Light efficiency of fringe-field switching nematic liquid crystal cell depending on dielectric anisotropy value of a liquid crystal

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Abstract

The light efficiency of fringe-field switching (FFS) mode was found to be dependent on the magnitude of dielectric anisotropy, indicating that the voltage-dependent maximal effective cell retardation value in the on state is a function of magnitude of the dielectric anisotropy of the LC.

1. Introduction

Nowadays, liquid crystal displays (LCDs) are being used in all types of information displays. The image quality of the LCDs has greatly improved in recent years due to the development of new LC modes such as film compensated twisted nematic (TN) [1], in-plane switching (IPS) [2-3], FFS [4-6], and multi-domain vertical alignment (MVA) including patterned VA (PVA) [7]. But, their light efficiency is quite poor, normally less than 10 %, due to the use of an absorptive color filter, polarizer, limited aperture ratio and insufficient light efficiency by the LC layers. In LCDs, light modulation occurs either by phase retardation or a polarization rotation effect using the LC layers. In general, the light efficiency of a LC cell depends only on the retardation, $d\Delta n$, of the LC layer, where d is the thickness of the LC layer and Δn is the birefringence of the LC, i.e., it remains unchanged as long as the retardation value is the same regardless of whether d or Δn is changed.

In IPS mode, the light efficiency of the LC cell is not dependent on the dielectric anisotropy of the LC because the in-plane field drives the LC to rotate [8]. However, in FFS mode, the light efficiency strongly depends on the dielectric anisotropy of the LC because the LC above the electrode is tilted upward along the fringe-electric field line for a LC with a positive $\Delta\varepsilon$ (+LC), while the tilt angle for the LC with a negative $\Delta\varepsilon$ (-LC) is not so high [9]. In addition, unlike in the other devices such as TN, IPS, and MVA, the light efficiency of a LC cell is strongly dependent on the cell gap because the rotation angle of the LCs at the center of the electrodes is determined by the rotating angle of the neighboring molecules [10].

This paper reports the experimental and calculated results showing that the light efficiency of FFS mode depends on the magnitude of $\Delta\varepsilon$ of the +LC, which violates the conventional concept that the light efficiency of a LC device is independent of $\Delta\varepsilon$.

2. Simulation

In FFS mode, the LCs are aligned homogenously in the initial state with their optic axis coincident with one of the crossed polarizer axes so that in the off state, the cell appears black. Considering the electrode structure, a common electrode with a plane shape located below the pixel electrodes with slit forms with passivation layer between the pixel and common electrodes. With a bias voltage, a fringe electric field with both horizontal and vertical components is generated, which rotates the LCs above the whole electrode surface, giving rise to transmittance, as shown in **Fig. 1.** The interesting feature of FFS mode is that the transmittance oscillates periodically along the electrodes, due to the different twist angle of the LC along the electrode position. At position C where a strong horizontal field (E_y) exists, the LC is twisted enough by a dielectric torque proportional to ∣Δε∣E_y^2, giving rise to high transmittance. The lower transmittance at the center of the electrode (position A) than those at the edge of the electrode (position C) as well as between the center and edge of the electrodes (position B) arises from the low twist angle compared with the other regions. According to previous studies [10], there is no horizontal electric field to rotate the LC at position A so that the twist angle of the LC at that position is determined by the elastic torque of the neighboring molecules (proportional to $\mathbf{n_A}\cdot\mathbf{n_B}(\mathbf{n_A} \times \mathbf{n_B})$, where $\mathbf{n_A}$ and $\mathbf{n_B}$ represents the LC directors at position A and B, respectively) [10], particularly position B. In addition, with bias voltage, the LC reorientation at position C and B does occur due to dielectric torque at first and then it at position C does occur due to elastic torque between neighboring molecules. Because of this abnormal switching principle of the FFS mode, the transmittance at position A decreases with decreasing cell gap because more LCs are influenced by surface anchoring, i.e., surface anchoring overcomes elastic torque. Especially, when using the +LC, the LCs at position B tilt upward to some degree in response to fringe-field direction so that lower elastic torque to twist the LC at position A is applied, giving rise to a relatively low transmittance compared with positions B and C. This means that the degree of tilt angle at position B strongly affects the twist angle of the LC at position A and can differ according to the magnitude of Δε of the +LC.

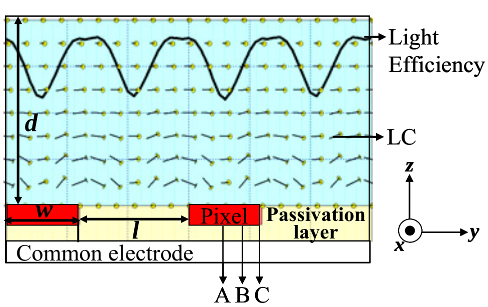

Fig. 1. Configuration of the LC molecules and corresponding transmittance in the white state of the FFS mode using a +LC.

Computer simulations and experiments were performed to determine if the transmittance is dependent on the magnitude of Δε. In the experiments, the width of the pixel electrode (*w*) and the distance (*l*) between them was 4 ㎛ and 6 ㎛, respectively. The thickness of the insulation layer was 6300Å, and the cell gap was 3.6 ㎛. Two different types of LCs, LC1 (Δn = 0.098, Δε = 5 at 20 ℃, 1 kHz) and LC2 (Δn = 0.0988, Δε = 9.4 at 20 ℃, 1 kHz) were selected because both had similar birefringence but magnitude of dielectric anisotropy were quite much different each other. The simulations were performed using commercially available software “LCD Master” (Shintech, Japan), where the motion of the LC director was calculated based on the Ericksen-Leslie theory, and the 2 X 2 extended Jones matrix was used for the optical transmittance calculation [11]. In the simulations, the same electrode structures as those in the experiment were applied and all the physical properties of LC1 and LC2 kept the same each other except for Δε. For simulations, elastic constants of the LC, K1, K2, and K3 are assumed to be 9.7 pN, 5.2 pN, and 13.3 pN, respectively. In both the experiment and calculation, the rubbing angle was 80° with respect to the horizontal component of the fringe electric field with a pretilt angle of 2°.

3. Results and discussions

Figure 2 shows the measured and calculated voltage-dependent transmittance (V-T) curves. As clearly shown, both results show that the cell with LC1 has a better transmittance as that with LC2, i.e. the transmittance of the cell with Δε = 5 is approximately 6 % higher than that with Δε = 9.4. Although the simulated results did not consider difference of both LCs in elastic constants, both are in good agreements. In addition, in the FFS mode with positive dielectric anisotropy, the optimal cell retardation value which show maximal transmittance is close to 0.4 ㎛, i.e., the cell with LC2 should show a better transmittance than the cell with LC1 since Δn of the LC2 is slightly higher than that of the LC1. However, the result is reversed. In experiments, the elastic constants between two LCs are different each other, however, for simulations the same parameters are used. Nevertheless, both results show some consistency that the transmittance depends on magnitude of dielectric anisotropy of the LC and in fact this behavior has never been reported in other devices. The driving voltages were higher in the cell with LC1 than in the cell with LC2 because it is proportional to $(1/\Delta\varepsilon)^{1/2}$.

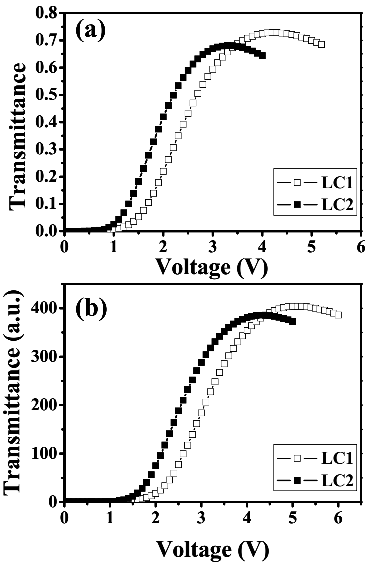

Fig. 2. (a) Calculated and (b) measured voltage-dependent transmittance curves in the two different +LCs with different dielectric Δε.

To confirm he dependency of the transmittance on Δε in the FFS mode, the transmittance was calculated as a function of Δε of the +LC while keeping other physical parameter the same, as shown in **Fig. 3.** The calculated results clearly show that the transmittance increases linearly with decreasing Δε of the +LC with a negative slope of 0.685.

Fig. 4. shows rubbing angle dependent transmittance and operating voltage as a function of the magnitude of Δε. As the rubbing angle changes from 62° to 86° transmittance change in LC1 is about 18.6 % while it is 28.2 % in LC2. Operating voltage increases linearly with decreasing rubbing angle in LC1 and LC2, as expected. Therefore, as increasing Δε, change of transmittance depending on rubbing angle is lager.

Since the transmittance in FFS mode with +LC is strongly dependent on the electrode position, the transmittance for the LC1 and LC2 was compared. As shown in **Fig. 5,** the decreased transmittance of LC 2 arises from decreased transmittance along the electrode positions A and B, particularly at position A. In order to understand this behavior in more detail, the LC director profile along the LC layers was calculated at positions A and B at several grey (G) levels. In order to neglect difference in Δε for both LCs, the LC orientation at the same grey levels was compared, as shown in **Fig. 6.** An investigation of the tilt angle at position B reveals that both LC1 and LC2 to have a similar orientation at a low grey level G10.

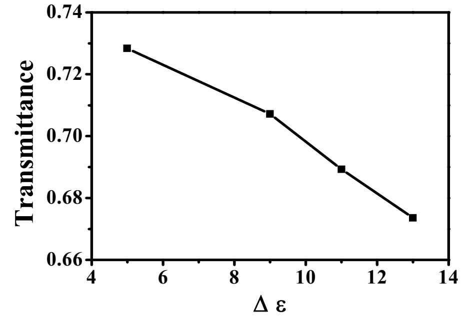

Fig. 3. Transmittance as a function of the magnitude of Δε of the +LC.

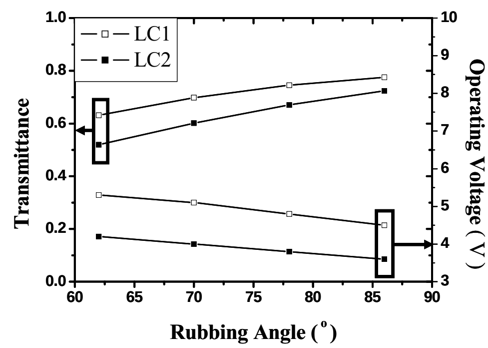

Fig. 4. Calculated rubbing angle dependent transmittance and operating voltage as a function of the magnitude of Δε.

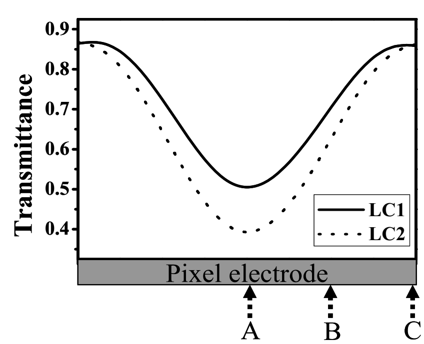

Fig. 5. Calculated transmittance above a pixel electrode as a function of the magnitude of Δε of the +LC.

However, as the voltage increases to a high grey level, a difference in the tilt angle between the two LCs is generated such that at G90, the maximum tilt angles for the LC1 and LC2 at z/d = 0.2 are 18^o and 21^o, respectively.

This is due to the stronger dielectric torque between the LC and the vertical field component for a LC2 than that for a LC2 on account of the higher dielectric anisotropy in the LC2 than in the LC1. The elastic torque to rotate the LCs above position A would be different due to the difference in tilt angle for both LCs. As indicated in Fig. 6(b), the maximum twist angles for the LC1 and LC2 at z/d = 0.4 in G100 are 30^{o} and 24^{o}, respectively. Consequently, LC2 has a lower transmittance than LC1 because the transmittance at position A is proportional to $\sin^2 2\Psi$ where Ψ is the angle between the LC director and the transmission axes of the crossed polarizers.

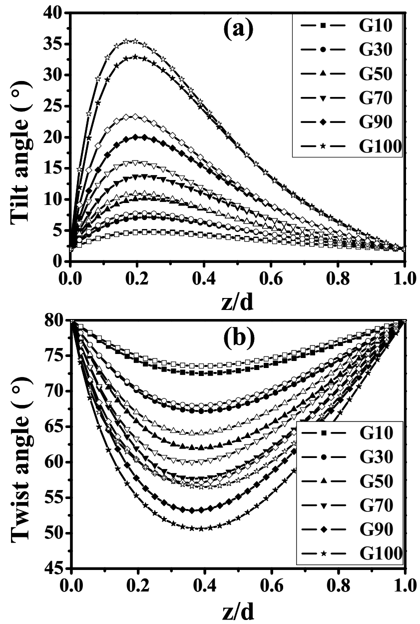

Fig. 6. Voltage-dependent the LC's (a) tilt angle at electrode position between the center and edge, and (b) twist angle at the center of the pixel electrode for two different LCs with different Δε. The filled and unfilled symbols indicate LC1 and LC2, respectively.

4. Summary

This study examined the transmittance of FFS mode according to the magnitude of positive dielectric anisotropy of the LC. Unlike in conventional LC modes such as TN and IPS modes, the transmittance depends on the dielectric anisotropy such that the transmittance increases with decreasing dielectric anisotropy of the LC. This unexpected behavior in the FFS mode arises from the fact that the rotating angle of the LC is determined by the dielectric torque and elastic torque depending on the electrode positions. It is believed that this concept can be applied to the development of a LC for a high performance FFS device.

5. Acknowledgements

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