [18], these ORP values correspond to Bragg reflection wavelength $\lambda_B = 380$ nm. The thickness of each polarizer is 240 μm, and the white light extinction ratio of the polarizers is >20 000:1. The BPLC cell gap is 7.5 μm, the IPS electrode width/gap is 5 μm/5 μm, and the electrodes are aligned at 45° to the absorption axis of the polarizer. The peak transmittance of this BPLC cell in normal direction is $\sim$55%, according to Techwiz simulation. Then the light leakage in dark state and CR are calculated by MATLAB.

Fig. 1 shows the simulated isocontrast contours with a white light: 60% green light (λ = 550 nm), 30% red light (λ = 650 nm), and 10% blue light ($\lambda = 450$ nm). The CR at normal direction is $\sim$1500:1, which is close to the experimental results

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TABLE I
SIMULATION PARAMETERS

BPLC material properties		
Wavelength (nm)	Optical rotatory power (°/μm)	Saturated birefringence: Δn_s
450	0.31	0.20
550	0.10	0.19
650	0.04	0.17
Polarizer properties		
Wavelength (nm)	Refractive index: n_e	Refractive index: n_o
450	1.5+i*0.0014	1.5+i*4.1*10^{-5}
550	1.5+i*0.0021	1.5+i*3.1*10^{-5}
650	1.5+i*0.0027	1.5+i*2.9*10^{-5}

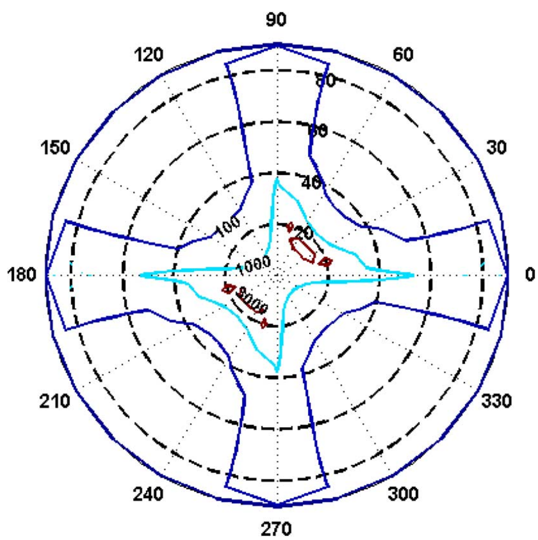

Fig. 1. Simulated isocontrast contour of a BPLC cell sandwiched between crossed polarizers.

reported in [3] and [4]. In the following sections, we propose three approaches to improve the CR of a BPLC device. Results are compared against the benchmark shown in Fig. 1.

III. ROTATING THE ANALYZER

The easiest way to compensate the polarization rotation effect of BPLC is to rotate the analyzer. When the absorption axis of the analyzer is rotated to match the polarization direction of the outgoing light, the lowest light leakage will be achieved. It should be noted that polarization rotation angle is wavelength dependent [18]. Therefore, rotating analyzer could only minimize the light leakage at one wavelength, rather than the entire visible spectrum. For display applications, we choose to minimize the light leakage at $\lambda = 550$ nm, in order to guarantee the highest white light contrast.

Fig. 2(a) shows a new BPLCD configuration without any compensation film, in which the analyzer is rotated by a small angle θ away from the crossed state. Arrows represent the absorption axes of polarizer and analyzer, respectively. To achieve minimal light leakage at $\lambda = 550$ nm, as mentioned above, θ is calculated to be 0.75°. In Fig. 2(b), one biaxial film is added to improve the viewing angle [20], [21]. The thickness of biaxial film is set as 27.5 μm, and the refractive indices are: $n_x = 1.51$, $n_y = 1.50$ and $n_z = 1.505$. Here n_x axis is indicated by an arrow within the film plane, and n_z axis is in the normal direction of the biaxial film. To maximize the viewing angle, the n_x axis of the biaxial film should be perpendicular to the absorption axis of the analyzer.

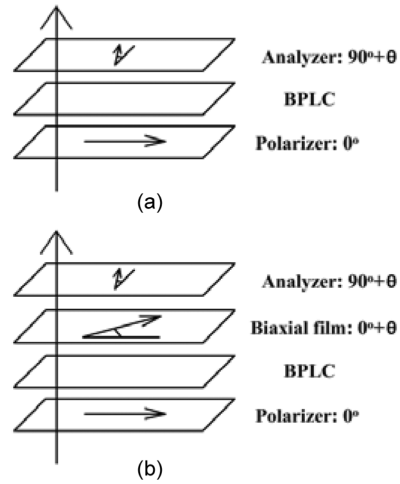

Fig. 2. Polarizer and compensation film configuration of the rotated analyzer design: (a) without compensation film and (b) with one biaxial film.

Figs. 3(a) and 3(b) plot the isocontrast contour of the new BP LCD configuration without and with biaxial film, respectively. In Fig. 3, the CR in normal direction is about 3700:1, which is more than twice of the normal contrast in Fig. 1. Besides, in Fig. 3(b), the $\mathrm{CR} = 100:1$ envelop covers all viewing directions within 85° polar angle. So the configuration in Fig. 2(b) is a good design for wide view display applications.

An interesting discovery from our simulation is that green light contributes 60% luminance in the bright state, but only causes 5% light leakage in the dark state. Therefore, it is difficult to further improve the CR by reducing green light leakage. In order to achieve a higher CR, red and blue lights have to be considered comprehensively.

IV. WIDE VIEW BROADBAND CIRCULAR POLARIZER

Our second approach is to use Hong's broadband and wide-view circular polarizers (CPs) [22]. The CP converts a linearly polarized incident light into circular. Therefore, the polarization rotation effect inside BPLC will not affect the extinction ratio of the CP. Besides, it is designed for broadband applications, so the light leakage at 450, 550, and 650 nm are suppressed simultaneously. The third important feature is that this CP has a wide viewing angle, and no additional viewing angle compensation is needed.

Fig. 4 depicts the simulated isocontrast contour of a BPLC cell sandwiched between these broadband circular polarizers. The CR at normal direction is as high as 12 000:1. Besides, in the entire viewing zone the CR is over 100:1, satisfying the wide viewing angle requirement.

V. DISPERSIVE $+A$ FILM

The configuration based on Hong's broadband wide view circular polarizer demonstrates high contrast ratio and wide viewing angle. However, this design requires four layers of biaxial films, which not only increases the cost but also introduces extra manufacturing error. A good compensation using

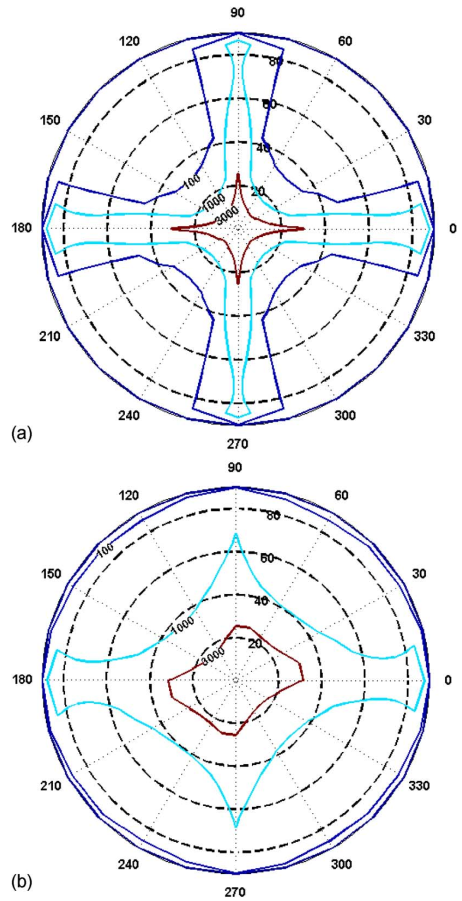

Fig. 3. Simulated isocontrast contour of a BP LCD shown in Fig. 2. (a) Rotated analyzer, without viewing angle compensation and (b) rotated analyzer, with one biaxial film.

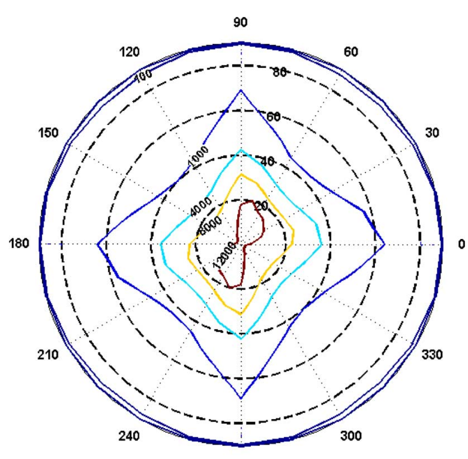

Fig. 4. Simulated isocontrast contour of a BPLC device sandwiched between two broadband wide-view circular polarizers.

fewer compensation films is always desired. The A films have been widely used in the viewing angle compensation of nematic LCDs [23]. Here we demonstrate that dispersive positive A film is also a possible solution for the polarization rotation compensation of BPLCDs, as Fig. 5 shows.

The BPLC layer is sandwiched between two identical dispersive $+A$ films. The principal axes of these two $+A$ films deviate a small angle from the absorption axis of the polarizer, one in

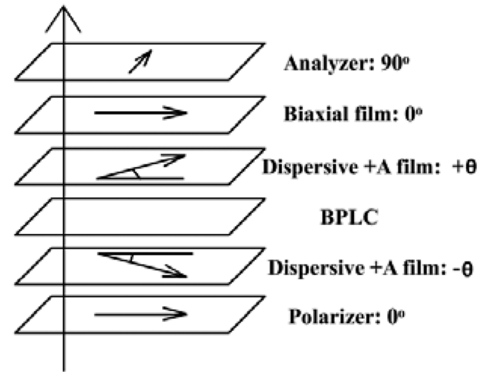

Fig. 5. Compensation configuration based on dispersive $+A$ films.

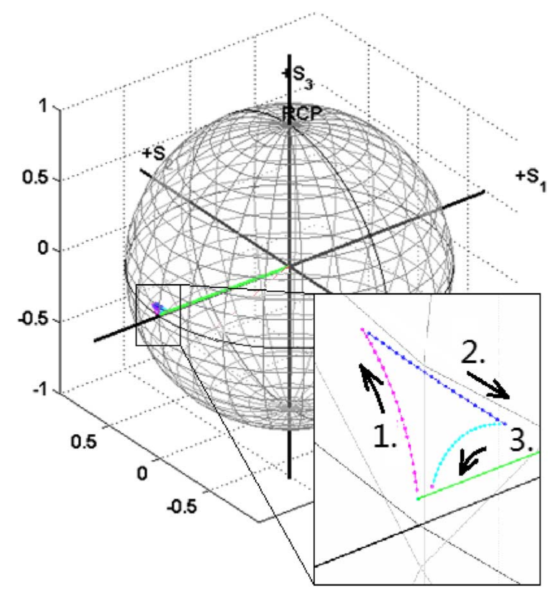

Fig. 6. Poincaré Sphere showing polarization state changes when the light traverses through $+A$ films and BPLC layer.

clockwise direction and the other in counter-clockwise direction ($\pm\theta$ in Fig. 5). The angle θ and the dispersion of the $+A$ film are optimized to compensate the polarization rotation effect of BPLC, which will be explained in detail below. In addition to the dispersive $+A$ films, one biaxial film is added to widen the viewing angle.

The function of dispersive $+A$ film is described by the Poincaré Sphere in Fig. 6. The zoomed-in curves on the surface of the sphere are shown in the inset. Curves 1–3 indicate the polarization state change when the linearly polarized light propagates through the first $+A$ film, the BPLC layer and the second $+A$ film in normal direction, respectively.

The linearly polarized incident light is converted into an elliptically polarized light, after passing through the first $+A$ film (Curve 1). Then the polarization rotation process inside BPLC layer is represented by Curve 2, which is along a latitudinal line on the sphere surface. Finally, the polarization state change through the second $+A$ film corresponds to Curve 3. The outcoming light from the second $+A$ film becomes linearly polarized again, and its polarization direction is the same as the incident light. In another word, the polarization rotation effect of BPLC is compensated by the $+A$ films. In the Poincaré Sphere,

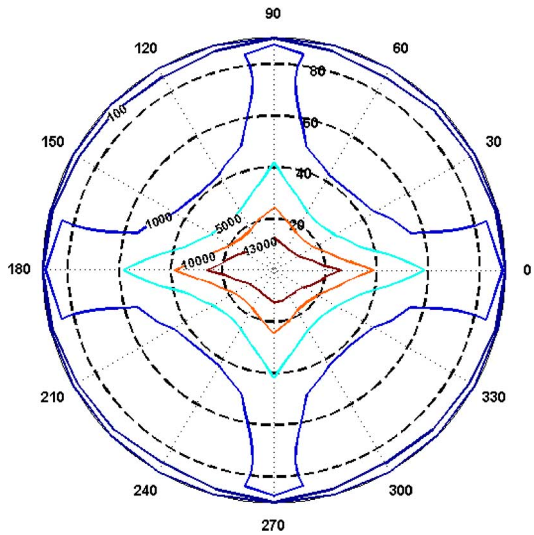

Fig. 7. Simulated isocontrast contour of the BPLC device with two dispersive $+A$ films, as shown in Fig. 5.

the lengths of Curves 1 & 3 relate to the birefringence of $+A$ films. On the other hand, the length of Curve 2 is determined by the polarization rotation angle of BPLC, which is wavelength dispersive. Therefore, by selecting a proper dispersion of $+A$ films, it is possible to achieve perfect compensation in the entire visible spectrum.

Based on the mechanism described above, the parameters of dispersive $+A$ films are optimized for the same BPLC material described in Section II. The $+A$ film thickness is 10 μm. The small angles between principal axes of $+A$ films and polarizer absorption axis are $\pm\theta = \pm 1.5^\circ$. The birefringence of the $+A$ films is 0.008 for $\lambda = 450$ nm, 0.005 for $\lambda = 550$ nm and 0.004 for $\lambda = 650$ nm. The parameters of the biaxial film are the same as mentioned in Section III. The compensation result is shown in Fig. 7. A $\mathrm{CR} = 13500 : 1$ is achieved in normal direction. Within 85° polar angle, the CR is over 100:1. The high CR on axis is due to the specifically designed dispersion of the $+A$ films, which optimizes the compensation result for all three wavelengths simultaneously.

VI. Conclusion

Polarization rotation effect of BPLC is the major source causing the dark state light leakage, which degrades the contrast ratio. We have proposed three approaches to compensate this effect and improve the contrast. Rotating analyzer is a simple and cost effective solution, but its improvement is rather limited. Hong's circular polarizer design renders a good compensation result, but the film structure is complicated. Dispersive $+A$ film based compensation method exhibits the best performance, although the requirement for specific dispersion would probably raise the cost.

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