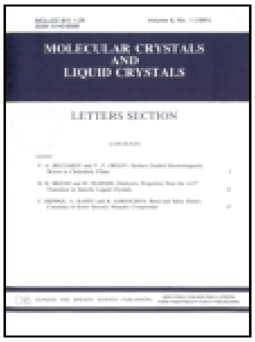

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Molecular Crystals and Liquid Crystals

ISSN: 1542-1406 (Print) 1563-5287 (Online) Journal homepage: http://www.tandfonline.com/loi/gmcl20

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To cite this article: Kuan-Chung Huang, Yun-Han Lee & Wei Lee (2015) Reflective Displays Based on Dye-Doped Bistable Chiral-Tilted Homeotropic Nematics, Molecular Crystals and Liquid Crystals, 617:1, 100-106, DOI: 10.1080/15421406.2015.1076332

To link to this article: http://dx.doi.org/10.1080/15421406.2015.1076332

Mol. Cryst. Liq. Cryst., Vol. 617: pp. 100–106, 2015
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ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2015.1076332

Reflective Displays Based on Dye-Doped Bistable Chiral-Tilted Homeotropic Nematics

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Bistable or multi-stable displays have been attracting a great deal of attention owing to the demand for energy-efficient mobile devices as well as the arousal of environmental concerns. One of the candidates with the merit of bistability is the bistable chiral tilted-homeotropic nematic mode which can easily switch between the twist-like and homeotropic-like stable states. Introducing dichroic dyes into this optically bistable system, we demonstrated a bistable-liquid-crystal-display mode without the need of polarizers. A proper mixture of dichroic dyes of blue, orange, red, yellow and cyan colors that evenly cover the visible spectral range was considered and the electro-optical performance of the resulting device was addressed in this study.

Keywords Liquid crystals; reflective displays; bistable displays; dyes

Introduction

Liquid crystals (LCs) are used as a ubiquitous display material in the current major display devices. However, the LC displays (LCDs) still have a problem of low light efficiency. The transmittance of a typical transmissive LCD suffers at least a 50% loss when the light goes through the first polarizer, and beyond that it has another one-third loss from the color filters. It remains a big challenge to improve the performance of LCDs at the increased panel size, prolonged battery life and reduced power consumption. For this reason, many different approaches have been proposed, such as the electrophoretic display (EPD) [1, 2], cholesteric LCD (ChLCD) [3], electrowetting display (EWD) [4, 5] and interferometric display (IMOD) [6].

The E-ink Company uses the EPD technology with the electric field to control charged particles having black and white colors on oppositely hemispherical sides. The flow under electric field can thus produce the dark and bright states, respectively [7, 8]. The ChLCD is a relatively well-known display technology with several different display modes being proposed, modes with polymer stabilization were also proposed, featuring desirably bistable characteristics [9]. The EWD exploits the wetting properties of a surface under an applied electric field. The solid-electrolyte contact angle is changed owing to an applied potential

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difference between the solid and electrolyte. On doping the electrolyte with different types of dyes, desired color display may be achieved. The IMOD can create various colors via interference of reflected light. The color is modulated by the electric field to tune the thickness of microscopic cavities.

In recent years, one of the bistable switching modes using a dual-frequency (DF) LC was proposed which is known as the bistable chiral tilted-homeotropic nematic (BHN) mode [10]. Encapsulating the DF-LC with a high pre-tilt angle ($\sim 70^\circ$) and a small cell-gap-to-pitch-length ratio $d/p \sim 1$, the BHN cell can switch between the tilted-homeotropic (tH) stable state and the tilted-twist (tT) stable state. The related stimulation results were calculated and reported elsewhere for the BHN system [11, 12]. In a typical guest–host LC display [13] functioning by the nature of mesogenic aligning of doped dichroic dyes, it is possible to eliminate the use of polarizers [14]. By doping dichroic dyes into a highly twist-aligning LC system, one can obtain a LCD mode that effectively absorbs light of any polarization, which leads to a higher contrast ratio without the need of any polarizer [15]. In this study, we proposed to dope dyes into a BHN cell to obtain a bistable, polarizer-free display with the merit of good energy efficiency. We believe that the dye-doped BHN system has the potential as a new display device in the future.

Experimental

BHN Cell Fabrication

A series of dye-doped BHN samples were fabricated with the tT state being the dark state and tH state being the bright state. The DF-LC employed is HEF951800-100 (HCCH, China) with extraordinary and ordinary indices of refraction $n_e = 1.718$ and $n_o = 1.496$ at 589 nm, 20°C, respectively. The DF-LC has a positive dielectric anisotropy below its crossover frequency f_c and a negative dielectric anisotropy at frequencies higher than f_c. We added the chiral agent S-811 (Merck) into the LC host to induce nematic twist and controlled *d/p* to be about 1. To achieve a pretilt angle of *ca.* 70°, we mixed two polyimides (PIs), SE150 (planar-alignment agent, Nissan, Japan) and AL-8395 (homeotropic-alignment agent, Daily Polymer, Taiwan), at different concentrations. At first, the PI mixture was spin-coated on pairs of 1.1-mm-thick glass substrates covered with indium–tin oxide (ITO). After soft bake at 80°C and 10 min. to evaporate the solvent, substrates were put into an oven at 200°C for 90 min. to induce cyclization. Upon cooling to room temperature, the substrates were sent to the rubbing machine, assembled and sealed with antiparallel configuration with a cell gap $d \sim 10\ \mu$m. To measure the pretilt angle from the substrate plane, we adopted the crystal rotation method as shown in Fig. 1(a). The measured pretilt angle was about 72° obtained from the transmittance minimum in the rotation-angle–transmittance curve as shown in Fig. 1(b). Without polarizers, the dichroic dyes used in this study are Blue (AB4), Orange (AZO1), Red (AR1), Yellow (AG1) and Cyan (AC1) (NEMATEL, Germany) at concentrations of 0.7, 0.6, 0.7, 0.6 and 0.7 wt%, respectively. The transmittance spectra of five single-dye-doped LC cells, as depicted in Fig. 2, were acquired with a high-speed fiber-optic spectrometer (Ocean Optics HR2000+) in conjunction with a halogen light source (Ocean Optics HL2000). An arbitrary function generator (Tektronix AFG 3022B) was exploited to supply the voltage pulses to switch between two arbitrary states of the BHN cell.

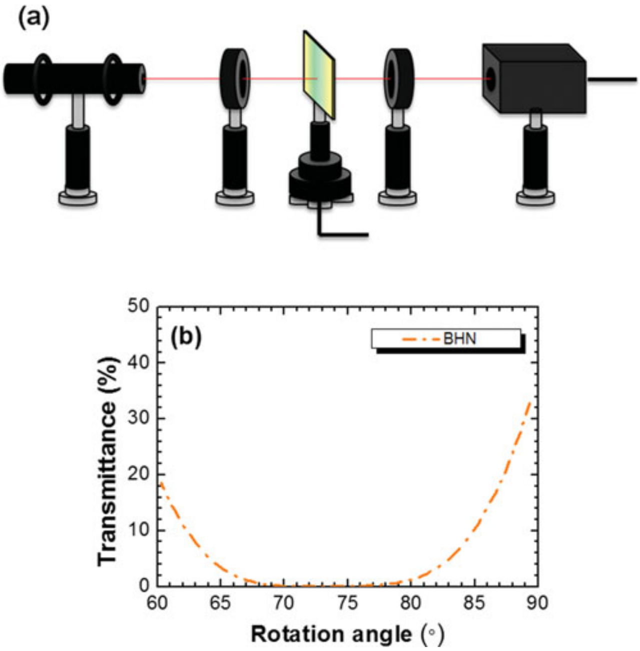

Figure 1. (a) The crystal rotation method setup for measuring the pretilt angle of a BHN cell and (b) the result of the angle–transmittance plot.

Measurements

Figure 3 illustrates the switching mechanisms of a dye-doped BHN as well as their photographs in the four states. When a 1-kHz 10-V_{rms} pulse is applied, the system is held in

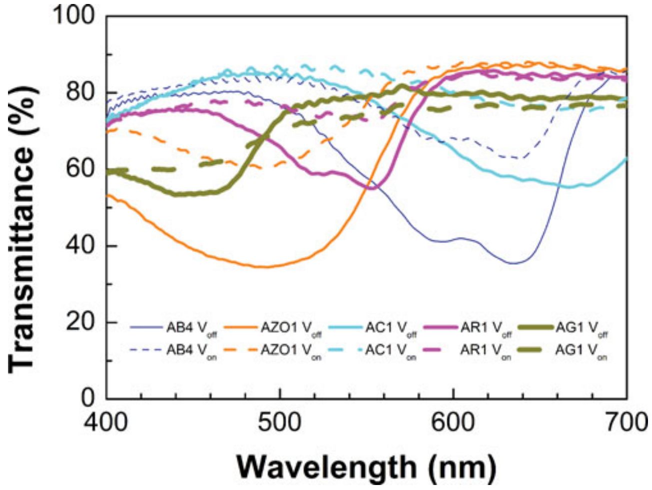

Figure 2. Transmittance spectra of 360°-twist chiral LC samples doped individually with 0.7-wt% AB4, 0.6-wt% AZO1, 0.7-wt% AC1, 0.7-wt% AR1 and 0.6-wt% AG1 under 10 V at 1 kHz (V_{on}) and 0 V (V_{off}). The cell gap is 10.0 ± 0.1 μm.

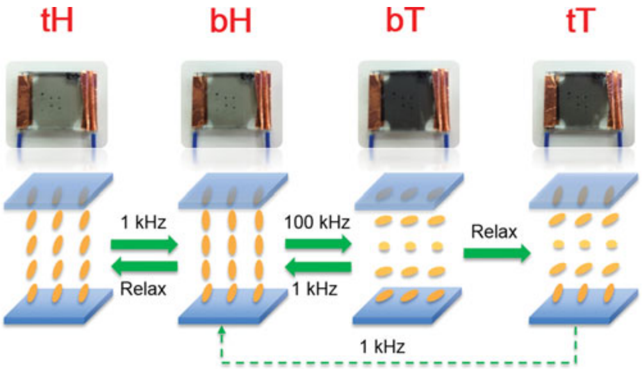

Figure 3. Configurations of the four states in a dye-doped BHN cell and the switching mechanisms.

the biased-homeotropic (bH) state with the highest transmittance. Removing the field leads to the relaxation to the stable tH state, which is the bright stable state. To achieve the dark state, a 10-V_{rms} pulse at 1 kHz is needed to switch the system to the bH state first. Instantly switching the frequency from 1 kHz to 100 kHz gives rise to the transit to the biased-twist (bT) state with the maximal absorbance due to the effect of the DF-LC. Upon releasing the field, the system degenerated to the stable tT state with lower absorbance. It is possible to apply the voltage at other frequencies to revert to the bright state and repeat the process as well.

Results and Discussion

Figure 4 shows the transmittance spectra of a dye-doped BHN cell in various states. In the bH state, all dye molecules are virtually aligned homeotropically with LC molecules; in this case, the absorption long axis is vertical to all polarizations so that the transmittance reaches its maximum. In the voltage-off tH state, dye molecules deviate from the normal

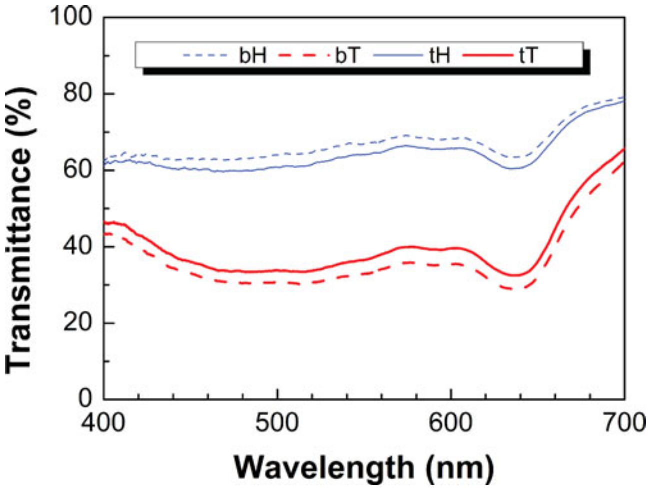

Figure 4. Transmittance spectra of a BHN cell doped with five dyes.

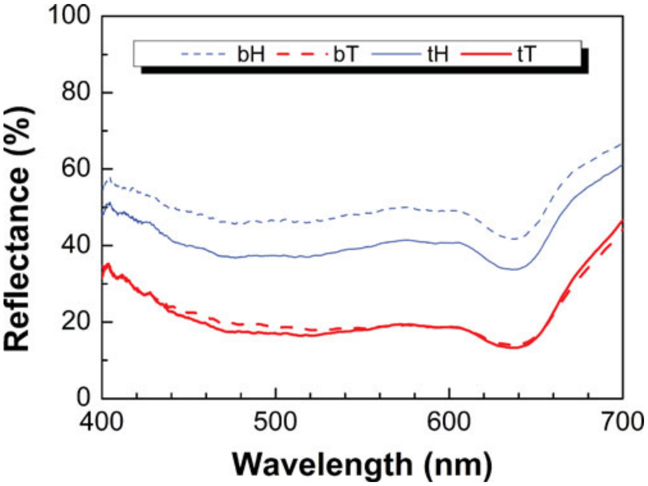

Figure 5. Reflectance spectra of a dye-doped BHN cell.

orientation owing to the tilted alignment and the transmittance is reduced. In the bT state, high absorption was observed due to dye molecules aligned in a twist configuration with the long axis nearly parallel to the polarization direction of a large fraction of the light. When switching to the stable tT state, the absorption ratio just slightly decreases in comparison with the voltage-sustained bT state. Accordingly, the transmittance can be bistably controlled by switching the cell between the tT and tH states. Moreover, one can presumably increase the pretilt angle to reduce the mesogenic-axis deviation from the bH state so as to further improve the transmittance in the tH state and, in turn, promote the overall contrast ratio.

Next, we investigated the reflectance spectra in different states for the BHN cell, as shown in Fig. 5. The performance is substantially in line with the transmittance spectra. As can be seen in the figure, the contrast ratio was very limited due to the low absorption of the tT and bT states. The contrast ratio obtained was roughly 3:1 at a wavelength around 500 nm. The small contrast can be attributed to the adiabatic following effect, the phenomenon that the polarization vector of the incident beam effectively follows the twist of the LC directors when the wavelength is far smaller than the pitch length.

To clarify the assumption, the polarization dependence of transmission in these four states was studied with a linearly polarized light at 500 nm where the sample has maximal absorbance. At different polarization angles, the transmittance with normally incident light is shown in Fig. 6. In the bT state, the transmittance increases with the polarization angle from 0° to 90°. Such dependency is a clear piece of evidence for the adiabatic following that occurs when a twisted-nematic system satisfies the following condition [16]:

$$\lambda << \Delta n \cdot \mathrm{d}, \tag{1}$$

where λ stands for the wavelength of incident light and Δn represents the LC's birefringence. The adiabatic following effect renders the light polarization to follow the long axis of LC molecules, which is also the long axis (absorption axis) of dye molecules. As a consequence, the absorption reaches maxima in 0° polarization, where the initial polarization direction is parallel to the rubbing direction. In the case with a non-zero polarization angle, the polarization nearly remains at the same angle with respect to the absorption axis throughout

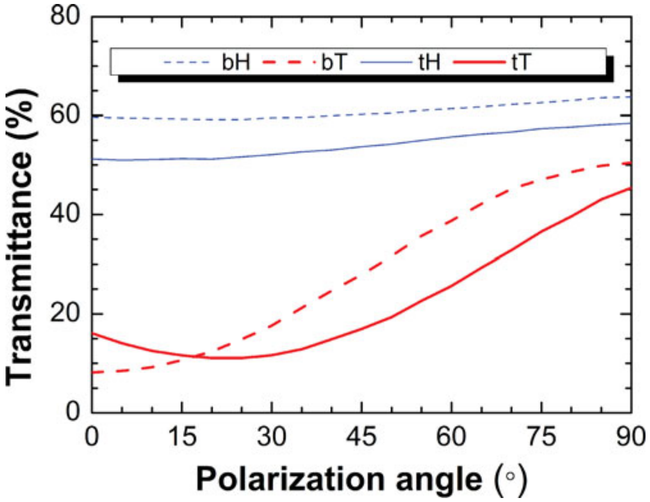

Figure 6. Polarization-angle dependence of transmittance at wavelength of 500 nm in four BHN states.

the light passage in the LC bulk. For 90° polarization, the polarization remains perpendicular to the absorption axis, resulting in the minimal absorption. As such, when unpolarized light is incident on the sample, only one polarization experiences high absorption despite the fact that the mesogen was in twist alignment, which explains the low absorption of in the tT and bT states. Notably in the tT state, the maximal absorption shifts from 0° to 25°. It can be understood as a result of the tilted alignment near the surface, which implies a reduced effective birefringence and a weak adiabatic following. In the weak adiabatic following, the incident light at 0° polarization does not follow tightly with the mesogen and the long axis of dye molecules and, thus, experiences reduced absorbance. At 25°, the initial offset in polarization compensated with the reduced rotation and the maximal absorbance was reached. In the bH state the transmittance almost has no change with respect to the polarization since the direction of dichroic dyes is nearly vertical to the substrate. The tilted alignment of tH state leads to a small polarization dependency of its absorption with the maximal absorption occurring along the rubbing direction. This polarization-dependent behavior indicates the possibility to further enhance the contrast ratio in the reflective mode by adding a retarding film to rotate the polarization by 90° before its second pass through the cell [17].

Concluding Remarks

In conclusion, we have demonstrated a polarizer-free reflective display mode by doping five dyes into a BHN system. Two optically bistable states, tH and tT, were achieved and can be used as bright and dark states, respectively. The other two voltage-sustained states, bH and bT states, can be used to generate the dynamic gray scale or enhance the contrast ratio. We found that the contrast ratio is limited to 3:1 even in the reflective mode, which we identified as a result of the adiabatic following through the study on polarization dependency. Possible improvements include refining material properties such as using dyes with a high dichroic ratio, and fine tuning systematic properties such as the pretilt angle and *d*/*p* value. It is also possible to enhance the contrast by adding a phase retarding film behind the cell in the reflective mode. With further development, we believe this low-power-consumption reflective display mode can finally reach a performance of practical usage.

Funding

This work was sponsored by the Ministry of Science and Technology, Taiwan, under grant Nos. NSC 101-2112-M-009-018-MY3 and NSC 103-2923-M-009-003-MY3.

References

[1] Isao, O. US Patent No. 3668106 A, issued 6/6/1972.

[2] Lin, Z.-P., Pan, H., Cheng, C.-M., & Bush, A. US Patent No. 6525866 B1, issued 2/25/2003.

[3] Sha, Y.-A., Liao, C.-C., & Wang, H.-L. US Patent 7505094 B2, issued 3/17/2009.

[4] Lippmann, M.-G. (1875). *Ann. Chim. Phys.*, *5*, 494.

[5] Hayes, R. -A., & Feenstra, B. J. (2003). *Nature*, *425*, 383.

[6] Gabtu, S, Khazeni, K., & Sampsell, J. US Patent 7944604 B2, issued 5/17/2011.

[7] Jacobson, J.-M. US Patent 6120588 A, issued 9/19/2002.

[8] Albert, J.-D., Comiskey, B., & Jacobson, J.-M., Zhang, L., Loxley, A., Feeney, R., Drzaic, P., & Morrison, I. US Patent 6262706 B1, issued 7/17/2011.

[9] Yang, D.-K., Lu, Z., & Doane, J.-W. US Patent 6061107 A, issued 5/9/2000.

[10] Hsu, J.-S., Liang, B.-J., & Chen, S.-H. (2004). *Appl. Phys. Lett.*, *85*, 5511.

[11] Hsu, J.-S., Liang, B.-J., & Chen, S.-H. (2006). *Appl. Phys. Lett.*, *89*, 051920.

[12] Liang, B.-J., & Lin, C.-L. (2007). *J. Appl. Phys.*, *102*, 124504.

[13] Heilmeier, G.-H., & Zanoni, L.-A. (1968). *Appl. Phys. Lett.*, *13*, 91.

[14] Cole, H.-S., & Kashnow, R.-A. (1977). *Appl. Phys. Lett.*, *30*, 619.

[15] White, D.-L., & Taylor, G.-N. (1974). *J. Appl. Phys.*, *45*, 4718.

[16] Yeh, P., & Gu, C. (2009). *Optics of Liquid Crystal Displays, 2nd ed.*, Wiley: New York.

[17] Lee, Y.-H., Huang, K.-C., Lee, W., & Chen, C.-Y. (2014), *J. Disp. Technol.*, *10*, 1106.