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Analysis of Light Modulation in the Fringe-Field Switching Liquid Crystal Mode

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The light modulation mechanism in conventional liquid crystal displays (LCDs) presents either phase retardation or polarization rotation effects only. However, in the fringe-field switching (FFS) mode, both effects exist depending on the electrode positions when the electrode width and distance is larger than 2 μm. Interestingly, when the electrode width and distance are reduced to less than 2 μm, only the polarization rotation effect exists. Further, reduction of the electrode width and distance gives rise to improved response time and light efficiency in the FFS mode.

Keywords: electrode structure; fringe-field switching; light modulation; liquid crystal

INTRODUCTION

In these days, as the application field of liquid crystal displays (LCDs) becomes wider, from small-size displays such as mobile phone and

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laptop PCs, to large-size ones such as LCD monitors and LC-TVs, the image quality and response time of the LCDs has become more and more important. There are several LC modes to realize a high image quality such as in-plane switching (IPS) [1], fringe-field switching (FFS) [2–5], and multi-domain vertical alignment (MVA) [6,7]. Among them, the IPS and FFS mode have a intrinsically wide viewing angle, and the in-plane and fringe electric field rotate the homogenously-aligned LC almost in plane, respectively. However, the different driving fields in the two devices cause a difference in their electro-optic behavior. The IPS mode utilizing phase retardation effect shows low transmittance because the LCs above the center of the pixel electrode do not rotate. However, the FFS mode driven by a fringe electric field has not only a wide viewing angle but also high transmittance because the LCs upper electrodes rotate with low driving voltage [2]. Further, the FFS mode utilizes mixed concepts of both polarization rotation and phase retardation effects depending on electrode positions [8,9]. Owing to many advantages such as a wide viewing angle and high transmittance, the FFS mode is being applied to various application fields such as mobile phones, desktop computers, laptops, monitors and LC-TVs [10,11].

There were many more studies to improve the performance of the FFS mode. To improve the light efficiency, the dependency on cell gap and pixel electrode width and distance between them is studied [8,9]. When the cell gap decreases, the light efficiency of the LC cell decreases since more LCs are affected by strong surface anchoring, so that the LC above the center of the electrodes becomes harder to rotate as the cell gap decreases [8]. In the case of optimized pixel electrode width and the distance between them, the transmittance is increased because of increased density of the horizontal electric field [9]. In the response time of the FFS device with conventional electrode structure, the decaying response time of the FFS mode is rather slow compared to that of the VA mode because of twist deformation and low operating voltage only if one assumes both modes have the same cell gap.

This article investigates the mechanism of the light modulation and response time according to electrode structures in the FFS mode using an LC with positive dielectric anisotropy of the LC.

Switching Principle and Simulation Conditions

Figure 1 shows a schematic cell structure of the FFS mode with local director orientation in the off and on states. The pixel electrode is in

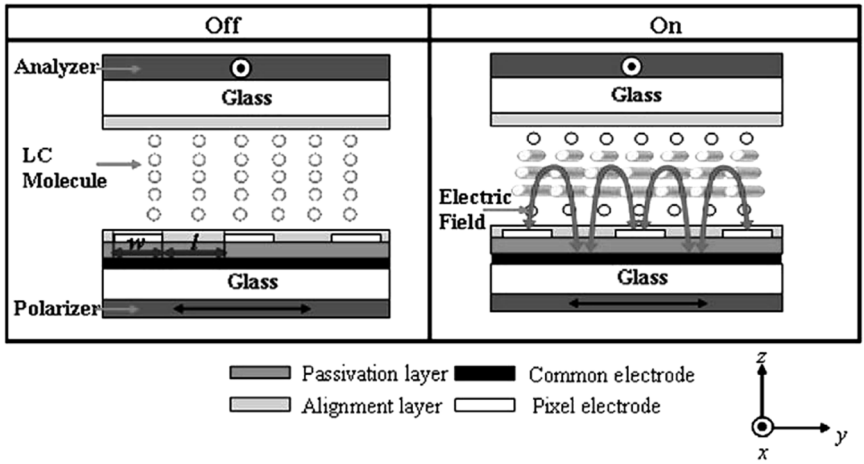

FIGURE 1 Schematic cell structure of the FFS mode with orientation of the LC director in off and on state and fringe field.

a slit shape with electrode width (w) and the distance (l) between them, and the counter electrode is in a plane shape with a passivation layer between the pixel and counter electrode. The LCs are homogeneously aligned in an initial state in which the optic axis of the LC is coincident with one of the crossed polarizer axis, and thus the cell appears to be black in the absence of an electric field. With bias voltage, the fringe electric field which has both horizontal (E_y) and vertical (E_z) component is generated between pixel and common electrodes. Then the dielectric torque between E_y and LC director rotates the LC, giving rise to a bright state. However, the intensity of is periodically oscillating along electrode direction resulting from electrode structure so that the reorientation of the LC in response to the field is also strongly electrode-position dependent. Consequently, at the edge of pixel electrode, the LC is mostly twisted near bottom surface due to strong E_y while it is mostly twisted around middle of cell gap at the center of pixel electrode due to nonexistence of E_y. This different configuration of the LC causes a way of light modulation to be electrode position dependent. In the FFS mode with conventional electrode width larger than 3 μm and a +LC, the transmittance is generated by light modulation of both phase retardation and polarization rotation effects along the electrode positions [12]. Therefore, the normalized light transmission in the FFS mode using

a +LC is determined by the following equation:

$$T/T_0 = A\sin^2(B\pi d\Delta n/\lambda) + C\left(1 - \frac{\sin^2(\pi/2\sqrt{1+(2Dd\Delta n/\lambda)^2}}{1+(2Dd\Delta n/\lambda)^2}\right)$$

where A, B, C, and D are fitting parameters, d is a cell gap, Δn is a birefringence of LC medium, and λ is the wavelength of the incident light. The first term is related to the phase retardation effect while the second is related to polarization rotation effect.

We performed a simulation using the commercially available software "LCD Master" (Shintech, Japan), where the motion of the LC director is calculated based on the Eriksen-Leslie theory and a 2×2 extended Jones matrix is applied for an optical transmittance calculation [13]. For the electro-optic calculations, the LC has physical properties, such as dielectric anisotropy $\Delta\varepsilon = +8.2$, rotational viscosity $\gamma = 80\,\text{mPa}\cdot\text{s}$, $\Delta n = 0.1$, $K_{11} = 9.7\,\text{pN}$, $K_{22} = 5.2\,\text{pN}$, and $K_{33} = 13.3\,\text{pN}$. The strong anchoring at both substrates with anchoring energy much larger than $10^{-3}\,\text{Jm}^{-2}$ is assumed such that the LCs does not rotate at the interface. The surface pretilt angle for both substrates is 2°, the cell gap is $4\,\mu\text{m}$, and the initial rubbing direction is 80° with respect to the horizontal component of the fringe electric field. Further, the number of LC layers per $1\,\mu\text{m}$ along the y axis in the 2-dimensional simulator are assumed to be 8 and the calculated LC orientation in this article is achieved after a relaxation time of 100 ms.

Simulation Results and Discussion

To investigate electro-optic characteristics along the electrode structures in the FFS mode, the width of the pixel electrode and the distance between pixel electrodes is reduced while maintaining the ratio of l/w at 1.5. Figure 2 shows the light efficiency and operating voltage (V_{op}) for three different electrode structures. The light efficiency indicates average value in a distance from pixel to counter electrode. When $w = 3\,\mu\text{m}$ and $l = 4.5\,\mu\text{m}$, the light efficiency is 0.78, and the V_{op} is 4 V. When $w = 2\,\mu\text{m}$ and $l = 3\,\mu\text{m}$, light efficiency and V_{op} increase to 0.80 and 4.7 V. Also, as w and l decrease to $1\,\mu\text{m}$ and $1.5\,\mu\text{m}$, the light efficiency increases to 0.88. This value is almost the same as that of the LC with negative dielectric anisotropy, however, the V_{op} increases to 8 V.

We investigate why the transmittance increases when w and l decrease. Figure 3 reveals light efficiency and the LC director orientation along the electrode position in the white state depending on

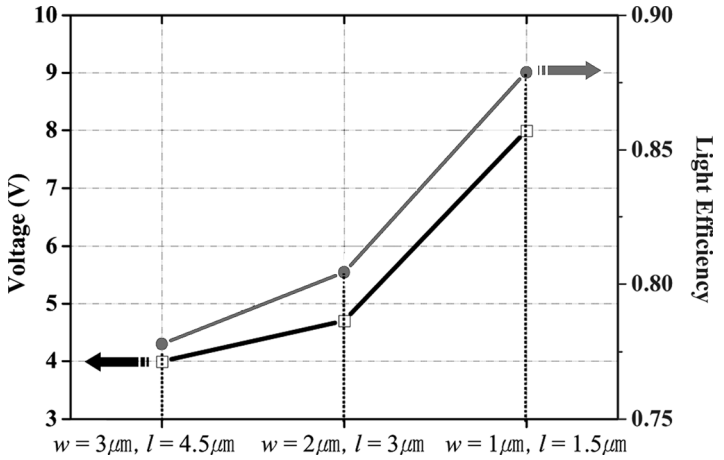

FIGURE 2 Operating voltages and light efficiency for different electrode structures.

electrode structure. In the conventional FFS device with an electrode width of 3 μm, the transmittance is lowest at the center of the pixel electrode and highest at the edge of the electrode [12]. In the device, the fringe-electric field, whose intensity of E_y and E_z is dependent on the horizontal as well as the vertical position, is generated such that the dielectric torque on the LC is electrode-position dependent, and thus the LC orientation periodically changes along electrodes, resulting in oscillating transmittance as shown Figure 3(a). However, when the width of the pixel electrode decreases to 2 μm and 1 μm, the light efficiency is almost the same along the electrode position,

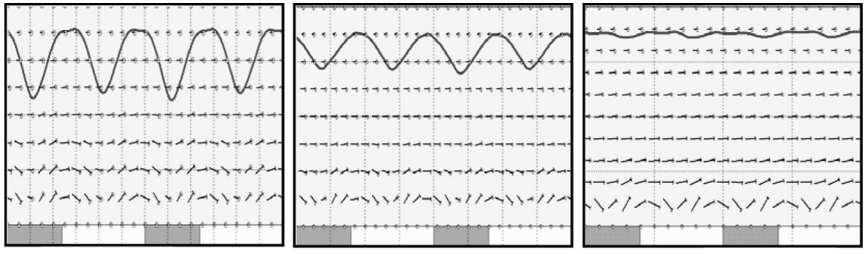

FIGURE 3 Light efficiency and the LC director orientation dependent on electrode position in the white state when the electrode width is (a) 3 μm, (b) 2 μm, and (c) 1 μm.

i.e., independent of the electrode position. To understand this in detail, the LC orientation in a white state is calculated at three different electrode positions, as shown in Figure 4. When $w = 3\,\mu m$, the maximal twisted angle from the initial position is strongly dependent on electrode position such that it is about 70° near the bottom substrate at the edge of the electrode (a_1) and about 30° around the middle of the cell at the center of the electrode (a_3). From these director profiles, we can assume that light modulation does occur using polarization rotation effect at position a_1 and phase retardation effect at position a_3. When w is 1 μm, a maximal twist angle larger than 70° occurs just near the bottom electrode surface, that is, below $z/d = 0.1$, at electrode

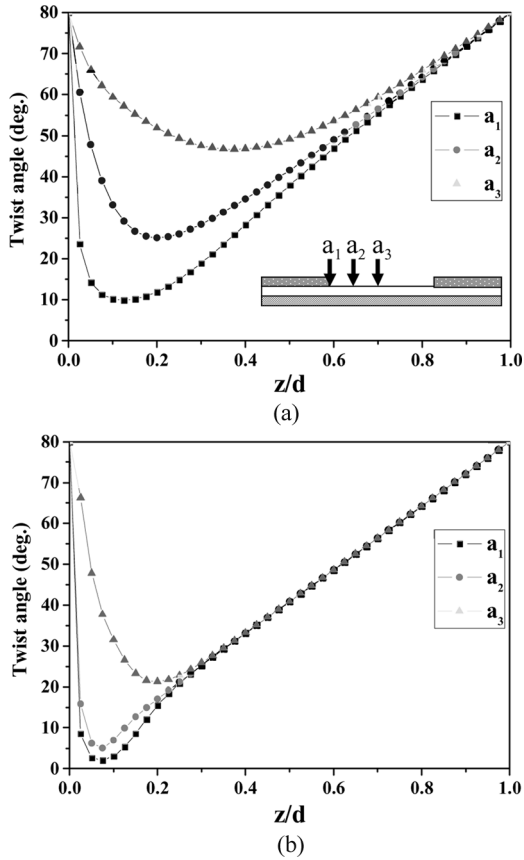

FIGURE 4 Director profile of twist angle at three different electrode positions; (a) $w = 3.0\,\mu m$, $l = 4.5\,\mu m$, and (b) $w = 1.0\,\mu m$, $l = 1.5\,\mu m$.

positions a_1 and a_2. Even at electrode position a_3, it is larger than 60° and its vertical position is below $z/d = 0.2$. These large twist angles at all electrode positions imply that the mechanism of light modulation may be changed from mixed concepts of both polarization rotation and phase retardation effects to polarization rotation only.

To confirm which effect plays a role in light modulation, the transmittance is calculated by rotating the LC director of the white state at electrode positions a_1 and a_3 under the crossed polarizer counterclockwise, as shown in Figure 5. As indicated, the transmittance at a_3 is a maximum with 0.72 at $\Phi = 12°$ and then the transmittance appears to be minimum with 0.1 at 57°, i.e., at an every additional 45°, the maxima and minima of light transmittance does occur alternatively. However, the transmittance in a_1 does not show an extinction of light like that at a_3, though it oscillates due to the twist orientation of the LC. From this one can conclude that light modulation occurs using polarization rotation effect at a_1, while it occurs using phase retardation effect at a_3. However, when w and l decrease, the degree of oscillation of the transmittance at a_3 is greatly reduced and, in addition, the angle of Φ, which shows the minima and maxima of the transmittance, is the same each other at the two electrode positions a_1 and a_3, The condition for the extinction of light like in the previous case. This means that light modulation occurs using polarization rotation effect only.

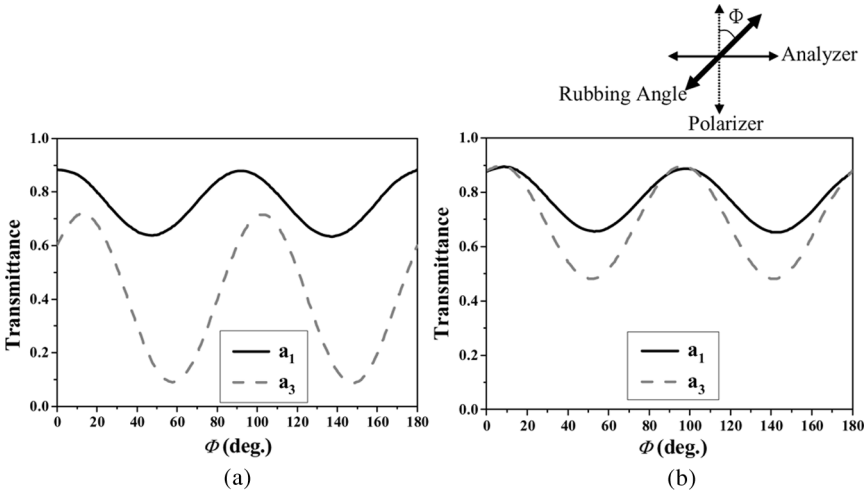

FIGURE 5 Transmittance as a function of the rotation angle of the crossed polarizer in the white state; (a) $w = 3\,\mu m$, $l = 4.5\,\mu m$ and (b) $w = 1\,\mu m$, $l = 1.5\,\mu m$.

Now, if the transmittance is determined only by the polarization rotation effect in the FFS mode, the first term in the transmittance equation should be neglected, that is, the optimal cell retardation value that shows maximal light efficiency should be changed when the electrode structure is changed. Therefore, we calculated the transmittance as a function of $d\Delta n$ (here, d is fixed) for two different electrode conditions and compared it with the 90° twisted nematic (TN) mode (See Fig. 6). The optimal cell retardation value is 0.40 μm in the normal FFS mode and is 0.48 μm in the TN mode. Interestingly, when w and l decrease to 1 μm and 1.5 μm, the optimal cell retardation value becomes 0.48 μm which is the same as that of the TN mode, confirming again that the light is modulated by the polarization rotation effect.

Next, we calculate the response time characteristic depending on the electrode structures. In general, the rise time of the LC device is strongly related to the intensity of the electric field and the rotational viscosity of the LC. In conventional FFS mode, the field-dependent LC reorientation is first determined by dielectric torque at a_1 and then by following elastic torque associated with interactions between neighboring LC molecules at a_3. This two-step process may cause rising response time to be slow compared to the IPS mode, of which the LC orientation between electrodes is purely determined by dielectric

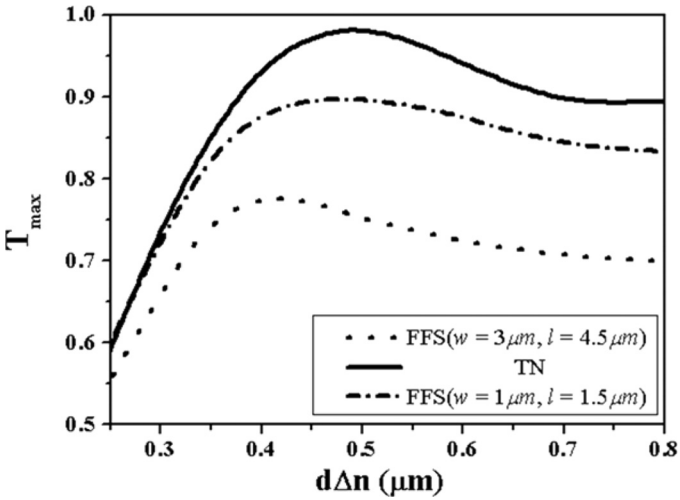

FIGURE 6 Calculated maximum transmittance as a function of cell retardation value depending on electrode structure in the FFS mode compared to the TN mode.

TABLE 1 Calculated Response Time and Elastic Energy Dependent on Electrode Structure

w, l	3 μm, 4.5 μm	1 μm, 1.5 μm
τ_{on}(ms)		
90%	27	11
80%	25.5	10.5
τ_{off}(ms)		
90%	31	16
80%	23	12
Elastic energy	3.59	13.00

torque [14]. The decay time is purely determined by restoring the force of the LCs such that it is inversely proportional to the twist elastic constant K_{22} of the LC, and directly proportional to the rotational viscosity and d^2. In addition, the larger the difference in elastic energy between the on and off states, the faster the relaxation time be comes. Therefore, we expect that the FFS device with $w = 1\,\mu m$ and $l = 1.5\,\mu m$ should give rise to a faster rising time than those with- $w = 3\,\mu m$ and $l = 4.5\,\mu m$ because the field-response LC reorientation in the former is purely determined by dielectric torque and in addition, the applied field intensity is higher in the former than in the latter. Even in decaying time, the former should be faster than the latter because the LC deformation is much larger in the former than in the latter. Finally, the response time and elastic energy in white state are calculated as presented in Table 1. When $w = 3\,\mu m$, the rising and decaying time is 27 ms and 31 ms, respectively, in case of 90% variation of the transmittance. However, with narrowed w and l, the rising time is decreased by about 58% (27 ms → 11 ms), and the decaying time is also decreased by about 47% (31 ms → 16 ms), which is associated with an increase in the average elastic energy at all of the electrodes when w and l become narrow.

CONCLUSION

This study demonstrates how light modulation varies as the electrode structure in the FFS cell changes when an LC with positive dielectric anisotropy is used. In the conventional FFS mode, phase retardation and polarization rotation effects exist along the electrode positions. However, when the electrode width and distance between electrodes is reduced to less than 2 μm, only the polarization rotation effect exists, like we see in the TN cell. Consequently, the optimal cell retardation value in such an FFS cell is the same as that of a TN cell.

Furthermore, the response time is also improved due to strong dielectric torque and a high force of restitution.

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