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Yan Li

*University of Central Florida*

Meizi Jiao

*University of Central Florida*

Shin-Tson Wu

*University of Central Florida*

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# Transflective display using a polymer-stabilized blue-phase liquid crystal

Yan Li, Meizi Jiao, and Shin-Tson Wu\*

College of Optics and Photonics, University of Central Florida, Orlando 32816, Florida, USA

\*swu@mail.ucf.edu

**Abstract:** A wide view, submillisecond response, and single-cell-gap transflective display using a blue-phase liquid crystal (BPLC) is proposed. To balance the optical phase retardation between transmissive (T) and reflective (R) regions, in-plane protrusion electrodes are formed with different gaps in the two regions. This display exhibits reasonably high optical efficiency and well matched voltage dependent transmittance and reflectance curves. Using biaxial films and broadband wide-view circular polarizers, the viewing angle with 100:1 contrast ratio is obtained over the entire viewing cone in the T region, and 10:1 over 50° in the R region. The potential application is emphasized.

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

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## 1. Introduction

Wide-view transfective liquid crystal displays (TR-LCDs) are attractive for mobile applications because of their good sunlight readability [1,2]. A major technical challenge of TR-LCDs is to balance the optical path-length disparity between the transmissive (T) and reflective (R) regions. In T mode the backlight passes through the LC layer once, while in R mode the ambient light traverses the LC layer twice. To achieve the same phase retardation for T and R modes, both double-cell-gap and single-cell-gap TR-LCDs have been developed [1,2]. Each approach has its own pros and cons. To reduce power consumption, a TR-LCD using color-sequential LED backlight for T mode has been proposed [3]. By eliminating spatial RGB (red, green, and blue) color filters, the optical efficiency and resolution density are all tripled. However, to suppress color breakup due to sequential colors the LC response time has to be less than ~1 ms which imposes a big challenge to nematic LCs [4,5].

Polymer-stabilized blue-phase liquid crystal (BPLC) [6–8] exhibits several revolutionary features, such as submillisecond gray-to-gray response time [9], optically isotropic dark state which leads to inherently wide viewing angle, insensitive to cell gap if in-plane switching (IPS) electrodes are used [8,10], and no need for alignment layer. Unlike nematic LC devices which are based on the molecular reorientation, the physical mechanism of BPLC is governed by electric-field-induced birefringence, known as Kerr effect [11].

In this paper, we propose a wide view and single-cell-gap TR-LCD using polymer-stabilized BPLC. To reduce operating voltage, we use protrusion electrodes so that the electric fields penetrate deeply into the bulk LC layers. To balance the optical phase retardation and obtain well-matched voltage-dependent transmittance (VT) and reflectance (VR) curves, we design the T and R regions to have different electrode gaps. The wider electrode gap in the R region generates a weaker electric field in order to accommodate the double pass of the ambient light. To obtain wide viewing angle, we employ two broadband wide-view circular polarizers and biaxial films.

## 2. Device structure and principle

Figure 1 depicts the device structure of the proposed single-cell-gap transfective BP LCD. The cell is sandwiched between two crossed circular polarizers. Each pixel is divided into T and R regions. In both regions, trapezoid protrusion electrodes are formed in order to lower the operating voltage [12]. The dimensions of the protrusions are defined as follows:  $w_1$  is the top width,  $w_2$  is the bottom width,  $h$  is the protrusion height, and  $l_T$  and  $l_R$  are the space between common (C) and pixel (P) electrodes in T and R regions, respectively. If the protrusion height is less than 2  $\mu\text{m}$ , then the transmittance and reflectance are insensitive to cell gap as long as it exceeds ~6  $\mu\text{m}$ . Thus, we choose the cell gap in both regions to be 10  $\mu\text{m}$ . However, the gap  $l_T$  is intentionally made smaller than  $l_R$  so that the R region exhibits a weaker fringing field which, in turn, generates a smaller induced birefringence. This design is crucial for balancing the phase retardation between the T and R modes. In a TR-LCD, the backlight passes the T region once, but the ambient light traverses the R region twice. The weaker induced birefringence in the R region compensates the double pass of the ambient light. The matched VT and VR curves will enable the single gamma curve driving which simplifies the electronic circuits. Moreover, in a polymer-stabilized BPLC cell no surface alignment layer is needed which eases the fabrication process.

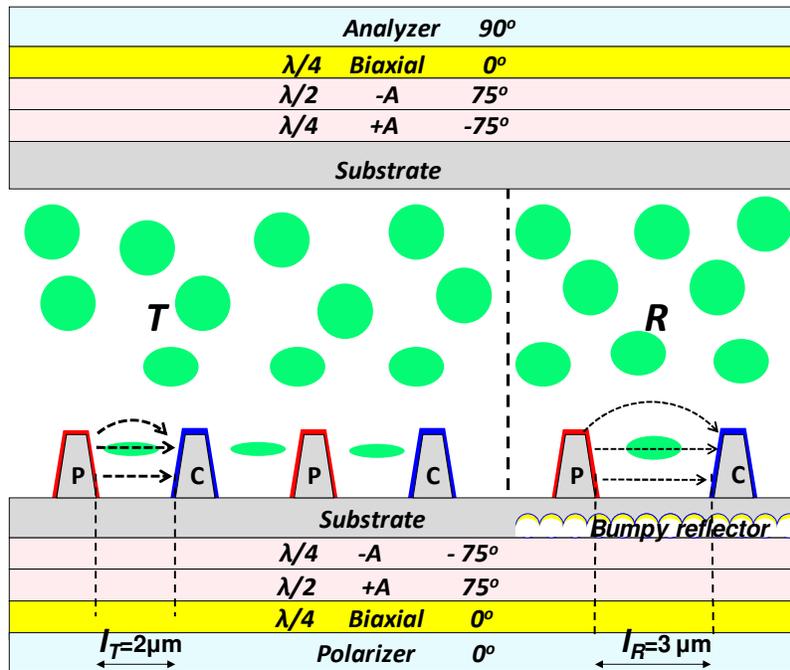


Fig. 1. Device structure of the single-cell-gap transfective BP LCD. P stands for pixel electrode, C for common electrode, and dashed lines with arrows represent electric fields in the T and R regions.

To obtain normally black mode for both T and R regions, we use two broadband and wide-view circular polarizers [13] consisting of positive and negative A-plates as Fig. 1 shows. The combination of positive and negative A-plates results in a much better viewing angle because they compensate well to each other over a large viewing zone. The BPLC is optically isotropic in the voltage-off state, thus the proposed crossed circular polarizer configuration works equally well for both T and R modes. This is another major advantage for using BPLC in transfective displays because it does not require any negative C-plate [14] or in-cell phase retarder [15]. These components are generally required for TR-LCDs employing a nematic LC.

To achieve an even better contrast ratio over wide viewing angles, two biaxial  $\lambda/4$  plates are placed below the top linear polarizer and above the bottom linear polarizer, as Fig. 1 shows. A conventional  $\lambda/2$  biaxial compensation film would assure a good viewing angle for the T region, but could not improve the R region too noticeably. However in our configuration, when the ambient light passes through the biaxial  $\lambda/4$  plates twice in the R region, it is equivalent to experience a  $\lambda/2$  retardation as happening in the T region. As a result, the compensation effect in the T and R regions are similar which leads to a wide viewing angle in both T and R regions.

### 3. Results and discussion

To validate the device design, we simulated the electro-optic characteristics of this transfective BP LCD. We first used commercial software 2Dimos to calculate the electric potential and electric field (E) distributions. The induced birefringence  $\Delta n_{ind}$  was then calculated from Kerr effect [10,16]:

$$\Delta n_{ind} = \lambda K E^2 = (\Delta n)_o (E / E_s)^2, \quad (1)$$

where  $\lambda$  is the incident light wavelength,  $K$  is the Kerr constant,  $(\Delta n)_o$  is the maximum induced birefringence, and  $E_s$  is the saturation field. It is known that Kerr effect holds only in the low field region. As the electric field keeps on increasing, the induced birefringence would gradually saturate [17]. Unless specifically mentioned, throughout our simulations we assume  $K = 12.7 \text{ nm/V}^2$  and  $(\Delta n)_o = 0.2$  at  $\lambda = 550 \text{ nm}$ . After we have obtained the birefringence distribution, we apply extended Jones matrix methods to calculate the electro-optical properties [18,19]. In order to achieve low operating voltage and high transmittance, the parameters of the protrusion electrode are optimized at:  $w_1 = 0.5 \mu\text{m}$ ,  $w_2 = 1 \mu\text{m}$ ,  $h = 2 \mu\text{m}$ ,  $l_T = 2 \mu\text{m}$ , and  $l_R = 3 \mu\text{m}$ . And the optimized biaxial film has  $N_z = (n_x - n_z)/(n_x - n_y) = 0.5$ .

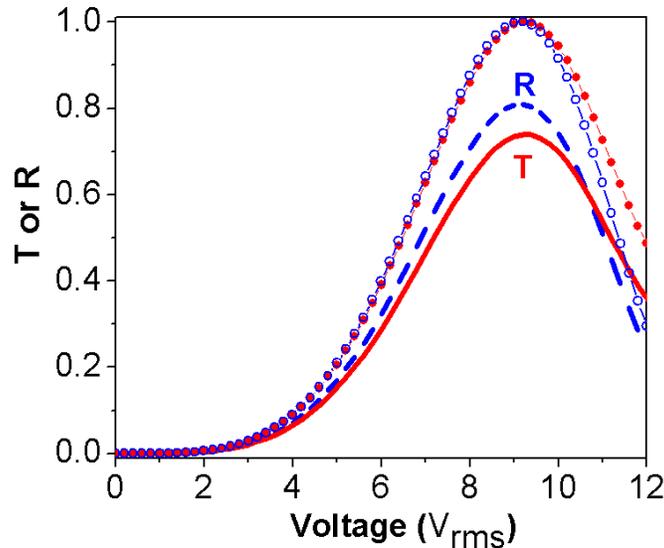


Fig. 2. Simulated VT and VR curves for the proposed transfective BP LCD. The solid red and dashed blue lines represent simulated VT and VR curves, and the closed circles and open circles represent normalized transmittance and reflectance.

Figure 2 shows the simulated VT and VR curves at  $\lambda = 550 \text{ nm}$ , both of which are normalized to the transmittance of two parallel polarizers (34.83%). Red curve (solid line) represents the transmittance, with a peak of  $\sim 74\%$ , and blue curve (dashed lines) represents the reflectance with a peak of  $\sim 81\%$ . Both T and R modes have a reasonably high optical efficiency. The on-state voltage for both regions occurs at  $\sim 9.2 \text{ V}_{\text{rms}}$ , thus this device can be addressed by amorphous-silicon thin film transistors (a-Si TFTs). The closed and open circles represent the normalized transmittance and reflectance, respectively. They overlap with each other quite well, which enables a single gamma curve driving.

Figures 3(a) and 3(b) depict the simulated isocontrast contour plots of the T and R regions, respectively. To take the color dispersion into account, in our isocontrast simulation, we assume the white light spectrum contains 60% green ( $\lambda = 550 \text{ nm}$ ), 30% red ( $\lambda = 650 \text{ nm}$ ), and 10% blue ( $\lambda = 450 \text{ nm}$ ). From Fig. 3, the averaged contrast ratio in the T region remains quite superb: the 1000:1 contrast ratio (CR) is over  $45^\circ$  viewing cone and 100:1 is over the entire viewing cone. In the R region,  $\text{CR} = 10:1$  is over  $50^\circ$ . These wide-view characteristics originate from the optically isotropic property of the BPLC.

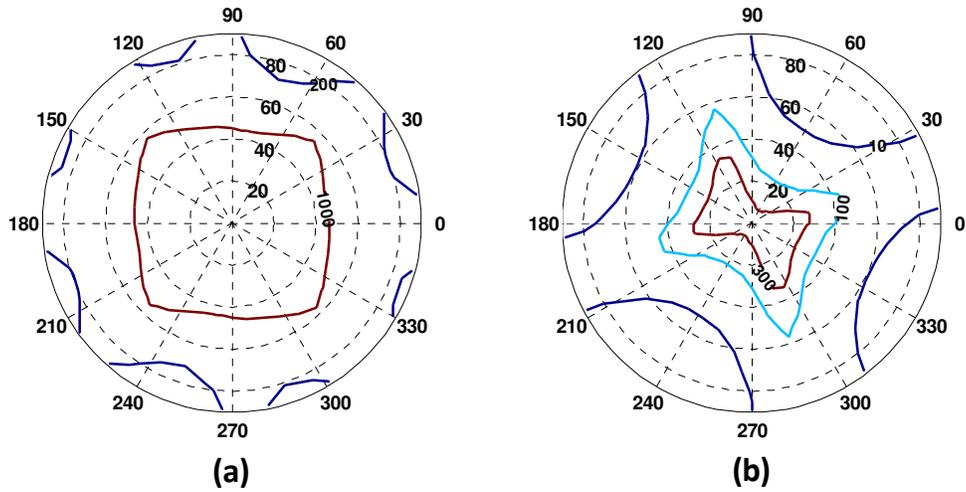


Fig. 3. Simulated isocontrast contour plots for (a) T mode and (b) R mode of the proposed TR-LCD.

For the proposed BPLC device, the operating voltage ( $\sim 9.2 V_{rms}$ ) is still higher than a conventional nematic LCD whose operating voltage is usually  $< 7 V_{rms}$ . Two approaches have been commonly taken to lower the operating voltage of BPLC devices: employing a large Kerr constant material, and optimizing the electrode configuration. Here we focus on improving the device configuration while keeping the Kerr constant at  $K = 12.7 \text{ nm/V}^2$  at  $\lambda = 550 \text{ nm}$  and room temperature ( $\sim 23^\circ\text{C}$ ) [20].

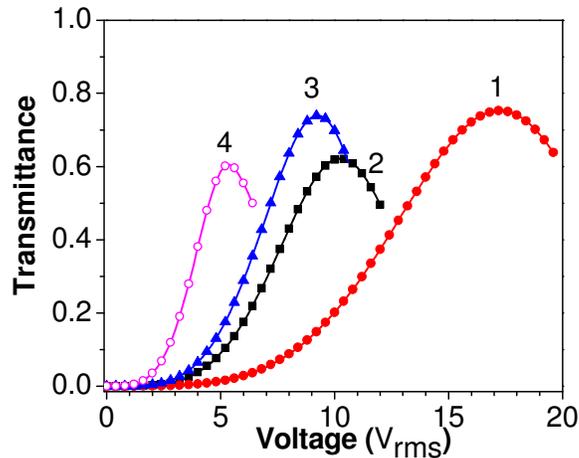


Fig. 4. Simulated VT curves with different protrusion-electrode device structures. 1)  $w_1 = 1 \mu\text{m}$ ,  $w_2 = 2 \mu\text{m}$ ,  $h = 2 \mu\text{m}$ , and  $l_T = 4 \mu\text{m}$ ; 2)  $w_1 = 1 \mu\text{m}$ ,  $w_2 = 2 \mu\text{m}$ ,  $h = 2 \mu\text{m}$ , and  $l_T = 2 \mu\text{m}$ ; 3)  $w_1 = 0.5 \mu\text{m}$ ,  $w_2 = 1 \mu\text{m}$ ,  $h = 2 \mu\text{m}$ , and  $l_T = 2 \mu\text{m}$ ; and 4)  $w_1 = 0.5 \mu\text{m}$ ,  $w_2 = 1 \mu\text{m}$ ,  $h = 2 \mu\text{m}$ , and  $l_T = 1 \mu\text{m}$ .

Figure 4 shows the simulated VT curves of four different electrode designs for T region. Curves 1 and 2 share the same protrusion shape ( $w_1 = 1 \mu\text{m}$ ,  $w_2 = 2 \mu\text{m}$ , and  $h = 2 \mu\text{m}$ ) but with different electrode gaps  $l_T$  ( $4\text{-}\mu\text{m}$  for curve 1 and  $2\text{-}\mu\text{m}$  for curve 2). As the electrode gap gets smaller, the peak voltage is reduced from  $\sim 17 V_{rms}$  to  $\sim 10 V_{rms}$ . However, the tradeoff is the lower transmittance (from  $\sim 75\%$  to  $\sim 63\%$ ). The decreased transmittance results from

increased ratio of dead zones as the electrode gap decreases. In an IPS structure, the dead zones occur at the middle of the electrodes. Curves 3 and 4 have a smaller protrusion dimension ( $w_1 = 0.5 \mu\text{m}$ ,  $w_2 = 1 \mu\text{m}$ , and  $h = 2 \mu\text{m}$ ) and a smaller electrode gap  $l_T$  ( $2\text{-}\mu\text{m}$  for curve 3 and  $1\text{-}\mu\text{m}$  for curve 4). The influence of gap variation as mentioned before stays true in the comparison of curves 3 and 4. Although curve 4 exhibits a very low operating voltage ( $\sim 5 \text{ V}_{\text{rms}}$ ), its transmittance is reduced to  $\sim 60\%$ . We also studied the effects of protrusion height (results are not shown here). Increasing the protrusion height is an effective way to reduce the operating voltage without sacrificing transmittance too noticeably. However, the fabrication of small and steep protrusion electrodes using current lithography remains a challenge. As the nanoimprinting technology advances, the fabrication of small dimension protrusion electrodes will no longer be a hurdle. Thus, the operating voltage could be further reduced, which is highly desirable for mobile display devices.

An important advantage of the proposed TR-LCD is its submillisecond gray-to-gray response time [9]. If the transmissive BP LCD employs spatial color filters, the inherent fast response time is helpful for reducing motion picture image blurs. Moreover, such a fast response feature enables color sequential mode in the T region with RGB LED backlight [3]. The removal of color filters would triple the optical efficiency and resolution density in the T region. In the R region, color filters are optional. Without color filters, the reflectance will be greatly enhanced except that the display will appear black and white. On the other hand, if color filters are employed in the R region, then its performance in reflective mode will be comparable to a typical nematic TR-LCD. If the LED backlight is kept on, then the total optical efficiency will still be superior to that of nematic TR-LCD.

#### 4. Conclusion

We have proposed a fast response, wide view, and single-cell-gap transmissive display based on polymer-stabilized BPLC. In such a cell no surface alignment layer is needed which simplifies the fabrication process. Both T and R regions of this TR-LCD exhibit a reasonably high optical efficiency. The VT and VR curves match very well which enables a single gamma curve driving. The viewing angle (under white light) for T mode is excellent, and for R mode is also adequate for mobile display applications. This is because the BPLC has an optically isotropic dark state. Moreover, its submillisecond response time would reduce the image blurs, and if field sequential operation is employed in T region its optical efficiency and resolution density are both tripled. As the nanoimprinting technology advances, the fabrication of protrusion electrodes will become easier. As a result, the proposed transmissive BP LCD has great potential for mobile display applications.

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