Electro-optical characteristics of reflective liquid crystal mode using π-cell for low power operation

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We demonstrated a reflective type of liquid crystal (LC) display with low power consumption using 180° twist and bend states in the π-cell. The driving voltage of the proposed operational mode depends on the cell and the LC parameters, such as the pretilt angle, the sample thickness, and the ratio of the sample thickness to the helical pitch of the LC. Under optimized conditions, this mode operates with less than 1.3 V and it exhibits excellent optical characteristics at all operational wavelengths. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2988266]

Liquid crystals (LCs) have been extensively studied and used for a wide range of display applications because of their efficient light control capabilities and low power consumptions. In conventional LC displays (LCDs), light passes through the LC layer from an internal light source. However, such transmissive LCDs are unsuitable for certain applications, including outdoor usage situations (due to sunlight, which is much brighter than the LCDs themselves) and applications with ultralow power requirements (due to the power consumption of the internal light source[1–6]). To overcome these disadvantages, reflective LCDs that remove the internal source by using an external light source have been developed.[7–15] Bistable LC modes, especially for ultralow power consumption such as bistable twisted nematic and zenithal bistable nematic devices, have been applied to realize reflective LCDs. However, these modes have substantial limitations to produce various gray levels for full color displays. Moreover, though the use of reflective LCDs operating at their normal modes in transmissive LCDs, such as the twisted nematic mode, produces gray levels sufficiently well, they require more power than those working in the bistable mode.

In this paper, a reflective LCD mode is proposed using the 180° twisted state of a modified π-cell that operates at very low driving voltages yet has sufficient gray scales to allow vivid color images to be produced. The cell conditions and material parameters have been optimized in order to reduce the driving voltages.

In a normal π-cell, since the initial stable state is a splay state and the optical transmittance is controlled between low and high bend states, the cell requires a reset voltage to convert from the splay to the bend state and a bias voltage to maintain the bend state.[16] Here, however, to reduce the operation voltage, we use the 180° twisted and bend states in the π-cell as this choice does not require a bias voltage, as shown in the schematic of Fig. 1(a). Furthermore, since the free energy difference between the two states is small, it is possible to change the state with low driving voltages. In this case, the initial splay state is converted to a bend state using the reset voltage, and the bend state transits to the 180° twisted state with decreasing voltage. With an applied voltage, the general deformation energy density f_d of a twisted LC cell is given by

$$f_d = \tfrac{1}{2}(K_{11}\cos^2\theta + K_{33}\sin^2\theta)\left(\frac{d\theta}{dz}\right)^2 + \tfrac{1}{2}\cos^2\theta(K_{22}\cos^2\theta + K_{33}\sin^2\theta)\left(\frac{d\phi}{dz}\right)^2 - 2\pi\left(\frac{K_{22}}{p}\right)\cos^2\theta\left(\frac{d\phi}{dz}\right) - \tfrac{1}{2}\varepsilon_o(\Delta\varepsilon\sin^2\theta + \varepsilon_\perp)E_z^2, \quad (1)$$

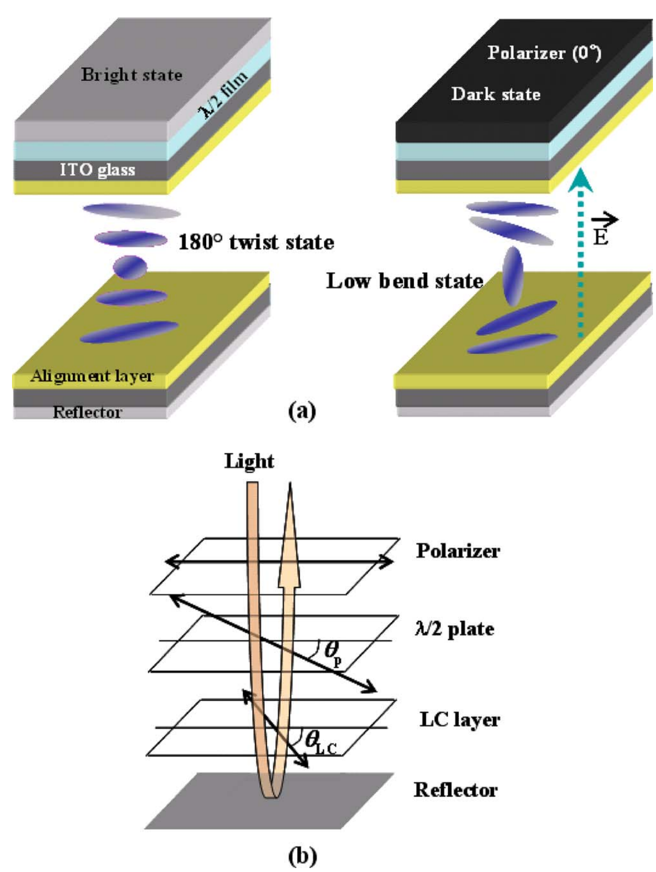

FIG. 1. (Color online) (a) A schematic diagram of the proposed LC cell and (b) optical configuration of the proposed reflective LC mode.

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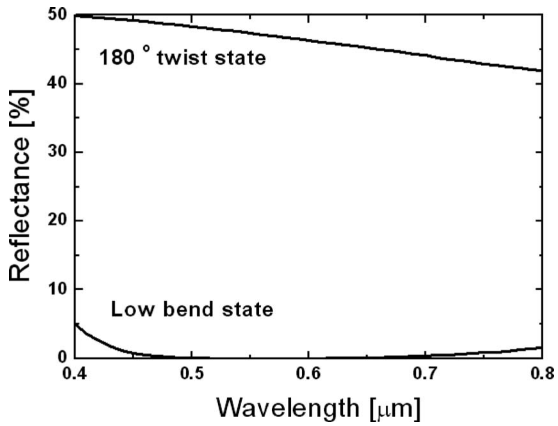

FIG. 2. Simulated dispersion characteristics of the proposed reflective LC mode.

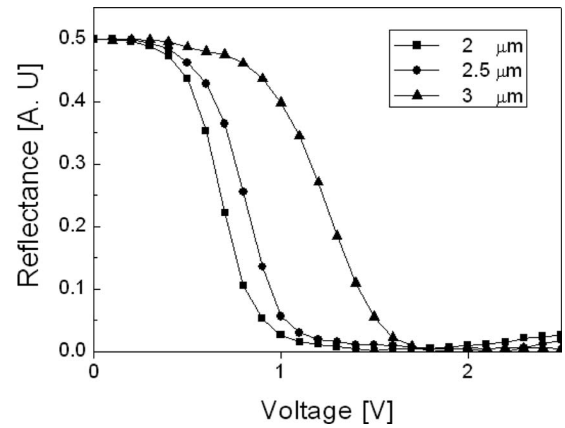

FIG. 3. The measured EO characteristics according to the cell gap in the proposed reflective LC mode.

where K_{11}, K_{22}, and K_{33} are the splay, twist, and bend elastic constants, respectively, and p is the chiral pitch of the LC. In Eq. (1), $d\theta/dz$, $d\phi/dz$, and E depend on the pretilt angle, the sample thickness, and the ratio of the sample thickness, respectively, to the helical pitch of the LC. The above parameters have been optimized in order to minimize the driving voltage.

Figure 1(b) shows the optical configuration of the proposed LC cell. In this experiment for measuring the reflectance, θ_{LC}, which is the angle between the rubbing direction of the $\lambda/4$ LC layer and the optical axis of the polarizer, and θ_P, which is the angle between the optical axes of the $\lambda/2$ film and the polarizer, are determined by using the wide band optical condition.[17] From theoretical calculations using the Jones matrix, it was found that the values of θ_P and θ_{LC}, which satisfy the white and dark states, are 15° and 75°, respectively.

Figure 2 shows the spectral characteristics of the above optical configuration simulated with a 2×2 Jones matrix method[18,19] where the LC cell gap and pretilt angle used in the simulations were 2 μm and 3°, respectively. The Cauchy formula using the one-band model as expressed by $\Delta n(\lambda) = A+B/\lambda^2$ ($A=0.0993$ and $B=14,040$) was used for the refractive index dispersion of the LC.[20] The optical configuration exhibits good dispersion properties across the entire visible range in both the dark and bright states, as expected.

For the experimental studies, the samples were prepared with cell gaps of 2, 2.5, and 3 μm to observe their performance dependence on the cell gaps with pretilt angles of 3° and 7°, using alignment layers of AL3046 (from Nissan Chem.) and JALS-1371 (from JSR) polyimide, respectively. A sample with a pretilt of 20° was also prepared by mixing homogeneous and homeotropic polyimides.[21] To adjust the retardation of the LC layer with respect to each cell gap and pretilt, three kinds of LC materials (MLC-3449–000, MLC-6233–000, and MJ00993, supplied by Merck) were used in the experiments, and their respective birefringence and dielectric constants are $\Delta n=0.132$ ($\Delta\varepsilon=7.8$), $\Delta n=0.0901$ ($\Delta\varepsilon=4.3$), and $\Delta n=0.151$ ($\Delta\varepsilon=11.1$). To determine the effect of the cell gap (d)-to-pitch (p) ratio d/p, this ratio was set to 0.1, 0.15, and 0.25 by adding the chiral opant S-811 (Merck) into the LC. A He–Ne laser of wavelength 632.8 nm was used as the light source, and a voltage with a 1 kHz square wave of varying amplitude was applied to the electrode for vertical switching.

Figure 3 shows the reflectance as a function of the applied voltage in samples with different cell gaps. The driving voltages at which the retardation of the LC cell is $\lambda/4$ (to achieve a dark state) were 1.5, 1.65, and 1.9 V when the cell gap was 2.0, 2.5, and 3 μm, respectively. In these cases, the pretilt and d/p were fixed to 3° and 0.2, respectively, and the results obtained show that the driving voltage increases with the cell gap. In Eq. (1), $d\phi/dz$ does not depend merely on the strength of the electric field, and the second term decreases with an increasing tilt angle. However, $d\theta/dz$ increases with increasing field strength in vertical switching if a hard anchoring condition is assumed. Therefore, the first term in Eq. (1) becomes more important with increasing electric field, and the LC tends to align in the direction of the electric field while maintaining the 180° twisted state. As a result, LCs are easily reoriented in the lower cell gap.

The pretilt angle of the LC is also one of the most important factors that influence the electro-optic (EO) characteristics of the LC cells because it determines the energy difference between the 180° twisted and bend states. Figure 4 shows the EO properties according to different pretilt angles. In these cases, the cell gap and d/p were fixed to 2.8 μm and 0.2, respectively, and the driving voltages decreased with increasing pretilt angle. The inset of Fig. 4 shows the free energy difference between the two states as a

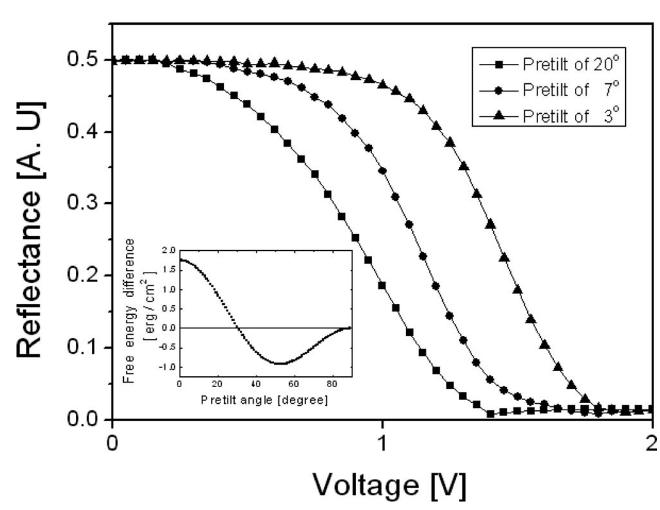

FIG. 4. The measured EO characteristics as a function of the LC pretilt angle while the LC is operating in the reflective LC mode.

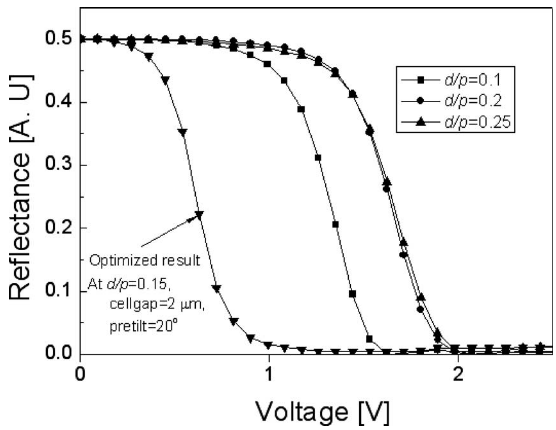

FIG. 5. The measured EO characteristics depending on d/p at the proposed reflective LC mode.

function of the pretilt angle using Eq. (1). As expected, a higher pretilt angle decreases the free energy difference between the two states, and if the pretilt angle is larger than 30°, the bend state is found to be more stable indicating that a sample with a greater pretilt angle is able to transit more easily to the bend state under a lower voltage.

The chiral twisting power of the LC affects the stability of the 180° twisted structure and the driving voltage. Figure 5 shows the reflectance with different d/p ratios (0.1, 0.2, and 0.25). In these cases, the LC pretilt angle and the LC cell gap were fixed to 3° and 3.4 μm, respectively, and the EO characteristics of the LC cells with d/p ratios of 0.2 and 0.25 are very similar to each other, with a driving voltage of 2 V. In contrast, the LC cell with a d/p ratio of 0.1 has a lower driving voltage of 1.7 V. From Eq. (1), the threshold voltage can be given by $V_{th}=\{1+[(K_{33}/K_{11}-2K_{22}/K_{11})+4(K_{22}/K_{11})\times(d/p)]\phi/\pi\}^{1/2}$,[22] which shows that the driving voltage, when using a smaller chiral dopant, easily reorients the LCs due to the decrease in the twist elastic energy. The stability of the twisted state is greatly affected by the chiral twisting power. Increasing the chiral dopant ($d/p>0.25$) can increase the retention time up to one month. To reduce the driving voltage, however, d/p should be decreased. In the cases in which the d/p ratio is 0.2 or 0.15, the retention time of the 180° twisted state was greater than 6 and 2 h, respectively. Theoretically, if the cells are refreshed once every 2 or 6 h, the cells will maintain the twisted state indefinitely without returning to the splay state. For the response time of this reflective mode with cell gaps of 2.5 μm, the rise and decay times of the LCs were measured as 9 and 26 ms. It means that the coarse response time required for the cell refresh corresponds to the decay time, which is the transit time from bend state to 180° twisted state. In addition, a viewing angle of 40° can be achieved along the diagonal direction of one side with a contrast ratio limit of 10:1 in this reflective mode without using a compensation film.

Combining the best conditions (a cell gap of 2 μm, a pretilt angle of 20°, and a d/p of 0.15) for the lowest driving voltage, a reflective LCD with a driving voltage of 1.3 V was obtained, as shown in Fig. 5. A more detailed and appropriate combination of LC cell parameters may lead to a lower driving voltage of under 1 V.

In conclusion, a reflective type of nematic LCD has been proposed using the 180° twisted state of a π-cell. In restrictive experiments, a lower driving voltage was obtained using a lower cell gap, a higher pretilt angle, and a smaller chiral dopant. It is believed that such lower driving voltages can be achieved by optimizing the cell parameters in this reflective mode, so the proposed reflective LCDs are suitable for e-books with ultralow power consumption and various gray levels.

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