Electro-optical characteristics of a chiral hybrid in-plane switching liquid crystal mode for high brightness

Jin Seog Gwag[1], **Kyunghwa Sohn**[1], **Young-Ki Kim**[2], **and Jae-Hoon Kim**[1,2,3*]

[1]*Research Institute of Information Display, Hanyang University, Seoul 133-791, Korea*
[2]*Department of Information Display, Hanyang University, Seoul 133-791, Korea*
[3]*Department of Electronics and Computer Engineering, Hanyang University, Seoul 133-791, Korea*
[4]*School of Electrical Engineering, Pusan National University, Busan 609-735, Korea*
jhoon@hanyang.ac.kr

Abstract: We propose a new in-plane switching (IPS) nematic liquid crystal (LC) mode which uses a twist effect with a hybrid LC alignment and interdigitated electrodes as an approach for a high brightness. This is optimized to a normally white mode to minimize loss of transmittance at the electrode compared to the conventional IPS mode. The proposed mode shows an excellent dark state because the bulk LCs are aligned in parallel to the optic axis of the polarizer under low electric fields. Consequently, this proposed mode exhibits a much higher contrast ratio (980:1) than that of the conventional IPS mode (550:1).

OCIS codes: (230.0230) Optical devices; (230.3720) Liquid-crystal devices.

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1. Introduction

Electrically-controlled optical anisotropy of the liquid crystal (LC) at each pixel on liquid crystal displays (LCDs) can control the intensity of light from the backlight by modulating the polarization of the light. Electro-optical effects such as contrast ratio, response time, and viewing angle depend mainly on the configuration of the LC molecular alignment between electrodes. Several types of LCD modes, which are determined by these initial configurations, have been proposed, including twisted nematic (TN), vertically aligned (VA), and in-plane switching (IPS) modes [1-16].

The TN mode has been most widely used in mass production of LCDs because of its high transmittance and simple fabrication process, but it is limited by a narrow viewing angle and gray inversion at side viewing angles. To overcome these drawbacks, advanced LC modes [1-4] have been developed, such as IPS and VA modes which allow for wider viewing angles.

The IPS mode has good wide viewing angle characteristics. Moreover, because the effective birefringence of the LC layer at off-axis viewing angles is similar to that of on-axis angles, the IPS mode displays uniform gray levels and colors [1]. However, the IPS mode in a normally black state has relatively low transmittance, even in the state of maximum brightness, because the LCs are vertically aligned on the electrode, due to the direction of the electric field. Therefore, the transmittance in typical IPS mode with a 4:6 structure (the ratio of electrode width to electrode gap) is about 60-65% of the transmittance in TN mode. It is also difficult to optimize the fully dark state because of the deviation of the easy axis of the LCs from the rubbing direction, and because of a misalignment between the easy axes of the top and bottom substrates [17, 18]. To solve these problems, Oka *et al*. presented a normally white IPS mode with a 90˚ TN, called an in-plane switching twisted nematic mode (IT mode) [19]. Though this mode shows very high transmittance without applying a voltage as in the conventional 90˚ TN mode, it also shows a bad dark state even under a high in-plane field due to the 90˚ difference in rubbing directions between the top and bottom substrates. To obtain a good dark state, a very high in-plane field which can rotate the LCs on the top or bottom surface by 90° along the field direction is required. The modified threshold electric field, E_{th}, is related to the azimuthal anchoring, W_a, by $E_{th}= W_a/(2(K_{22}\Delta\varepsilon)^{1/2})$ [20]. Here, K_{22} and $\Delta\varepsilon$ are the twist elastic constant and dielectric anisotropy of the LC, respectively. Based on this equation, the threshold electric field required to rotate the surface LCs by 90° is ≈ 10 V/μm for a typical LC. This is too high to be used in general TFT-LCDs.

In this paper, we propose a chiral hybrid IPS (CH-IPS) mode to minimize loss of transmittance in the white state, and to reduce misalignment of the easy axes on the top and bottom substrates in the black state.

2. Principle of CH-IPS mode

Figure 1 shows the schematic diagram of the proposed CH-IPS mode. We adopt a twisted

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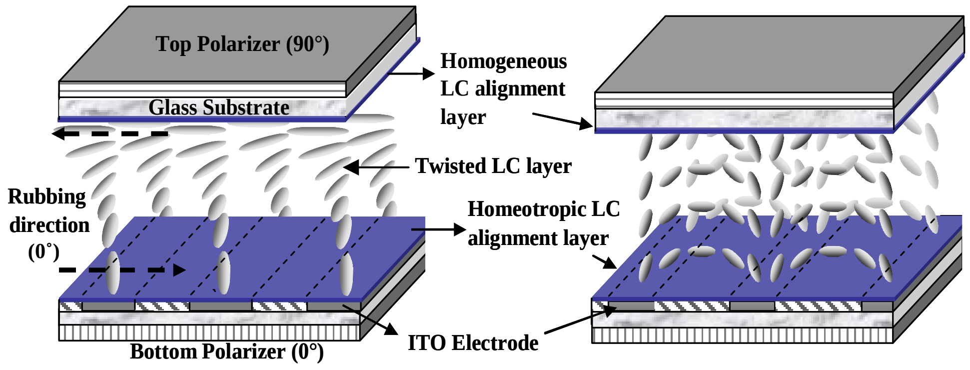

field off state

(a)

field on state

(b)

Fig. 1. Schematic diagram of LC behavior at field off and on states in CH-IPS mode.

configuration to enhance transmittance without an applied field, and a hybrid alignment of LCs to reduce misalignment with the electric field. As shown in Fig. 1(a), the hybrid alignment can be realized by using homogeneous and vertical alignment layers on the bottom and top substrates, respectively. In general, when the homogeneous LC alignment layers are rubbed in same direction on the top and bottom substrates, the LC molecular are twisted in periods of 180° depending on the amount of chiral dopants present in the LCs. It is therefore difficult to obtain continuously twisted LCs by controlling the chiral dopant level. However, in our proposed mode using a homeotropic LC alignment layer, we can create continuously twisted LCs based on the dopant amount by setting the ratio of the cell gap (d) to the chiral pitch (p) because the LCs on the vertical LC alignment layer have no specific azimuthal direction. Therefore, the CH-IPS mode is optimized to the normally white mode which achieves a high transmittance in the initial state by adjusting the values of d and p. Also, a very good dark state can be achieved in CH-IPS mode if we make the in-plane direction of the field the same as the rubbing directions of the top and bottom substrates, as shown in Fig. 1(b). Since the bulk elastic energy is much lower than the surface energy, a good dark state is easily obtained under a lower voltage than that required in the IT mode. If we consider the modified critical electric field, E_c , roughly estimated as $E_c = \pi/(d((K_{22}/\Delta\varepsilon)^{1/2})$, [21] then the critical electric field required to rotate bulk LCs by 90° is ≈ 1 V/μm; just one-tenth the value of E_{th} required for surface LC rotation. This is low enough to use in general TFT-LCD applications. In addition, homeotropic alignment of the LCs on the bottom substrate leads to a better dark state. As a result, we expect that the CH-IPS mode will display a better dark and white state than IT and the conventional IPS modes, respectively.

We used a homeotropic LC alignment layer (AL60702, JSR) on the bottom substrate and a homogeneous LC alignment layer (JALS1085, JSR) on the top substrate. An interdigitated electrode for in-plane switching was formed on the bottom substrate. We placed two crossed polarizers with optics axes of 0° and 90° on the bottom and top substrates, respectively. The top and bottom substrates were rubbed parallel to the optical axis (0˚) of the polarizer coincident with the horizontal direction of the field supplied by the interdigitated electrode. The LC and chiral dopant used in this experiment were ZKC-5085 (Chisso) with birefringence Δn=0.15, and S-811 (Merck), respectively. We used the Jones matrix to calculate theoretically transmittance of CH-IPS mode. The Jones matrix of a twisted liquid

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crystal can be expressed as

$$J_{LC} = e^{i\frac{\pi d}{\lambda}}(n_e^{'} + n_o)\begin{bmatrix} a & b \\ -b^{*} & a^{*} \end{bmatrix}$$

Here,

$$a = \frac{1}{\sqrt{1+u^2}}\sin\phi\sin(\sqrt{1+u^2}\phi) + \cos\phi\cos(\sqrt{1+u^2}\phi) + i\frac{u}{\sqrt{1+u^2}}\cos\phi\sin(\sqrt{1+u^2}\phi),$$

$$b = \frac{1}{\sqrt{1+u^2}}\cos\phi\sin(\sqrt{1+u^2}\phi) - \sin\phi\cos(\sqrt{1+u^2}\phi) + i\frac{u}{\sqrt{1+u^2}}\sin\phi\sin(\sqrt{1+u^2}\phi)$$

where ϕ is the twisted angle of LC and

$$u = \frac{\pi d}{\lambda\phi}\left(\frac{n_e}{\sqrt{1+((n_e/n_o)^2-1)\sin^2\theta}} - n_o\right).$$

Here d, λ, n_e, n_o, and θ are cell-gap, wavelength of light, the extraordinary refractive index, the ordinary refractive index, and the pretilt angle of LC, respectively. We divide liquid crystal layer into N layers with different pretilt angles from 0° to 90° and assume that optic axes of each layer are changed linearly to azimuthal direction from 0° to twist angle by the chirality. In this optical calculation, ϕ of each layer can be zero. Then the transmittance of the twisted hybrid state can be found as follows:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}\begin{bmatrix} \cos\alpha_N & -\sin\alpha_N \\ \sin\alpha_N & \cos\alpha_N \end{bmatrix}\begin{bmatrix} a_N & b_N \\ -b_N^{*} & a_N^{*} \end{bmatrix}\begin{bmatrix} \cos\alpha_N & \sin\alpha_N \\ -\sin\alpha_N & \cos\alpha_N \end{bmatrix}\begin{bmatrix} \cos\alpha_{N-1} & -\sin\alpha_{N-1} \\ \sin\alpha_{N-1} & \cos\alpha_{N-1} \end{bmatrix}\cdots$$

$$\cdots\begin{bmatrix} \cos\alpha_2 & \sin\alpha_2 \\ -\sin\alpha_2 & \cos\alpha_2 \end{bmatrix}\begin{bmatrix} \cos\alpha_1 & -\sin\alpha_1 \\ \sin\alpha_1 & \cos\alpha_1 \end{bmatrix}\begin{bmatrix} a_1 & b_1 \\ -b_1^{*} & a_1^{*} \end{bmatrix}\begin{bmatrix} \cos\alpha_1 & \sin\alpha_1 \\ -\sin\alpha_1 & \cos\alpha_1 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix}, \qquad (1)$$

where α are the angles between the optic axes of each liquid crystal layer and the optic axis of the bottom polarizer. In this case, theoretically, the maximum transmittance in CH-IPS mode from Eq. (1) is about 95% at a 140° twisted LC state with Δnd=0.65, as if the light is wave-guided by the Mauguins condition as in the TN mode. However this can lead to a disclination between the top and bottom LC layers under an electric field. To create a more stable LC bulk state under field, the *d/p* and cell gap were set to 0.33 and 4.5 μm, respectively. In this case, the LC was twisted 120° from the bottom to the top substrates, and the transmittance was over 90%. The LC molecules were well aligned in a direction parallel to the bottom polarizer under relatively low voltages due to the low bulk elastic strength as compared to the surface anchoring strength. Namely, under the relatively low horizontal electric field, $\alpha_1=\alpha_2\cdots=\alpha_N$, then LC cell shows an excellent darkness because the incident light whose polarization direction is coincident with the optic axis of LC layer passes through LC layer without any change of polarization.

3. Experimental result

Figure 2 shows the alignment textures in CH-IPS mode under a polarizing microscope with different conditions of sample preparation. We found that LC alignment with the electric field was greatly affected by the direction of LC injection and injection temperature. If we injected LCs perpendicularly to the rubbing direction of the homogeneous alignment layer at the temperature of the nematic phase, we observed disclination lines in the center of the electrode by the defect domain with the reverse twist, as shown in Fig. 2(a). When voltage was applied and instantly removed, the disclination lines increased gradually from the domain boundary as shown in Fig. 2(b). This made it difficult to control the gray level. To remove these reverse twist domains, we injected LCs along the rubbing direction of the homogeneous alignment layer near its nematic-isotropic transition temperature (T_{NI}). Stable LC alignment may be related to the smooth fluid flow induced by the abrupt decrease of LC viscosity at T_{NI}. In our experiment, LCs were injected at 107°C - 108°C because the T_{NI} of ZKC-5085 is 108°C. This led to a uniform alignment texture as shown in Fig. 2(c). If the defect domain did not exist, then the disclination line did not occur, even at gray levels, as shown in Fig. 2(d).

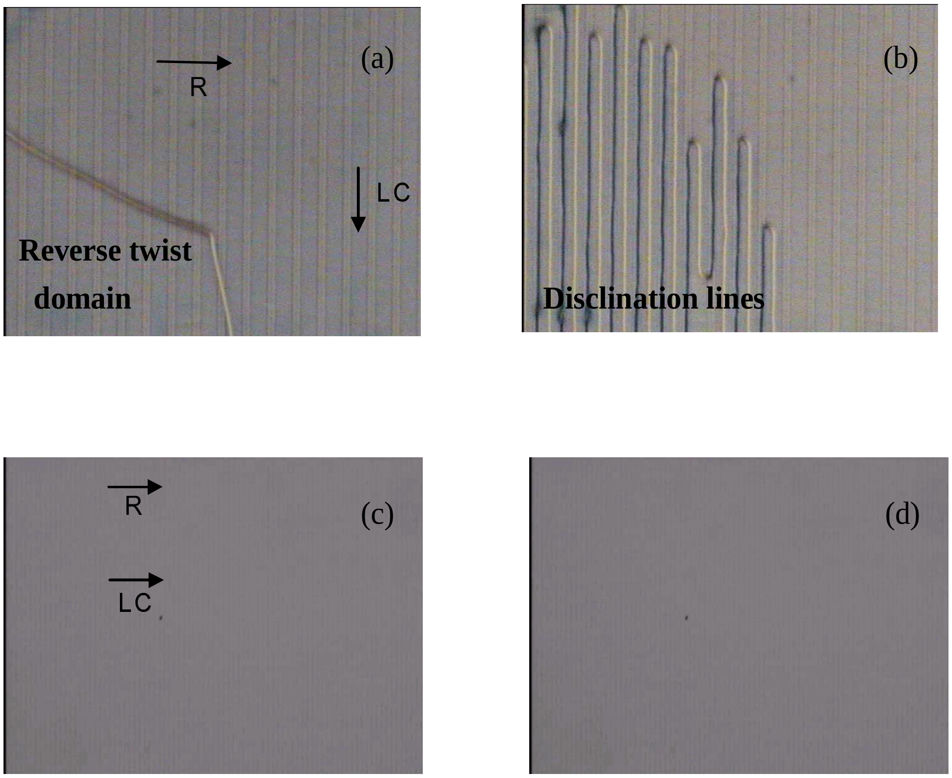

Fig. 2. Alignment textures of CH-IPS sample under a polarizing microscope with different sample preparation conditions. (a) LCs were injected perpendicular to rubbing direction at 50 °C. (b) after electric field was applied to (a) and instantly removed. (c) LCs were injected in the rubbing direction at 108 °C. (d) after electric field was applied to (c) and removed. The arrows indicate the rubbing direction (R) and the direction of LC injection (LC).

To verify the proposed mode, we compared transmittance as a function of applied voltages in CH-IPS mode with that in IT and conventional IPS modes. The interdigitated electrode with electrode-gap of 20 µm at all LC cells was used for a horizontal field. We applied a 1 kHz square-wave voltage to the electrode for horizontal switching. A halogen lamp was used as a light source, and a signal function generator (DS345 of Stanford Research Systems) was used as a voltage source. Figure 3 shows measured EO characteristics and photo images taken at the maximum white and dark states of the CH-IPS, IPS, and IT cells with uniform LC alignment. As shown in the figure, the transmittance of the CH-IPS mode in white state was about 30% higher brightness than that of the IPS mode and the darkness of the CH-IPS mode corresponding to dark level of the IPS mode is obtained under 9 V. Therefore, the CH-IPS mode exhibited a much higher contrast ratio (980:1) than that shown by the IPS mode (550:1) due to high transmittance in the bright state. On the other hand, as previously estimated, the IT mode showed considerable light leakage even in more than 10 V due to surface LC directors with strong anchoring strength. Consequently, the contrast ratio of it with respect to a dark state under 10 V was barely 9:1 that is not suitable for LCD applications. As expected, in CH- IPS mode, most of the bulk LCs were aligned in the direction of the ~1 V/µm electric field. For the response time of the CH-IPS mode, the rising and decay times were measured at 6 ms and 42 ms under room temperature, respectively.

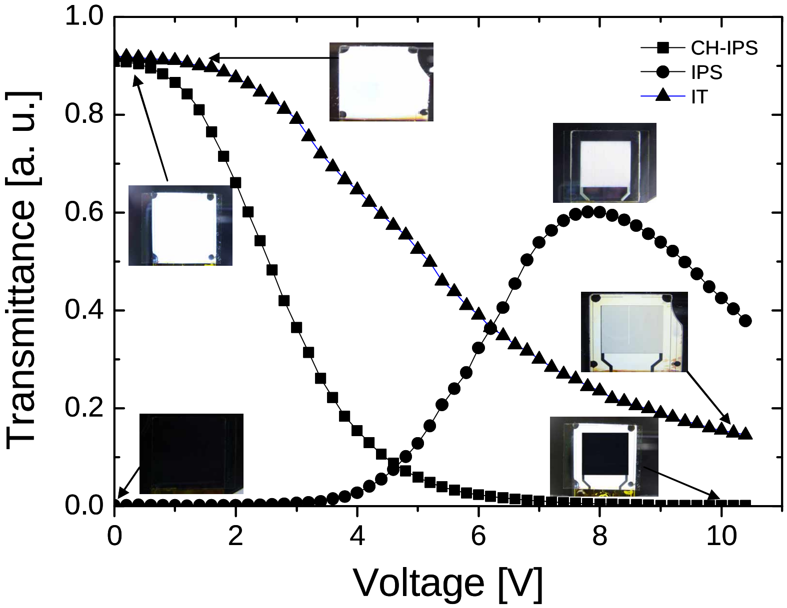

Fig. 3. The measured optical transmittance curves as a function of electric field for the CH-IPS, IT, and conventional IPS modes. The photo images show the bright and dark states of the samples.

4. Conclusion

We proposed a new LCD mode (CH-IPS) using the chiral effect of hybrid LC alignment with IPS electrodes to achieve greater brightness than in the conventional IPS mode. The high brightness and good dark states are obtained due to the twist effect and hybrid alignment, respectively. As a result, the CH-IPS mode exhibits excellent isocontrast (980:1). The disclination line leading from the defect domain created by the reverse twisted LCs can be removed by controlling the LC injection direction and temperature.

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