Low-Power Displays With Dye-Doped Bistable Chiral-Tilted Homeotropic Nematic Liquid Crystals

Yun-Han Lee, Kuan-Chung Huang, Wei Lee, and Chao-Yuan Chen

***Abstract*—Energy-efficient display has been drawing much attention in recent years due to the prevailing of mobile devices as well as the rising environmental concerns. A chiral nematic system with appropriately configured pre-tilted angle and pitch length is capable of switching between the twist-like and homeotropic-like states with the merit of bistability. Introducing dichroic dyes into this system, we demonstrated a bistable scheme of liquid-crystal display without the need of polarizers.**

***Index Terms*—Liquid crystals (LCs), reflective displays.**

I. Introduction

MOBILE devices, known for their convenience and powerful information transfer, are becoming indispensable in the next generation. Currently, most devices like smart phones and pads use liquid crystal (LC) with proper arrangement of the color filter and polarizers as display components. While having excellent quality, these light absorbing accessories lead to low energy efficiency and, in turn, short battery life. For this reason, different approaches have been proposed, and one of the most successful examples is electrophoretic ink [1], [2]. With the electrical control of two-sided microcapsules, it reaches high contrast, outstanding stability with acceptable response. However, ghost image of such devices makes it necessary to refresh the entire screen in black before carrying out the next frame, hence making it of poor user experience [3].

Well known for its polarizer-free potential, the dye-doped LC display mode, or the guest–host mode [4], [5], exploits the nature of molecular aligning and differential absorption. When dyes (guest) are introduced into liquid-crystal systems (host), the dominant axis of absorption is aligned at a certain angle with respect to the liquid-crystal molecular director, and the control of absorption can be achieved through the electrical control of the liquid-crystalline host. Proposed by White and Taylor, a system of highly twist-aligning dye-doped LC can absorb light polarized along all axes, thus eliminating the need of extra polarizers [6]. Recently, Lin *et al.* suggested a display mode utilizing such mechanism to bistably switch between the uniform lying helix phase and cholesteric phase with properly chosen chiral-dopant concentrations [7]. This method exhibits good contrast ratio (CR), large viewing angle as well as high stability. However, the switching between stable states requires high operation voltage (over 100 $\mathrm{V_{rms}}$) and thus prevents it from further application.

Another possible candidate for bistable switching display is the bistable chiral-tilted homeotropic nematic (BHN) mode. Utilizing dual-frequency LC, BHN is capable of switching between the tilted homeotropic state (tH) and tilted twist state (tT) when the cell configuration is optimized with d/p around one and the pretilt angle around 70° [8], [9]. While both the tT and tH states can stay at their configurations at zero applied voltage, the other two possible states are the biased twist (bT) and biased homeotropic (bH) states, which are sustainable under biased voltage. Reports of BHN has been focused on its stability [10]–[12], low operation voltage, fast switching, viewing angle as well as detailed energy calculation [13], [14]. In this study, we proposed to introduce dichroic dyes into a BHN system, therefore inducing the bright and dark states for the tH and tT states, respectively. We demonstrated that the bistable switching is applicable though with further improvements needed.

II. Experimental

The dichroic dyes used in this study are AB4, AZO1 and AC1 (NEMATEL), which appear blue, orange and cyan, respectively. A mixture of them roughly cover the visible wavelength region. Fig. 1 depicts the transmittance spectra of three 10-μm-thick, 360°-twisted antiparallel-aligned cells consisting separately of 0.8-wt% AB4, 0.6-wt% AZO1 and 0.7-wt% AC1 in LC in order to mimic the case in a typical BHN cell.

The dual-frequency nematic LC employed is HEF951800-100 (HCCH) with extraordinary and ordinary indices of refraction $n_{\mathrm{e}} = 1.718$ and $n_{\mathrm{o}} = 1.496$ at 589 nm, 20 °C, respectively. The chiral agent S-811 (Merck) was added to induce a nematic twist configuration with a cell-gap-to-pitch-length ratio $d/p \sim 1$. Pairs of 1.1-mm-thick glass substrates were coated with indium-tin oxide (ITO). A mixture of SE-150 (planar-alignment agent, Nissan) and AL-8395 (homeotropic- alignment agent, Daily Polymer) was spin-coated on the ITO substrates, which were subsequently rubbed in antiparallel and assembled to form empty cells of $\sim$9.6 μm in gap. The chiral-configured nematic host doped with a mixture of dyes; i.e., AB4, AZO1 and AC1 at concentrations of 0.6%, 0.7%, and 0.6 wt%, respectively,

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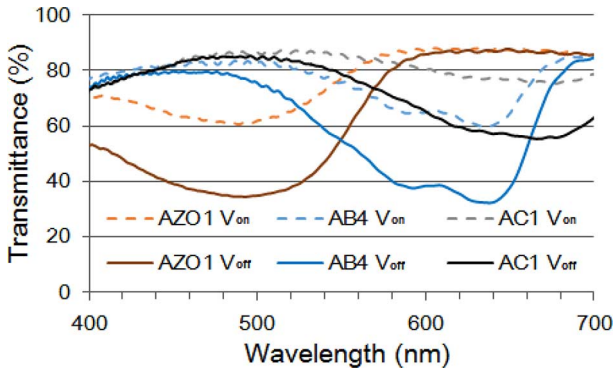

Fig. 1. Transmittance spectra of 360°-twist chiral LC samples doped individually with AB4, AO1 and AC1 at 0.8, 0.6 and 0.7 wt%, respectively, under a 1-kHz voltage of 10 V_{rms} and under zero applied voltage. The cell spacing is 10.0 ± 0.1 μm.

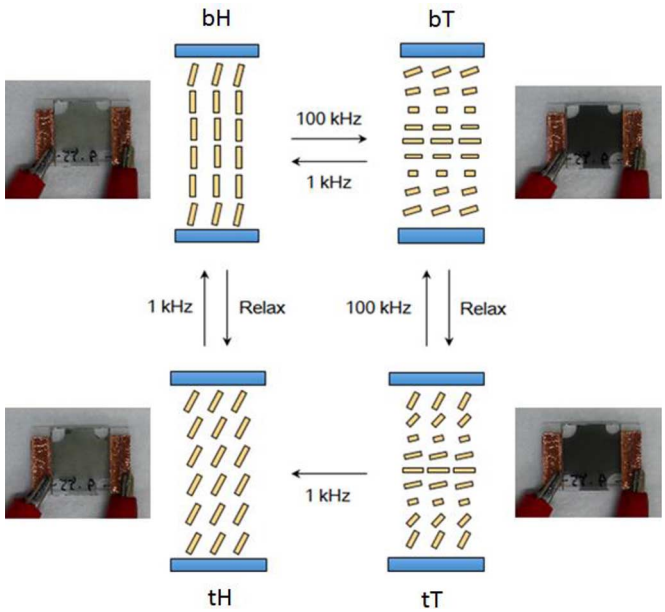

Fig. 2. Configurations of BHN molecules in the biased homeotropic (bH), biased twist (bT), tilted homeotropic (tH), and tilted twist (tT) states and the corresponding appearances of the cell. The switching is indicated by frequency onsets. The voltage involved is 10 V_{rms}. Photos were taken with a sheet of paper under the dye-doped BHN sample. No modification with any photographic or image processing software is applied.

was then injected into the cell by capillary action. The resulting pretilt angle was 70° measured from the substrate plane.

The transmission spectra 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 provide the pulses needed to switch between four states of BHN.

III. Results and Discussion

Fig. 2 shows the switching mechanisms of a dye-doped BHN as well as their real appearances in the four states. Applying 10 V_{rms} at 1 kHz, the system will be held at bH with the highest transmittance. The release of the field leads to the relaxation to the stable tH state, which is of reduced transmittance. A direct switching from the bright tH to bT or tT is not applicable. To

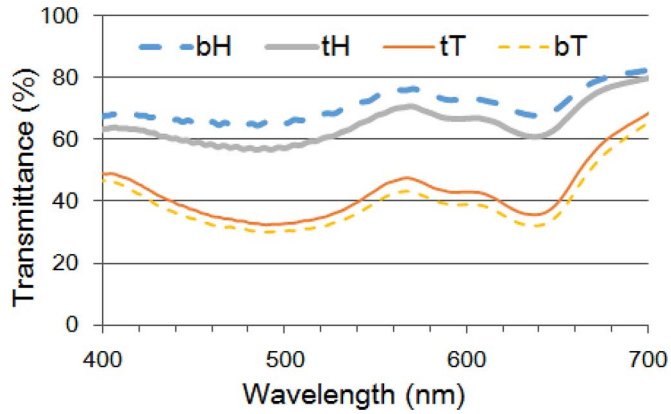

Fig. 3. Transmittance of the dye-doped BHN sample in different states.

promote to the dark bT state from the tH state, a short pulse of 10 V_{rms}, 1 kHz is needed to first boost the system to the bH state. Immediate agitation by a 10 V_{rms}, 100 kHz pulse holds the system in the absorbing bT state, and after releasing the field one obtains the tT state with roughly the same absorbance. Detailed switching mechanism and physical explanation can be found in [9]. Fig. 3 shows the transmittance of each state without any polarizer. In the bH state, where dyes are aligned normally to all polarizations, transmittance reaches the maximum. In the voltage-free tH state, however, the chiral-tilted alignment deviates from the normal, giving rise to reduced transmittance. In the tT state, the transmittance is further reduced since most of the nematic molecules, as well as dichroic dyes, are aligned in a twist fashion that yields high absorbance. The same holds for the bT state with a slightly increased absorbance for its suppressed tilt angle near the surface. This indicates that, with an improved configuration of higher pretilt angle, the transmittance in the bright stable state (tH) can be further improved. As the pretilt angle increases, a higher d/p ratio is required to maintain a bistable system [14]. This can lead to higher absorbance in the dark stable state (tT), for at a higher d/p ratio, one has more fraction of molecules aligning normal to the incident light.

We then investigated the polarization-angle dependence of transmission in the tT and bT states with a linearly polarized light at 500 nm where the orange dye AZO1 has maximal absorbance. At different polarization angles θ, transmittance at normal incidence is shown in Fig. 4. One can see that, for the bT state, the transmittance has its minimum as the polarization is nearly parallel to the rubbing direction (i.e., $\theta = 0°$). The transmittance grows with increasing θ and reaches maximum at near 90°. This can be understood as a result of adiabatic following, which is the main mechanism for the prevailing twisted nematic display mode. When a twisted nematic system satisfies the condition [15]:

$$\lambda \ll \Delta n \cdot d \tag{1}$$

where λ, Δn and d stand for the wavelength, birefringence and cell gap, respectively, the incident polarized light experiences a phase change that gives a net result of an effective rotation in its polarization at a fixed angle to the nematic director. When dye exists in such system, one may separate the incoming polarized light into parallel and perpendicular components with respect

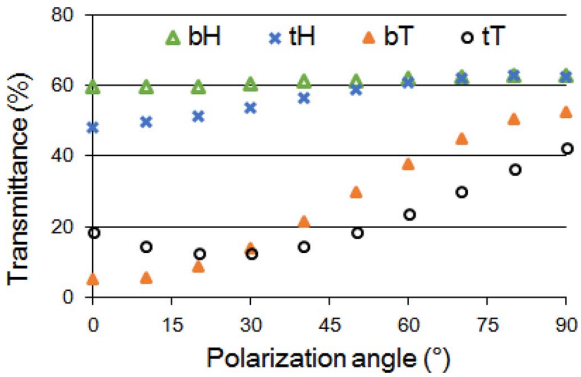

Fig. 4. Normalized transmittance varying with the polarization angle of the incident light in different states. The transmittance (at $\lambda = 500$ nm) is normalized to that obtained when the sample is removed.

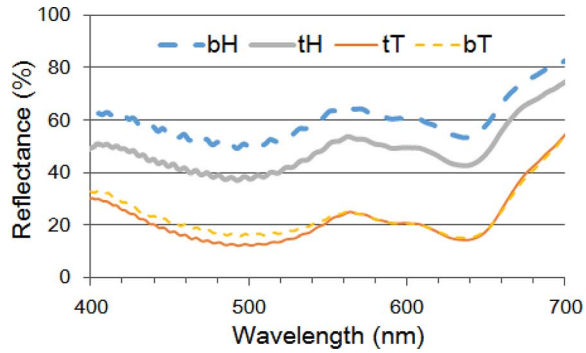

Fig. 5. Reflectance of the dye-doped BHN sample in different states.

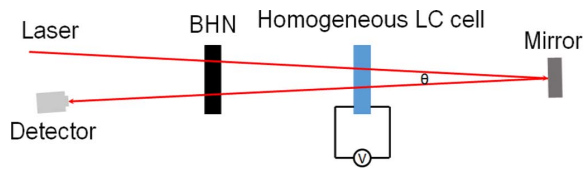

Fig. 6. Schematic setup to demonstrate a possible method to enhance the contrast ratio. The homogeneous LC cell was placed between BHN and the mirror. The rubbing direction was at 45° with respect to BHN cell. The laser wavelength used in the experiment was 632.8 nm. $\theta \sim 5°$.

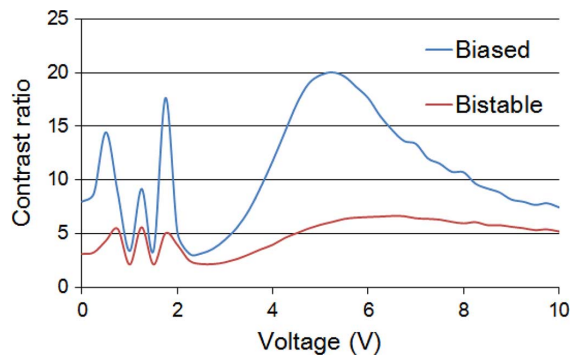

Fig. 7. Contrast ratio of the biased states (the reflectivity ratio of bH to bT) and the bistable states (the reflectivity ratio of tH to tT) as a function of the applied voltage across the homogeneous cell as a phase retarder. The contrast ratio was enhanced to 6.6 for the bistable case at 6.50 V_{rms}.

to the rubbing direction. Since the maximal absorbance axis of dyes is along the LC director in this work, the parallel component experiences the maximal absorbance, and the opposite is true for the perpendicular component. In the bT case, the adiabatic following rotates the polarization by 360° while the mesogenic long axis is parallel to the maximal absorption of dye because of the adiabatic following. The maximal absorption thus occurs at 0°. On the other hand, the tilted alignment near the surface in the tT case results in a reduced absorption of dichroic dye as well as a smaller effective birefringence that violates the adiabatic following condition. When the polarization angle is 0°, the weak adiabatic following deviates the polarization from the maximal absorbing axis over the cell, and thus the maximal absorption shifts from 0°. In the bH state, the molecules are aligned nearly normal to the substrate, giving rise to the minimal absorption. In comparison, the absorption in the tH state is slightly larger, possessing polarization dependency due to the slight tilt of the molecules from the rubbing direction. The differential absorbance of polarized light suggests that when employed in the reflective mode, the absorbance at twist state can be further enhanced with a wave plate (e.g. a quarter-wave plate) that rotates the polarization so the reflected light may experience the maximal absorbance again.

Next, to evaluated reflective spectra in different states, we placed a mirror behind the sample and measured the reflectance at an incident angle of 5° with results shown in Fig. 5. The behavior mostly agrees to the transmissive case; however, as one can see, the tT state actually has slightly lower reflectance than does the bT state in the blue-to-green spectral region. The average CR between the bistable tH and tT states for 500-nm light is determined to be 3.1.

Based on the fact that the absorption of a dye-doped BHN cell was polarization-dependent, here we demonstrate the possibility to enhance the CR in reflective mode by placing a 5.5-μm homogeneous cell between the BHN cell and a mirror. This homogeneous cell acted as a retarding plate that modified the polarization profile of the reflected light to maximize the anisotropic absorption. The homogeneous cell was infiltrated with E7 and the rubbing direction was at 45° with respect to the BHN cell. A 632.8-nm unpolarized laser was used with an angle of incidence $\sim 5°$. The schematic setup is shown in Fig. 6. The CRs between the biased states (the reflectivity ratio of bH to bT) and the bistable states (the reflectivity ratio of tH to tT) at different applied voltages on the homogeneous cell are shown in Fig. 7. For biased states, the CR was improved to 20.0 at an applied voltage of 5.25 V_{rms}, while the CR of the bistable states was enhanced to 6.6 at 6.50 V_{rms}.

IV. Conclusion

In summary, a polarizer-free display mode is proposed. We show that by introducing dyes into a dual-frequency chiral LC host with properly tuned pretilt angle and d/p value, a bistable display system can be realized. Such system consists of two stable states, tT and tH, functioning as the dark and bright states, respectively. The other two voltage-sustained states, bH and bT, may be used to increase contrast when necessary. The spectra of these states are presented. The polarization nature of the system was studied as well. We found that the absorption maximum occurs at a larger polarization angle in the tT state whereas it

reaches the maximum in the bT state when the polarization of incoming light is parallel to the rubbing direction. This finding can be well explained by the adiabatic following effect. The reflective spectra were measured and a CR of 3.1 was determined. We further demonstrated the possibility to enhance this contrast by using a homogeneous LC cell as a retarding plate to modify the polarization profile. The contrast in the reflective mode can reach 6.5 in a suited setting. The addition of a properly designed wave plate, refined BHN parameters (pre-tilt angle and d/p value), and optimized dye mixtures may also help to improve the contrast. Most essentially, dyes having larger dichroic ratios should be considered to replace those adopted in this work. This study opens the door to a new reflective display mode that features low power consumption due to its characteristic optical bistability.

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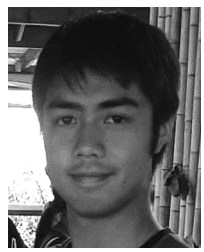

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