

# A reflective polarizer-free electro-optical switch using dye-doped polymer-stabilized blue phase liquid crystals

Yi-Hsin Lin,<sup>1,\*</sup> Hung-Shan Chen,<sup>1</sup> Tsung-Han Chiang,<sup>1</sup> Chun-Hung Wu,<sup>1</sup>  
and Hsu-Kuan Hsu<sup>2</sup>

<sup>1</sup>Department of Photonics, National Chiao Tung University, Hsinchu, Taiwan 30010, Taiwan

<sup>2</sup>Chimei-Innolux Corp., Tainan, Taiwan

\*yilin@mail.nctu.edu.tw

<http://www.cc.nctu.edu.tw/~yilin>

**Abstract:** We demonstrate a reflective polarizer-free electro-optical switch using dye-doped polymer-stabilized blue phase liquid crystals (DDPSBP-LC). At the voltage-off state, the dye molecules and liquid crystals form the structure of the double twist cylinders. As a result, the DDPSBP-LC is in dark state due to the combination of Bragg reflection and light absorption. At the voltage-on state, the blue phase structure is unwound locally. The DDPSBP-LC is then in bright state because of the small light absorption only. The applications of such a switch are shutter glass of 3D displays, and electronic papers.

©2011 Optical Society of America

OCIS codes: (230.3720) Liquid-crystal devices; (160.5470) Polymers.

---

## References and links

1. H. Kikuchi, M. Yokota, Y. Hisakado, H. Yang, and T. Kajiyama, "Polymer-stabilized liquid crystal blue phases," *Nat. Mater.* **1**(1), 64–68 (2002).
  2. Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S. T. Wu, "Electro-optics of polymer-stabilized blue phase liquid crystal displays," *Appl. Phys. Lett.* **94**(10), 101104 (2009).
  3. Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, and W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," *Appl. Phys. Lett.* **96**(11), 113505 (2010).
  4. S. T. Wu, and D. K. Yang, *Reflective liquid crystal displays* (Wiley, New Jersey, 2001).
  5. J. W. Doane, N. A. Vaz, B. G. Wu, and S. Zumer, "Field controlled light scattering from nematic microdroplets," *Appl. Phys. Lett.* **48**(4), 269–271 (1986).
  6. Y. H. Lin, H. Ren, and S. T. Wu, "High contrast polymer-dispersed liquid crystal in a 90° twisted cell," *Appl. Phys. Lett.* **84**(20), 4083–4085 (2004).
  7. Y. H. Lin, H. Ren, S. Gauza, Y. H. Wu, X. Liang, and S. T. Wu, "Reflective direct-view displays using a dye-doped dual-frequency liquid crystal gel," *J. Disp. Technol.* **1**(2), 230–233 (2005).
  8. Y. H. Lin, and C. M. Yang, "A polarizer-free three step switch using distinct dye-doped liquid crystal gels," *Appl. Phys. Lett.* **94**(14), 143504 (2009).
  9. Y.-H. Lin, J.-M. Yang, Y.-R. Lin, S.-C. Jeng, and C.-C. Liao, "A polarizer-free flexible and reflective electrooptical switch using dye-doped liquid crystal gels," *Opt. Express* **16**(3), 1777–1785 (2008).
  10. E. Grelet, P. J. Collings, M.-H. Li, and H.-T. Nguyen, "Optical activity measurements in the smectic blue phases," *Eur. Phys. J. E* **6**(2), 157–161 (2001).
  11. K. M. Chen, S. Gauza, H. Xianyu, and S. T. Wu, "Hysteresis effect in blue-phase liquid crystals," *J. Disp. Technol.* **6**(8), 318–322 (2010).
  12. L. Rao, Z. Ge, S. Gauza, K. M. Chen, and S. T. Wu, "Emerging Liquid Crystal Displays Based on the Kerr Effect," *Mol. Cryst. Liq. Cryst. (Phila. Pa.)* **527**, 30–42 (2010).
  13. H. F. Gleeson, and H. J. Coles, "Dynamic properties of blue-phase mixtures," *Liq. Cryst.* **5**(3), 917–926 (1989).
  14. Y. Hisakado, H. Kikuchi, T. Nagamura, and T. Kajiyama, "Large Electro-optic Kerr Effect in Polymer-Stabilized Liquid-Crystalline Blue Phases," *Adv. Mater. (Deerfield Beach Fla.)* **17**(1), 96–98 (2005).
  15. P. R. Gerber, "Electro-optical effects of a small pitch blue-phase system," *Mol. Cryst. Liq. Cryst. (Phila. Pa.)* **116**(1), 197–206 (1985).
  16. S. W. Choi, S. I. Yamamoto, Y. Haseba, H. Higuchi, and H. Kikuchi, "Optically isotropic-nanostructured liquid crystal composite with high Kerr constant," *Appl. Phys. Lett.* **92**(4), 043119 (2008).
  17. L. Rao, Z. Ge, S. T. Wu, and S. H. Lee, "Low voltage blue-phase liquid crystal displays," *Appl. Phys. Lett.* **95**(23), 231101 (2009).
-

## 1. Introduction

Polymer-stabilized blue phase liquid crystals (PSBP-LCs) within wide temperature range attract many attentions, such as in-planed switching liquid crystal displays (IPS-LCDs) and tunable focusing microlens arrays, owing to fast response time, alignment-free [1–3]. Such IPS-LCDs require two polarizers because of optical anisotropy induced by the electric fields; therefore, the optical efficiency is limited by the polarizers. It is urgent to develop polarizer-free electro-optical switch. Polarizer-free electro-optical switch can be achieved based on Guest-Host liquid crystal displays (GH LCD). By adding dichroic dye molecule into a host LC to eliminate the polarization dependency, several device configurations such as Cole-Kashnow cell, White-Taylor cell or double orthogonal cells have been proposed [4]. Besides light absorption, light scattering can also be adopted to achieve polarizer-free electro-optical switch with fast response time, such as dye-doped polymer-dispersed liquid crystals (PDLC) [5,6], dye-doped dual-frequency liquid crystal (DFLC) gel [7], and dye-doped LC gels [8,9].

In this paper, we demonstrate a reflective polarizer-free electro-optical switch using dye-doped polymer-stabilized blue phase liquid crystals (DDPSBP-LC). The mechanism is mainly the combination of electrically tunable light absorption and Bragg reflection. At the voltage-off state, the dye molecules and liquid crystals form the structure of the double twist cylinders. As a result, the DDPSBP-LC is in dark state due to both of Bragg reflection and light absorption. At the voltage-on state, the blue phase structure is unwound locally. The DDPSBP-LC is then in bright state because of the small light absorption only resulting from liquid crystal directors and the dye molecules are perpendicular to the substrate. The electro-optical properties are discussed. The applications of such an electro-optical switch are shutter glass of 3D displays, and electronic papers.

## 2. Sample preparation and operating principle

Figure 1 illustrates the structure and the operating principles of DDPSBP-LC. The structure consists of two ITO glass substrates, BPLC, dichroic dye molecules and polymer networks. The polymer networks locate in the disclination lines of the structure of the blue phase to stabilize the BPLC. The dye molecules are aligned with BPLC to form the structure of the double twist cylinders at  $V = 0$  as shown in Fig. 1(a). All the polarization of incident light experiences the same absorption with the average absorption coefficient ( $\alpha_{ave}$ ) which is  $[(\alpha_{\parallel} + 2\alpha_{\perp})/3]$ , where  $\alpha_{\parallel}$  is the absorption coefficient when the polarization of incident light is parallel to the long axis of dye molecules, and  $\alpha_{\perp}$  is when the polarization of incident light is perpendicular to the long axis of dye molecules. The DDPSBP-LC is in the dark state in reflective mode because of the light absorption and Bragg reflection. In Fig. 1(b), when the applied voltage ( $V$ ) is larger than critical voltage ( $V_c$ ), the blue phase structure tends to unwind and reorient parallel to the electric field locally. The dye molecules are rotated with the LC directors. As a result, the vertically realigned dye molecules with the same tilt angle result in the decrease of the polarization-independent light absorption and the unwind BPLC results in the decrease of Bragg reflection. The DDPSBP-LC is therefore in the bright state in reflective mode.

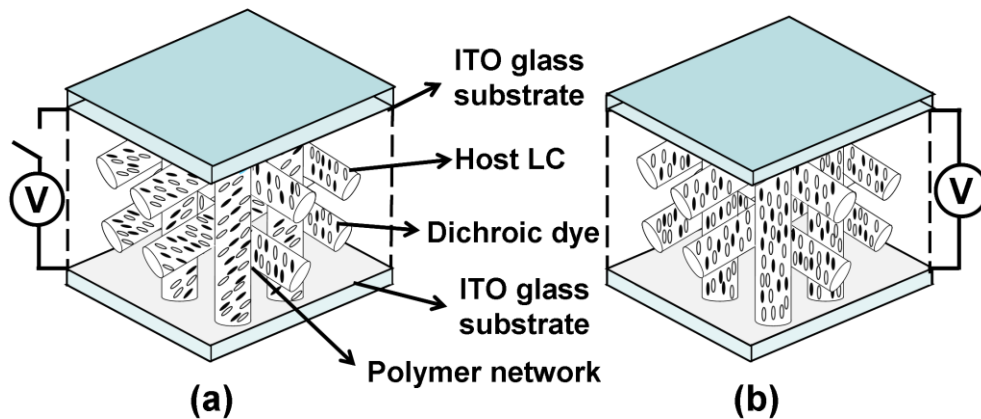


Fig. 1. The structure and operating principles of DDPSBP-LC at (a) voltage-off state, and (b) voltage on-state.

To prepare the sample of DDPSBP-LC, we mixed a positive nematic host LC ( $\Delta n = 0.142$ ) with two UV-curable monomers, EHA (2-Ethylhexyl, Fluka) and RM257 (Merck), a chiral molecules CB15 (Merck), dye molecules S428 (Mitsui Chemicals Inc.), and photo-initiator DMPAP (Aldrich) at 54.83: 2.86: 3.45: 36.69: 1.48: 0.69 wt% ratios. The mixture at isotropic state was filled into an empty LC cell consisting of two ITO glass substrates without any alignment layers with the cell gap of 7  $\mu\text{m}$ . We then cooled down the cell at the cooling rate of 0.1  $^{\circ}\text{C}/\text{min}$ , and the blue phase appeared at the temperature  $T < 34^{\circ}\text{C}$ . The cell was then exposed by UV light at 31.5  $^{\circ}\text{C}$  with intensity  $\sim 1.5 \text{ mW}/\text{cm}^2$  for 30 minute for photo-polymerization. After photo-polymerization, the DDPSBP-LC appeared blue phase when the temperature is between 20  $^{\circ}\text{C}$  and 40  $^{\circ}\text{C}$ .

### 3. Experiment and results

For the observation of the morphologies of DDPSBP-LC, we use a reflective polarizing microscopy to observe DDPSBP-LC with the temperature without an applied voltage. Figure 2 shows the morphologies of DDPSBP-LC at 24 $^{\circ}\text{C}$  and 38 $^{\circ}\text{C}$ . In Fig. 2, the mosaic structures of DDPSBP-LCs at 24 $^{\circ}\text{C}$  and 38 $^{\circ}\text{C}$  are similar, but the color is darker at 38 $^{\circ}\text{C}$  because the order of the optical activity of BPLC is temperature-dependent [10]. From the selective Bragg reflection of the Mozaic blue phase platelet structure, the averaged domain size of DDPSBP-LC is  $\sim 20 \mu\text{m}$ . The DDPSBP-LC reflects light strongly in blue regime owing to the Bragg reflection.

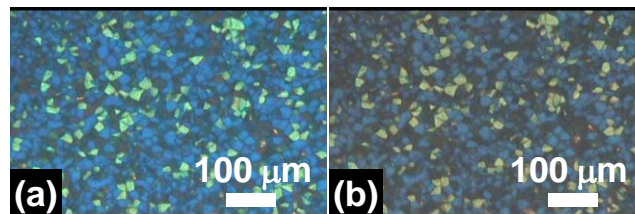


Fig. 2. The morphologies of DDPSBP-LC observing under a reflective polarizing optical microscopy at (a)24  $^{\circ}\text{C}$ , and (b) 38  $^{\circ}\text{C}$ .

To evaluate the electro-optical properties of DDPSBP-LC, we measured voltage-dependent reflectance of PSBP-LC under an unpolarized He-Ne laser (Melles Griot, Model 05-LGR-173,  $\lambda = 543 \text{ nm}$ ). A dielectric mirror was put behind the sample so that the laser beam double passed through the sample. The detector (New Focus Model 2031) was placed at 20 cm away from the DDPSBP-LC to recording the light reflectance. To calibrate the

substrate reflection losses, the reflectance of the BPLC at the isotropic state with the same cell gap is defined as unity. The measured results are shown in Fig. 3(a). In Fig. 3(a), the reflectance increases from ~21% to 68% with an applied voltage. The critical voltage ( $V_c$ ) is around  $20 V_{rms}$ . The contrast ratio (CR) is defined as a reflectance ratio of  $100 V_{rms}$  to  $0 V_{rms}$ . The measured CR is ~3.23:1. To make sure the polarization dependency, we also placed a polarizer in front of the sample and measured the voltage-dependent reflectance. The voltage-dependent reflectance at different polarization of incident light is shown in Fig. 3(a). The voltage-dependent reflectances are similar when we rotated the polarizer. That means the DDPSBP-LC is polarization independent. The slight difference in maximal transmittance in Fig. 3(a) is because the small polarization dependency of the unpolarized laser. Besides, the reflectance saturates at  $V > 100 V_{rms}$ . That is because LC molecules and dye molecules reorient almost parallel to the electric field. Figure 3(b) shows the electro-optical switch images of the DDPSBP-LC. The bottom ITO electrode was etched into a segmented number "8." For demonstration purpose, we placed a piece of white paper behind the bottom substrate to serve as a diffusive reflector. In Fig. 3(b), the voltage was  $100 V_{rms}$  in white regions and  $0 V_{rms}$  in dark regions. Since the electro-optical switch does not require a polarizer, the viewing angle is wide and the electro-optical switch is bright under room light condition. The DDPSBP-LC also shows the hysteresis when the voltage is ramped up (black solid line) and down (gray solid line), as shown in Fig. 3(a). That is because the polymer networks of DDPSBP-LC and the inherent property of BPLC. The hysteresis can be reduced by a different blue phase LC structure, such as BPII [11].

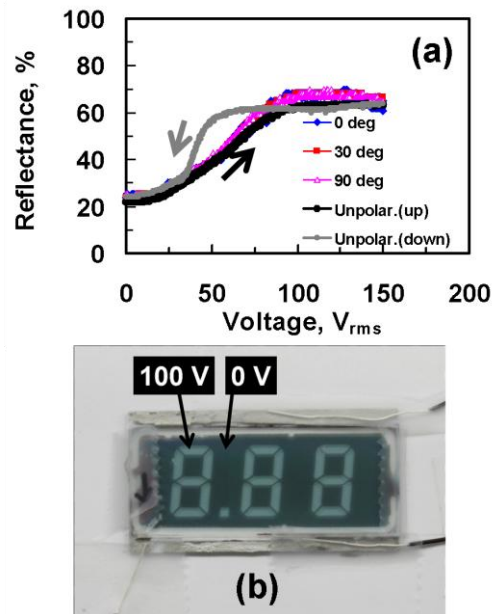


Fig. 3. (a) The voltage-dependent reflectance of DDPSBP-LC under an unpolarized light (black solid line), 0 degree linearly polarized light (blue diamonds), 30 degree linearly polarized light (red squares), and 90 degree linearly polarized light (pink triangles). The DDPSBP-LC shows the hysteresis when the voltage is ramped up (black solid line) and down (gray solid line). (b) Displayed image of the reflective polarizer-free electro-optical switch using DDPSBP-LC. Dye concentration: 2.5%. The voltage was  $100 V_{rms}$  at the white regions and  $0 V_{rms}$  at the dark regions. A white paper was placed behind the bottom substrate to act as a diffusive reflector.  $T = 24 ^\circ C$ .

The response time is also important for electro-optical switches. The measured response times are shown in Figs. 4(a) and 4(b). The rise time is ~1.16 ms which is the time difference when the reflection change from 0% to 90% as the voltage is switched from 0 to  $100 V_{rms}$ . The decay time is ~4.0 ms which is the time difference when the reflection change from 100%

to 10% as the voltage is switched from 100  $V_{rms}$  to 0. In Fig. 4(a), two-step response consisting of one short response time ( $\sim 0.04$  ms for rise time) and one long response time ( $\sim 1.12$  ms for rise time) is also observed. The reason why two-step response is might because the LC molecules bringing dye-molecules reorient first and then the lattice distortion occur. The response time for local reorientation of molecules is much faster than the response time of lattice distortion [12]. Compared to the typical response time of PSBP-LC less than 1 ms, the slower response time of our DDPSBP-LC is because of an locally unwinding of the blue phase structure to a homeotropic state [13]. To improve response time, we can increase the polymer concentration or decrease the pitch of DDPSBP-LC [14,15].

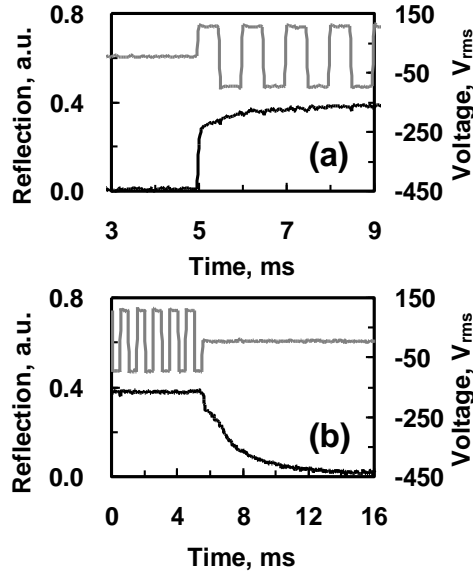


Fig. 4. The measured (a) rise time and (b) decay time of DDPSBPLC.  $T = 24$  °C.

## 5. Discussion

According to the Beer's law, the reflectance of the DDPSBP-LC at voltage-off ( $R_{off}$ ) and voltage-on ( $R_{on}$ ) states can be expressed as Eq. (1) and Eq. (2).

$$R_{on} = e^{-c \times \alpha_{\perp} \times 2d} \times B_v \quad (1)$$

$$R_{off} = e^{-c \times \frac{\alpha_{\parallel} + 2\alpha_{\perp}}{3} \times 2d} \times B_0 \quad (2)$$

where  $c$  is the concentration of dye molecules ( $\sim 1.5$  wt%),  $d$  is the cell gap ( $\sim 7$   $\mu\text{m}$ ),  $B_v$  and  $B_0$  are the reflectance resulting from Bragg reflection at voltage-on state and voltage-off states, respectively. In the experiments,  $\alpha_{\perp}$  is  $1.35$   $\mu\text{m}^{-1}$ ,  $\alpha_{\parallel}$  is  $11.07$   $\mu\text{m}^{-1}$ ,  $B_v$  is 99.6% and  $B_0$  is 54.9%.  $B_v$  and  $B_0$  were obtained by PSBP-LC. The CR then can be calculated from Eqs. (1) and (2)  $\sim 3.57$  which is slightly larger than the experimental result ( $\sim 3.23:1$ ). The reasons why the experimental result is slightly lower than the theoretical calculation is because: a) the order parameter of dye is low, b) the dye molecules are not completely perpendicular to the glass substrate at  $V \gg V_c$ , and c) some dye molecules are trapped by the polymer networks.

The order parameter ( $S$ ) of dye related to the absorption coefficient can be expressed as Eq. (3) [4].

$$S = \frac{\alpha_{\parallel}/\alpha_{\perp} - 1}{\alpha_{\parallel}/\alpha_{\perp} + 2} \quad (3)$$

The calculated  $S$  is 0.705 after putting the value of  $\alpha_{\perp}$  ( $\sim 1.35 \mu\text{m}^{-1}$ ) and  $\alpha_{\parallel}$  ( $\sim 11.07 \mu\text{m}^{-1}$ ) when we added dye of 1.5 wt% into the host LC of DDPSBP-LC. Compared to the order parameter ( $\sim 0.720$ ) for the dye of 1.5 wt% into nematic LC (E7),  $S$  is slightly smaller in host LC. We also calculated the  $\alpha_{\perp}$  and  $\alpha_{\parallel}$  in DDPSBP-LC by Eq. (1) and Eq. (2) and the reflectance at 0 and 100  $V_{\text{rms}}$ . The calculated  $\alpha_{\perp}$  is  $\sim 2.19 \mu\text{m}^{-1}$ ,  $\alpha_{\parallel}$  is  $\sim 8.82 \mu\text{m}^{-1}$ .  $\alpha_{\perp}$  is higher in DDPSBP-LC than in dye-doped host LC because the LC and dye molecules are not perfectly parallel to the electric field. Therefore, the CR is low in DDPSBP-LC.

On the other hand, the CR is lower than the polarizer-free electro-optical switch using dye-doped LC gels in Ref. 8 and Ref. 9. That is because the dark state in dye-doped LC gels results from the averaged absorption coefficient:  $(\alpha_{\parallel} + \alpha_{\perp})/2$  which is larger than the averaged absorption coefficient:  $(\alpha_{\parallel} + 2\alpha_{\perp})/3$  of the dark state in DDPSBP-LC. Therefore, the DDPSBP-LC has lower CR than dye-doped LC gels. To improve the CR, we can increase the order parameter of dye, the dye concentration, absorption of the dye, the cell gap, and Bragg reflection. Furthermore, we can enhance scattering effect into the DDPSBP-LC by increasing polymer concentration. However, the solubility is a problem when the dye concentration is higher than 2.5 wt% in our case, the reflectance at high voltage decreases with a large cell gap, and the driving voltage increases with a high polymer concentration.

## 6. Conclusion

In conclusion, we have demonstrated a reflective polarizer-free electro-optical switch using DDPSBP-LC. The mechanism is mainly the combination of electrically tunable light absorption and Bragg reflection. The CR is  $\sim 3.23:1$  and the response time is  $\sim 5.16$  ms at 100  $V_{\text{rms}}$ . We also discussed the reason and how to improve CR. To further reduce the driving voltage, we can adopt the host LC with high birefringence, large dielectric anisotropy ( $\Delta\epsilon$ ), and large ratio of bend elastic constant ( $K_{33}$ ) to splay elastic constant ( $K_{11}$ ) [16,17]. Besides, a large Kerr constant proportional to large dielectric anisotropy can also reduce the driving voltage because LC molecules can be locally oriented in a small electric field and the dye molecules is reoriented by LC molecules. We believe the polarizer-free electro-optical switch using DDPSBP-LC opens a window for many applications, such as light shutters, shutter glass of 3D displays, and electronic papers.

## Acknowledgments

The authors are indebted to Dr. Yung-Hsun Wu (Chimei-Innolux Corp.) and Prof. Long-Li Lai (National Chi Nan University) for discussions, and Prof. Hong-Cheu Lin (National Chiao Tung University) for the measurement of Differential Scanning Calorimetry. This research was supported by Chimei-Innolux Corp. and by the National Science Council (NSC) in Taiwan under the contract no. 98-2112-M-009-017-MY3.