SPECIAL TOPIC — Physical research in liquid crystal

# Low voltage transflective blue-phase liquid crystal display with a non-uniform etching substrate*

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A transflective polymer-stabilized blue-phase liquid crystal display (BP-LCD) with a non-uniform etching substrate is proposed. In-plane switching (IPS) electrodes on the bottom substrate are put on the different gaps, and the bottom substrate between the electrodes is etched into different depths in transmissive (T) and reflective (R) regions. This structure can balance the optical phase retardation in the two regions and is helpful to achieve well-matched voltag-dependent transmittance and reflectance curves. This transflective display has high optical efficiency, a wide viewing angle, and low operating voltage (approximately 6 V).

**Keywords:** blue-phase, Kerr effect, transflective liquid crystal display

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## 1. Introduction

Polymer-stabilized blue-phase liquid crystals (PS-BPLCs)[1–5] have unique advantages, such as sub-millisecond response time which offers the possibility to realize color-sequential displays using LEDs without noticeable color breakup,[6,7] an isotropic dark state which helps to achieve an inherently wide and a symmetric viewing angle,[8] and no need of alignment layer,[9] so they have aroused much interest of researchers. However, some drawbacks including high operating voltage, low transmittance, and hysteresis need to be improved. In order to overcome these technical barriers, the protrusion electrode,[10,11] wall-shaped electrode,[12] and corrugated electrode[13] have been proposed.

Transflective liquid crystal displays (TR-LCDs) have been widely applied in mobile electronic products such as smart phones and tablet PCs owing to their low power consumption and good readability of the sunlight environment.[14] The TR-LCD consists of transmissive (T) and reflective (R) regions, and the backlight passes through the LC layer only once in the T region, while in the R region the ambient light passes through the LC layer twice. In order to balance the optical phase retardation between the T and R regions, various double-cell-gap[15–18] and single-cell-gap[19–22] TR-LCDs have been proposed. Compared with double-cell-gap TR-LCDs, single-cell-gap TR-LCDs have a huge advantage in fabrication. However, several single-cell-gap TR-LCDs using polymer-stabilized blue-phase liquid crystals (PS-BPLCs)[23,24] are still have a high operating voltage. For example, a single-cell-gap transflective blue-phase liquid crystal display (BP-LCD) with the etched in-plane switching structure[23] exhibits well-matched voltage-dependent transmittance (VT) and reflectance (VR) curves and a wide viewing angle, but the voltage is high, that is 16 V. For another single-cell-gap TR-LCD using the polymer-stabilized BPLC,[24] the structure makes use of the space above the pixel electrodes as reflective regions and the space between pixel electrodes as transmissive regions. The operating voltage is 17 V, but it is still high.

In this paper, we propose a single-cell-gap transflective BP-LCD with a non-uniform etching substrate. In the T and R regions, in-plane switching (IPS) electrodes are put on different gaps, and the bottom substrate between the electrodes is etched into different depths. We design different electrode gaps and etching depths to make the T and R regions to obtain the same optical phase retardation. Moreover, the etched IPS structure can generate a deep penetrating fringe field which can lower the operating voltage. As a result, the well-matched VT and VR curves and low operating voltage are obtained.

## 2. Device structure and principle

Figure 1 shows the proposed single-cell-gap transflective BP-LCD. In order to obtain a normally black state and a relatively better viewing angle, we use two broadbands and wide-view circular polarizers consisting of positive and negative A-plates.[25] The BPLC layer is placed between two crossed circular polarizers. Each pixel is divided into the T and R regions. IPS electrodes are put on different gaps, and the bottom substrate between the electrodes is etched into different depths in two regions. Here, $W_1$ is the electrode width, which is the same

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in the T and R regions, $W_2$ is the width between the electrodes in the R region, and $W_3$ is the width between the electrodes in the T region. The bottom substrate between the electrodes is etched with depth $h_1$ in the R region and depth $h_2$ in the T region, and $d$ is the cell gap. The phase retardation is different in the T and R regions because the times of the backlight and ambient light pass through the LC layer are different. To achieve the same phase retardation in both T and R regions, we make the T and R regions to have different electrode gaps and etching depths. The gap $W_3$ is intentionally made smaller than $W_2$, and the depth $h_2$ is larger than $h_1$. This design can generate a stronger fringing field in the T region to balance the phase retardation between the T and R modes and match the VT and VR curves.

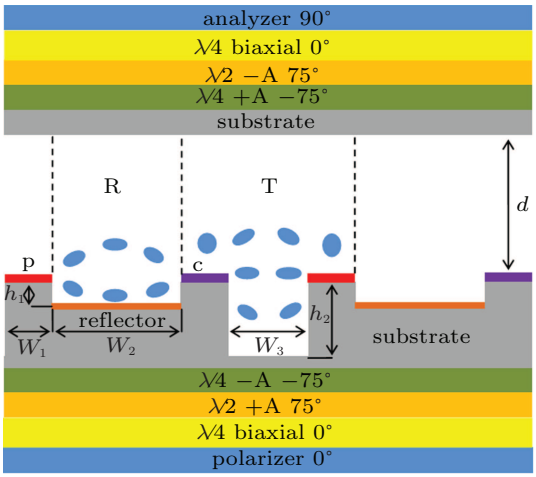



**Fig. 1.** (color online) Schematic structure of the transflective BP-LCD with a non-uniform etching substrate.

Unlike the conventional LCD which is based on molecular reorientation from anisotropy to anisotropy, for a BP-LCD, the induced birefringence is governed by the Kerr effect. At the voltage-off state, the BP-LC is optically isotropic, so there will be a good dark state. When a voltage is applied, the BP-LC is optically anisotropic and the induced birefringence emerges. The induced birefringence $(\Delta n)_{\rm ind}$ can be expressed by the following equation which is known as the extended Kerr effect model:[26]

$$(\Delta n)_{\rm ind} = \lambda K E^2 = (\Delta n)_{\rm s}\left(1 - \exp\left[-\left(\frac{E}{E_{\rm s}}\right)^2\right]\right), \qquad (1)$$

where $\lambda$ is the incident light wavelength, $K$ is the Kerr constant, $(\Delta n)_{\rm s}$ is the maximum induced birefringence, and the induced $(\Delta n)_{\rm ind}$ slowly saturates to $(\Delta n)_{\rm s}$ when the electric field $E$ is larger than a saturation field $E_{\rm s}$.

## 3. Simulation results and discussion

To validate the device design, we used the commercial simulation software TechWiz LCD 3D (SANAYI System Co., Ltd., Incheon, Korea) to simulate the electro–optic characteristics of the transflective BP-LCD. In our simulations, we assume $K = 16.3$ nm/V$^2$, $E_{\rm s} = 4.15$ V/μm, and $(\Delta n)_{\rm s} = 0.15$, at $\lambda = 550$ nm. The transmittance is normalized to that of two parallel polarizers (G-1220DU) (28.4%). Here, we choose the cell gap $d$ in two regions to be 8 μm.

Figure 2 shows the simulated VT and VR curves for the proposed transflective BP-LCD at $\lambda = 550$ nm. The parameters of the device: $W_1 = 1$ μm, $W_2 = 5$ μm, $W_3 = 3$ μm, $h_1 = 0.5$ μm, and $h_2 = 3$ μm. The device is an optimized structure, which can achieve low operating voltage and high optical efficiency. The red and blue solid lines represent the simulated VT and VR curves, respectively. We can see that the operating voltage at the peak of the transmittance ($\sim 79\%$) and reflectance ($\sim 90\%$) is equal at 6 V, and both two regions have high optical efficiency at this voltage. The red line with closed circles and the blue line with triangles represent the normalized transmittance and reflectance, respectively. A good match between the VT and VR curves is obtained to make the device single gamma driving.

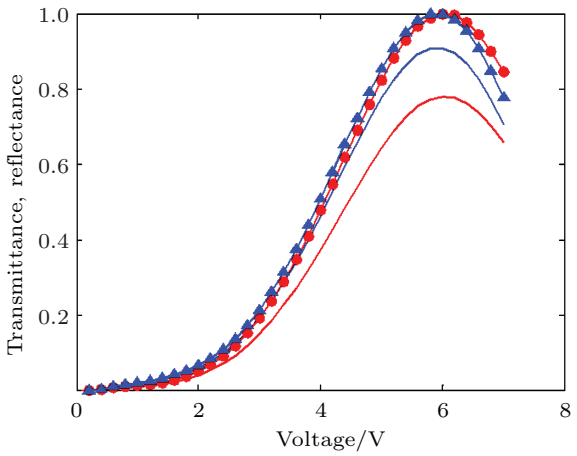



**Fig. 2.** (color online) Simulated VT (red line) and VR (blue line) curves for the proposed transflective BP-LCD, and the red circles and blue triangles represent the normalized transmittance and reflectance, respectively.

Tables 1 and 2 summarize the operating voltage, transmittance, and reflectance with different electrode gaps and etching depths. In these structures, the electrode width $W_1$ is set as 1 μm. When the etching depths $h_1$ and $h_2$ remain unchanged, as shown in Table 1, the operating voltages of the T and R regions become larger as the electrode gaps $W_2$ and $W_3$ increase. This is because the electric fields between electrodes become weaker when the electrode gaps increase. Therefore, we should choose the structure with the smaller electrode gap. As shown in Table 2, we keep the electrode gaps ($W_2$ and $W_3$) unchanged, and we can find that the voltage of the T region decreases, and the voltage of the R region increases, when the etching depth $h_2$ increases and $h_1$ decreases. As a result, the operating voltages at the peak of the transmittance and reflectance will be equal at 6 V, which contributes to make the

VT and VR curves to match with each other tolerably well. From the two tables, it is found that the reflectance is larger than the transmittance. According to our analysis, the disparity is caused by the electrode width $W_1$ in the T region which leads to low transmittance. To reduce the disparity, we can decrease the electrode width $W_1$ in the T region.

Figures 3(a) and 3(b) show the simulated VT and VR curves with different electrode widths $W_1$ at $W_2 = 5$ μm, $W_3 = 3$ μm, $h_1 = 0.5$ μm, and $h_2 = 3$ μm. When the electrode width $W_1$ decreases from 1.5 μm to 0.5 μm, the transmittance becomes higher, while the reflectance is insensitive to the electrode width. Moreover, we can find that the operating voltage at the maximum of the transmittance is reduced as the electrode width $W_1$ becomes smaller, but the operating voltage at the maximum of the reflectance remains the same. At $W_1 = 0.5$ μm, the transmittance is approximately 88%, the disparity of the transmittance and reflectance can be eliminated, and the VT and VR curves match with each other very well. However, the fabrication of the small electrode width using the current technology is very complicated.

Figures 4(a) and 4(b) show the simulated iso-contrast plots of the T and R regions at $\lambda = 550$ nm, respectively. In order to solve some light leakage at the off-axis direction of the two crossed polarizers, $\lambda/4$ biaxial compensation film with $N_z = (n_x - n_z)/(n_x - n_y) = 0.5$ is used to obtain a good wide viewing angle. From Fig. 4, we can find that the viewing angle is reasonably wide. The 1000:1 contrast ratio (CR) is over 40° viewing cone and CR=100:1 is nearly over the entire viewing cone in the T region. In the R region, CR=10:1 is over 55°.

**Table 1.** Operating voltage ($V_T$ and $V_R$) and the corresponding optical efficiency (T and R) of the proposed transflective BP-LCD with different electrode gaps ($W_2$ and $W_3$).

| $h_1$/μm | $h_2$/μm | $W_1$/μm | $W_2/W_3$/(μm/μm) | $V_T/V_{rms}$ | $V_r/V_{rms}$ | T/% | R/% |
|---|---|---|---|---|---|---|---|
| 0.5 | 3 | 1 | 4/2 | 5 | 5.4 | 55 | 92.2 |
| 0.5 | 3 | 1 | 5/3 | 6 | 6 | 79 | 90 |
| 0.5 | 3 | 1 | 6/4 | 8.6 | 6.4 | 77 | 90.3 |

**Table 2.** Operating voltage ($V_T$ and $V_R$) and corresponding optical efficiency (T and R) of the proposed transflective BP-LCD with different etching depths ($h_1$ and $h_2$).

| $h_1$/μm | $h_2$/μm | $W_1$/μm | $W_2/W_3$/(μm/μm) | $V_T/V_{rms}$ | $V_r/V_{rms}$ | T/% | R/% |
|---|---|---|---|---|---|---|---|
| 0.5 | 2.5 | 1 | 5/3 | 7.4 | 6.2 | 66.5 | 92.4 |
| 0.5 | 3 | 1 | 5/3 | 6 | 6 | 79 | 90 |
| 1 | 3 | 1 | 5/3 | 5.2 | 4.4 | 88 | 92 |

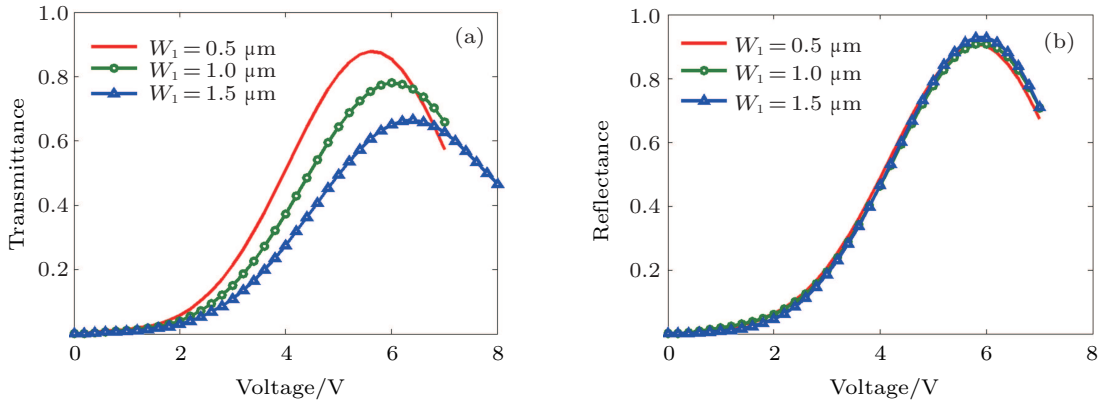



**Fig. 3.** (color online) Simulated (a) VT curves and (b) VR curves with different electrode widths for the proposed transflective BP-LCD at $W_2 = 5$ μm, $W_3 = 3$ μm, $h_1 = 0.5$ μm, and $h_2 = 3$ μm.

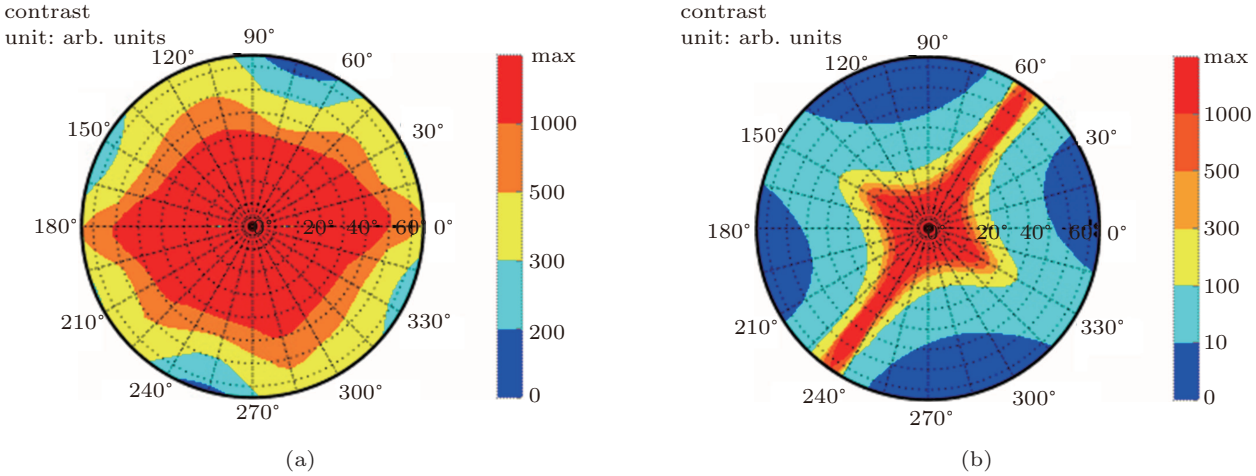



**Fig. 4.** (color online) Simulated iso-contrast plots for (a) T mode and (b) R mode of the proposedtransflective BP-LCD.

## 4. Conclusion

We proposed a wide-view single-cell-gap transflective display with a non-uniform etching substrate based on polymer-stabilized BPLCs. The etched IPS structure was formed in the T and R regions. By designing a set of optimal electrode gaps and etching depths, we can not only lower the operating voltage by generating a deep penetrating fringe field, but also make the VT and VR curves to match with each other very well which makes the device a single gamma curve driving. Both the T and R regions of this BP-LCD exhibit reasonably high optical efficiency. Moreover, the fabrication of the etched substrate and IPS electrodes is simple which makes this transflective device to have a great application potential in portable electronics.

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