Electro-optic properties of a homeotropic liquid crystal cell with 90° surface rubbings and a reverse-handed chiral dopant

Ju-Hyun Lee, Zhibing Ge, and Shin-Tson Wu[a)]
College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816

(Received 7 April 2007; accepted 21 April 2007; published online 14 May 2007)

The electro-optic properties of a 90° twisted-homeotropic liquid crystal (LC) cell with a chiral dopant whose handedness is opposite to the LC twist are studied. In the voltage-off state, the LC directors exhibit a homeotropic alignment. However, in the intermediate voltage state, the bulk LC directors behave like a homogeneous alignment due to the balanced torques between the electric field, surface anchoring, and reversed chiral dopant. Potential applications of this mode for liquid crystal displays, especially for dual-cell-gap transflective liquid crystal displays, are emphasized. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2739412]

The 90° twisted-nematic (TN) liquid crystal (LC) cell[1] has been widely used for notebook computers because of its simple fabrication process, high optical efficiency, and weak color dispersion. The weak color dispersion originates from the polarization rotation effect of the twisted LC directors.[2] However, its contrast ratio and viewing angle are limited. To widen viewing angle, a special discotic phase compensation film has been developed.[3] For large screen liquid crystal display (LCD) televisions, high contrast ratio and wide view are important. To achieve these goals, multidomain vertical alignment (MVA) mode (note that VA is originally called homeotropic alignment)[4] has been developed.[5,6] The MVA mode exhibits an excellent dark state which is insensitive to the cell gap, wavelength, and temperature. However, due to the birefringence effect the color shift of a MVA LCD at oblique angles becomes an important issue. Efforts to minimize color shift are being actively pursued.

The electric field-induced TN structure in a VA cell has been developed to combine the advantages of a VA mode for high contrast and a TN mode for weak color dispersions.[7–11] For simplicity, let us call this mode as chiral homeotropic (CH) cell. The CH cell is realized by doping a small amount of chiral compound to a negative dielectric anisotropy ($\Delta\varepsilon$) LC in a homeotropic cell. In the voltage-off state, the LC directors are aligned nearly perpendicular to the substrates (except for a small pretilt angle) in spite of the existence of the chiral dopant. The alignment layers on the top and bottom substrates are rubbed in orthogonal directions. As a result, this boundary condition induces a twisted structure upon the LC directors when the applied voltage exceeds a threshold (V_{th}). The chiral dopant is chosen so that its induced twist direction is the same as that induced by surface rubbing. However, the polarization rotation effect of the chiral homeotropic cell is weaker than that of a TN cell because its boundary layers are aligned perpendicular to the substrates. Therefore, for the CH cell to achieve similar polarization rotation effect to a TN cell would require a much thicker cell gap which results in a longer response time.

In this letter, we demonstrate a modified CH mode to overcome the drawbacks observed in the conventional CH mode. Different from the conventional CH mode, our mode uses a chiral dopant whose helical sense is reversed to that of the LC twist induced by surface rubbings. For simplicity, hereafter we call this mode as reversed chiral homeotropic (R-CH) mode. Due to the reversed sense of the chiral dopant, our R-CH mode shows several attractive features. For instances, its voltage-off state between two crossed polarizers is as dark as that of a VA cell and its voltage-on state ($V < 3\ \text{V}_{\text{th}}$) is like a homogeneous cell. A good dark state leads to a high contrast ratio and enriched phase retardation leads to a thinner cell gap which, in turn, reduces the response time. Moreover, when the R-CH mode is used in a dual-cell-gap transflective LCD,[12] its voltage-dependent transmittance (VT) and voltage-dependent reflectance (VR) curves overlap very well.

In order to examine the electro-optic characteristics of the R-CH mode, we performed numerical simulations and compared results with those of TN, VA, and CH modes. The LC material used in the simulations is ZLI-2293 for TN and MLC-6608 for VA, CH, and R-CH modes. Table I summarizes the parameters used in the simulations. The negative sign in d/p (cell gap/chiral pitch length) means that the twist direction of the LC director exerted by the chiral dopant is opposite to that induced by the surface rubbings. During simulations, we used MATLAB codes based on the finite element method to calculate the one dimensional static LC directors profile and extended Jones matrix method[13] to calculate the voltage-dependent transmittance and reflectance of our transflective LCD.

Figures 1(a) and 1(b) show the LC twist angle (the tilt angle is similar to those of a CH cell[11] and not shown here) under various operation voltages for the conventional CH mode and the R-CH mode, respectively. The threshold voltage of the cells is about 2.1 V_{rms}. In the CH mode [Fig. 1(a)] the LC twist angle increases monotonously along the cell gap direction. However, in the R-CH mode, besides the boundary regions the twist angle stays at 40°–50° in the bulk region when the applied voltage is between 2.2 and 6.0 V_{rms} which is $\sim 3\ \text{V}_{\text{th}}$. Therefore, in this voltage range the R-CH cell behaves like a homogeneous cell. This effect originates from the balanced torques from the electric field, twisting power of the chiral dopant, and the surface anchoring energy of the orthogonal boundary alignment layers. In the high voltage regime, the electric field is so strong that the chiral effect becomes less significant. Under such a circumstance, the LC directors are governed mainly by the electric field and sur-

a)Electronic mail: swu@mail.ucf.edu

 © 2007 American Institute of Physics
Downloaded 14 May 2007 to 132.170.55.113. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

TABLE I. LC and cell parameter used for computer simulations.

LC mode	TN	VA, CH, R-CH
LC materials	ZLI-2293	MLC-6608
Elastic constant $[K_{11}, K_{22}, K_{33}]$ (pN)	[12.5, 7.2, 17.9]	[16.7, 7.0, 18.1]
Dielectric constants $[\epsilon_{\text{para}}, \epsilon_{\text{perp}}]$	[14.1, 4.1]	[3.6, 7.8]
Refractive indices (λ=550 nm) $[n_o, n_e]$	[1.6312, 1.4880]	[1.5578, 1.4748]
Cell gap (transmissive part) d	3.3 μm	5.0 μm for VA and R-CH 5.0, 6.0, and 7.0 μm for CH
d/p (p: helical pitch)	+0.25	0 for VA, +0.25 for CH, and −0.25 for R-CH
Rubbing direction (bottom/top)	$0°(+x \text{ axis})/90°(+y)$	0°/90° for CH and R-CH 0°/180° ($-x$) for VA
Optic axis of polarizer (bottom/top)	0°/90°	0°/90° for CH and R-CH 45°/135° for VA
Pretilt angle (θ)	2°	88°
Anchoring	Strong anchoring in all the cells studied	

face anchoring effects. As a result, the twist angle increases monotonously along the cell gap direction, as shown in Fig. 1(b).

In the voltage-off state, the R-CH cell behaves like a VA cell so that its dark state is excellent. In the 1 $V_{\text{th}} < V < 3\ V_{\text{th}}$ region, as shown in Fig. 1(b), the bulk region behaves like a homogeneous cell. By contrast, from Fig. 1(a) the conventional CH cell has a continuous twist across the cell gap. Therefore, the R-CH cell exhibits larger phase retardation than the CH cell for a given $d\Delta n$ value. This effect is clearly illustrated in Fig. 2.

Figure 2 shows the VT curves of three CH cells with d =5, 6, and 7 μm and a R-CH cell with d=5 μm. In the low voltage region, both cells exhibit vertical alignment so that their dark state is excellent at normal incidence. As the voltage exceeds a threshold voltage ($V_{\text{th}} \sim 2.1\ V_{\text{rms}}$), the transmittance starts to increase. For the CH cells, it takes $\sim 7\ \mu$m to reach the 100% transmittance as compared to 5 μm for the R-CH cell. This is because the R-CH cell exhibits more birefringence effect than the CH cell. Due to the thinner cell gap requirement for the R-CH cell, its response time is faster than the corresponding CH cell.

This enriched birefringence effect of the R-CH cell makes it suitable for transflective liquid crystal display (TR-LCD) applications using dual cell gaps.[14] In a TR-LCD, each pixel is divided into two subpixels: one for transmission and another for reflection. In the transmissive mode, the backlight passes through the LC layer once while in the reflective mode the ambient light traverses the LC layer twice. To balance the phase retardation, the cell gap for the reflective pixels is made to be one-half of that of the transmissive pixels.

Figure 3 shows the normalized transmittance and reflectance of a TR-LCD using dual cell gaps under crossed *circular* polarizers. The surface reflections of all the optical components and absorption of polarizers are neglected. In a

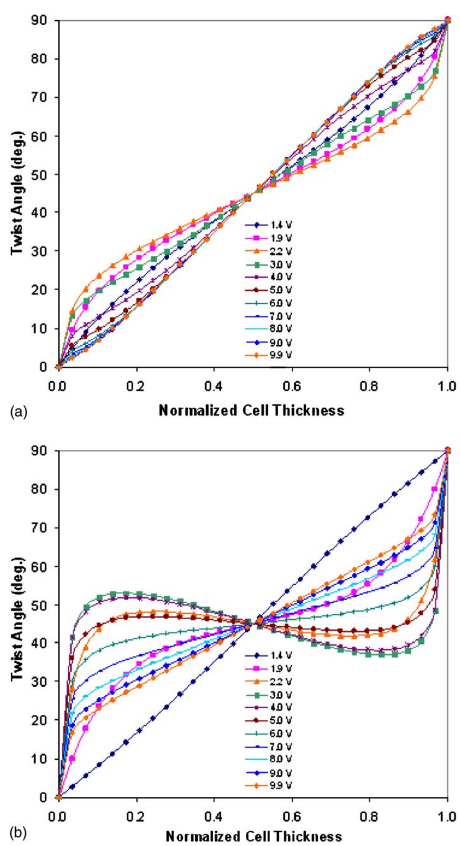

FIG. 1. (Color online) Director profiles (twist angle) under various operation voltages in (a) the conventional chiral homeotropic mode and (b) the reverse chiral homeotropic mode.

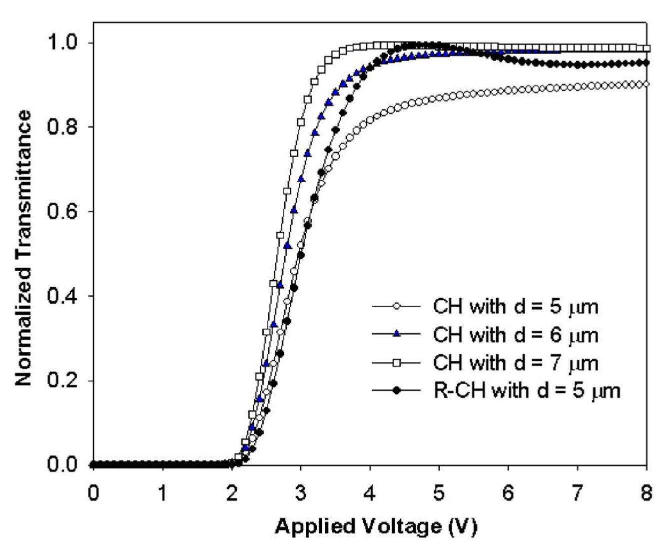

FIG. 2. (Color online) Transmittance curves of the conventional CH mode with different cell gaps compared to the transmittance curve of the R-CH mode. The LC cells are sandwiched between two crossed linear polarizers.

Downloaded 14 May 2007 to 132.170.55.113. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp

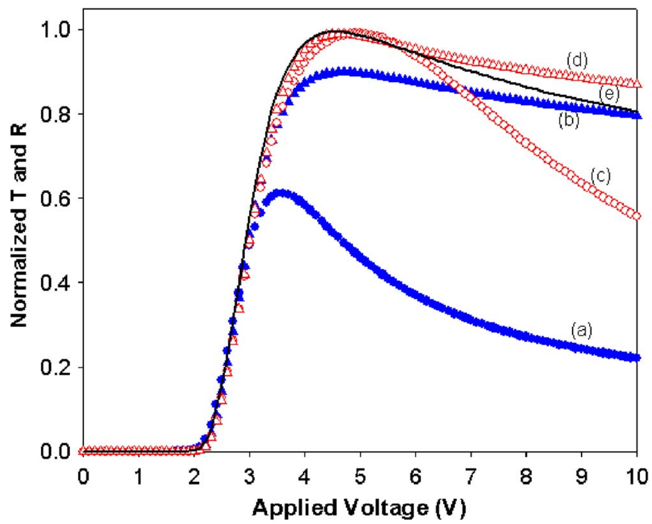

FIG. 3. (Color online) Normalized transmittance and reflectance curves of four LC modes as a function of operation voltage: (a) CH: VT curve (filled circle), (b) CH: VR curve (filled triangle), (c) R-CH: VT curve (open circles), (d) R-CH: VR curve (open triangles), and (e) VA: overlapped VT and VR curves (solid line).

TR-LCD, a broadband circular polarizer is commonly used in order to obtain a high contrast ratio for the reflective mode. Three LC modes CH, R-CH, and VA are compared here. Their VT and VR curves are labeled as [(a) and (b)], [(c) and (d)], and (e), respectively. For the VA cell shown in Fig. 3(e), the VT and VR curves overlap exactly because of the double cell gaps employed. From Figs. 3(a) and 3(b), the VT and VR curves of the CH cell-based TR-LCD do not reach 100%. This is attributed to the twisted LC directors and circular polarization employed. The polarization rotation effect of a TN cell works well for a linearly polarized light but not well for a circularly polarized light.[15] As a result, the twisted structure of the LC layer under crossed circular polarizers decreases the obtainable maximum transmittance and reflectance. On the other hand, the R-CH cell behaves like a homogeneous cell in the voltage-on state. Thus, its VT and VR curves overlap quite well below $V \sim 6\ V_{rms}$. Above $6\ V_{rms}$, the transmittance decreases faster than the reflectance, similar to the CH mode. This result can be explained from the LC director profile which goes back to the twisted structure, as shown in Fig. 1(b). In other words, in the R-CH cell, the birefringence effect is dominant in the low voltage regime while the twist effect reigns in the high voltage regime.

It is known that birefringence effect has larger color dispersion than the polarization rotation effect.[15] Thus, the VA cell would exhibit the largest color dispersion, then R-CH cell, CH cell, and finally TN cell. To verify this intuition, we compare the color dispersion of these four LC configurations in transmissive modes without using any compensation films. Under normal incidence of a standard white light, we calculated the color values, x and y, of the transmitted light as a function of operation voltage ranging from 0 to 10 V and plotted the results on the Commission Internationale de l'Eclairage (CIE) color coordinate.

As expected, the TN mode shows the weakest color variation which is inherited by the polarization rotation effect. In contrast, the VA mode which uses pure birefringence effect shows the largest color variation because of its pure birefringence effect. The conventional CH mode shows a slightly larger color variation than the TN mode. In a CH mode, the voltage-on state has a surface region where the LC directors are not perfectly switched due to the surface anchoring force. These boundary layers contribute to the birefringence effect more than the polarization rotation effect. While in a TN cell, the surface regions contribute to waveguiding effect more than birefringence effect. The color variation of the R-CH mode lies between the CH mode and the VA mode. Therefore, the R-CH mode has weaker color dispersion than the commonly employed VA cell in a TR-LCD.

Wide view angle is another important requirement for TR-LCDs. The viewing angle of the single-domain TN, VA, CH, or R-CH cells is inadequate and thus four domains have to be considered.[16] The VA cell is known to have a much higher contrast ratio than TN. Among the VA, CH, and R-CH cells compared, the VA cell requires the thinnest cell gap. Thus, its response time is the fastest, provided that the same LC material is employed. Nevertheless, its color dispersion is the strongest. On the other hand, the CH cell exhibits the weakest color dispersion, but its cell gap is the thickest. Therefore, the R-CH cell presents a good compromise between response time and color dispersion.

In conclusion, we have demonstrated a twisted-homeotropic cell with reverse-handed chiral dopant. Its voltage-off state is like a VA cell and voltage-on state like a homogeneous cell. Its advantage over the TN, VA, or conventional chiral homeotropic cells is higher contrast ratio, weaker color dispersion, and smaller cell gap, respectively. This operation mode is particularly attractive for transflective LCDs employing dual cell gaps.

The authors are indebted to the financial support from Chi Mei Optoelectronics.

[1] M. Schadt and W. Helfrich, Appl. Phys. Lett. **18**, 127 (1971).
[2] D. K. Yang and S. T. Wu, *Fundamentals of Liquid Crystal Devices* (Wiley, New York, 2006).
[3] H. Mori, J. Disp. Technol. **1**, 179 (2005).
[4] M. F. Schiekel and K. Fahrenschon, Appl. Phys. Lett. **19**, 391 (1971).
[5] Y. Koike and K. Okamoto, Fujitsu Sci. Tech. J. **35**, 221 (1999).
[6] H. Kim, J. Song, S. Park, J. Lyu, J. Souk, and K. Lee, J. Soc. Inf. Disp. **1**, 3 (2000).
[7] F. Ogawa, C. Tani, and F. Saito, Electron. Lett. **12**, 70 (1976).
[8] D. de Rossi and J. Robert, J. Appl. Phys. **49**, 1139 (1978).
[9] S. W. Suh, S. T. Shin, and S. D. Lee, Appl. Phys. Lett. **68**, 2819 (1996).
[10] J. S. Patel and G. B. Cohen, Appl. Phys. Lett. **68**, 3564 (1996).
[11] S. T. Wu, C. S. Wu, and K. W. Lin, J. Appl. Phys. **82**, 4795 (1997).
[12] M. Okamoto, H. Hiraki, and S. Mitsui, U.S. Patent No. 6,281,952 (August 28, 2001).
[13] A. Lien, Liq. Cryst. **22**, 171 (1997).
[14] X. Zhu, Z. Ge, T. X. Wu, and S. T. Wu, J. Disp. Technol. **1**, 15 (2005).
[15] S. T. Wu and D. K. Yang, *Reflective Liquid Crystal Displays* (Wiley, New York, 2001).
[16] R. Lu, X. Zhu, S. T. Wu, Q. Hong, and T. X. Wu, J. Disp. Technol. **1**, 3 (2005).

Downloaded 14 May 2007 to 132.170.55.113. Redistribution subject to AIP license or copyright, see http://apl.aip.org/apl/copyright.jsp