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Optimal Cell Retardation Value of a Fringe-Field Switching Mode Using a Liquid Crystal with Negative Dielectric Anisotropy

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Optimal cell retardation value at which the maximum transmittance occur in a fringe-field switching (FFS) mode is analyzed theoretically and experimentally. In the device, the rotation angle of liquid crystal (LC) director is dependent on electrode position. Nevertheless, the transmittance can be described using a uniaxial medium model within a certain cell retardation value like in the in-plane switching (IPS) mode, where the effective birefringence was reduced to about 76% of the original value.

Keywords: cell retardation; effective birefringence; fringe-field switching

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INTRODUCTION

Recently, the image quality of the liquid crystal displays (LCDs) is greatly improved, owing to the development of the new LC modes such as in-plane switching (IPS) [1], fringe-field switching (FFS) [2,3], multi-domain vertical alignment (MVA) [4] and patterned VA (PVA) [5]. The LC-TV using the IPS mode is commercialized at present and the technology is well known to the LCD researchers. Nevertheless, the device has several disadvantages such as low transmittance, high driving voltage and narrow cell gap margin.

The LC mode that can overcome such demerits of the IPS mode is the FFS mode. In the FFS mode, the LCs are homogenously aligned under crossed polarizers like in the IPS mode. However, the electrode structures are totally different from that of the IPS mode such that the ratio of electrode distance to electrode width is always smaller than 1 or no horizontal distance between pixel and common electrode. Consequently, the IPS mode utilizes horizontal field while the FFS mode uses a fringe field that has both horizontal and vertical components. The difference causes electro-optic characteristics of both devices to be different each other and further in the FFS mode, the electro-optic characteristics strongly depend on sign of dielectric anisotropy of the LC either positive (+LC) or negative (–LC). Extensive works on the FFS mode have been reported, regarding to light efficiency depending on the type of the LC [6], rubbing direction [7] and cell gaps using the −LC [8] and +LC [9], and operating voltage depending on cell gaps [10].

Recently, to describe the transmittance of the IPS cell, a uniaxial medium model was used and the results showed that the effective birefringence $\Delta n_{\rm eff}$ was reduced to 80% of the original value [11]. However, in the FFS mode using the +LC, a white state cannot be described by this model and the transmittance can be described by a mixing concept of birefringence and optical rotation [12]. In this paper, we study an optimal cell retardation value at which the maximum transmittance occurs using the −LC.

THEORITICAL BACKGROUND AND SWITCHING PRINCIPLE OF THE FFS MODE

The transmittance of the LC cell where homogeneously aligned nematic LC layer exists under crossed polarizers can be described by

$$T/T_o = \sin^2(2\psi)\sin^2(\pi d\Delta n/\lambda) \qquad (1)$$

where ψ is an angle between the transmission axis of the crossed polarizer and the optic axis of the LC, d is a cell gap, Δn is birefringence of the LC layer and λ is wavelength of an incident light. However, there exists some quantitative difference from the real IPS [11] and FFS devices since the LC layers near surfaces cannot rotate due to strong anchoring between LC and alignment layer. In other words, ψ is not constant along the LC layer with bias voltage and effective birefringence is also a function of applied voltage. Therefore, to explain the IPS cell correctly using a uniaxial medium modeling, Eq. (1) was changed by introducing the ψ_{app} and Δn_{eff} as follows [11]:

$$T = \sin^2(2\psi_{app})\sin^2(\pi d\ \Delta n_{eff}/\lambda) \qquad (2)$$
$$T = A\ \sin^2(\pi d B\ \Delta n/\lambda)$$

where ψ_{app} is the apparent optic axis rotation angle, and A and B are fitting parameters. However, this model considers the LC layer only between electrodes where the horizontal field exists mainly, that is, the deformation of the LC layer assumes to be constant along horizontal direction.

In the FFS mode, the LC director orientation is rather complex compared to that in the IPS mode such that the rotation angle of the LC director depends on electrode position since the dielectric torque to rotate the LC is periodically oscillating along electrode position. Figure 1 shows a simulated result of the LC director orientation in a

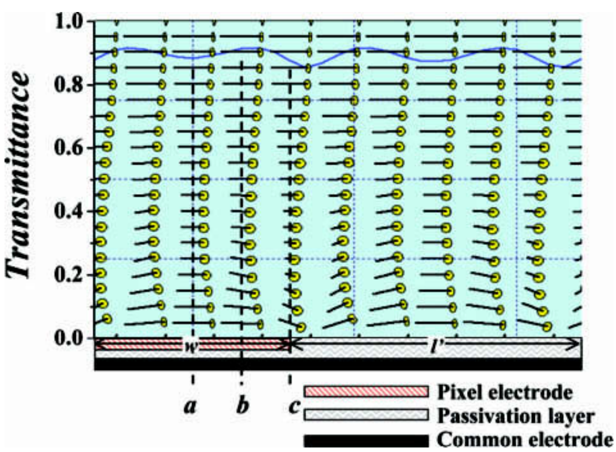

FIGURE 1 Configuration of the LC molecules and corresponding transmittance in the white state of the FFS mode using a $-$LC.

white state along with the electrode positions and their corresponding transmittance. For this calculation, we used the commercially available software LCD Master (Shintech, Japan). The LC has physical properties, such as $\Delta\varepsilon = -4.0$, $\Delta n = 0.09$, $K_{11} = 13.5\,\text{pN}$, $K_{22} = 6.5\,\text{pN}$ and $K_{33} = 15.1\,\text{pN}$. Optical transmittance was calculated based on the 2×2 extended Johns matrix method. The width (w) of the pixel electrode and the distance (l') between them are $3\,\mu\text{m}$ and $4.5\,\mu\text{m}$, respectively. The surface pretilt angle for both substrates is 2°, the initial rubbing direction is 12° with respect to the horizontal direction, and the cell gap is $4\,\mu\text{m}$. As can be clearly seen, the LC director orientation strongly depends on electrode position and as the results, the transmittance oscillates, too, with a periodic unit from distance a (electrode center) to c (electrode edge) approximately. The detail observation informs that at position a, the LC layer is twisted most around the middle of the cell while at position c, it is twisted near electrode surface due to strong horizontal field. This indicates that in the FFS mode, the ψ_{app} cannot be defined as a single eigenvalue; instead, it cannot be defined at position c since the light modulation occurs with polarization rotation [12]. Nevertheless, the contribution to total transmittance from each electrode position is about the same each other.

RESULTS AND DISCUSSION

First of all, the LC orientation is calculated as a function of applied voltages at three electrode positions, as shown in Figure 2. The maximum twist angle increases as the electrode position approaches electrode edge at the same voltage and also, the most twisted angle near electrode edge occurs at $z/d = 0.2$ but moves to higher vertical position, $z/d = 0.4$ as the electrode position approaches the electrode center. Next, we tried to calculate the apparent optic axis rotation

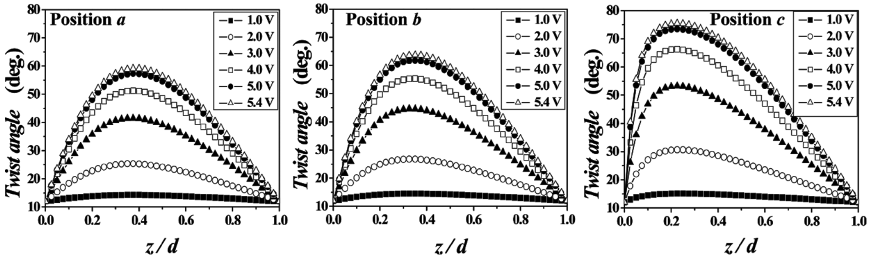

FIGURE 2 Orientation of the LC's twist angle as a function of applied voltage at three different positions a, b, and c.

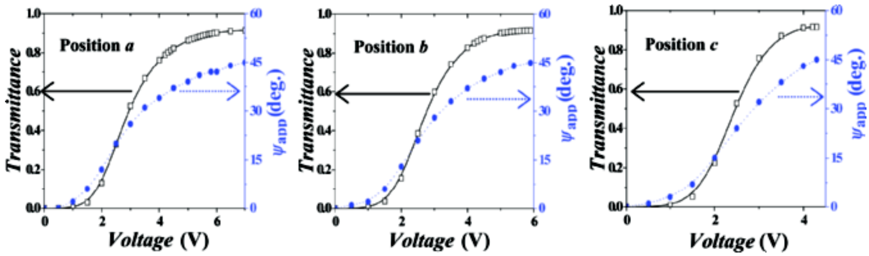

FIGURE 3 Calculated transmittance and the LC's apparent rotation angle as a function of applied voltage at three different positions *a*, *b*, and *c*.

angle with increasing voltage up to an operating voltage (V_{op}) at which the maximum transmittance occurs, as shown in Figure 3. At position *a*, the optic axis of the LC in on-state could be achieved by calculating an angle at which the transmittance does occur less than 0.1 by rotating crossed polarizers. As indicated, ψ_{app} was 45° when the transmittance reaches the maximum. However, at position *b*, the optic axis of the LC in on-state could not be achieved since the clear dark state cannot be achieved at any angle of rotation of the crossed polarizer. Instead, if we consider the angle that shows the least transmittance (higher than about 0.1), ψ_{app}, it can be obtained and the results show similar behavior compared to those at position *a*. At position *c*, the least transmittance was larger than 0.3 so that the optic axis of the LC in on-state do not exist. However, if we define ψ_{app} in a similar way like in the position *b*, it also reaches 45° when the transmission reaches the maximum. In the IPS mode which considers the LC layers between electrodes, that is, the region in which the LC layer experiences twist deformation mainly by in-plane field, the rotation angle of ψ_{app} was clearly 45° so that the transmittance of the cell can be governed by Δn_{eff} according to Eq. (2).

In the FFS mode, the LC orientation depends on electrode position. Therefore, we have calculated the maximum transmittance as a function of cell retardation vale while changing Δn at fixed cell gap of 4 µm at three different electrode positions, as shown in Figure 4. Here, T_{ave} indicate transmittance indicates the average value of light transmittance at a distance of 7.5 µm ($= w + l'$). The results show that the optimal $d\Delta n$ that shows maximum transmittance is 0.35 µm at positions *a* and *b*, however at *c*, it is 0.36 µm. Consequently, the maximum occurs at 0.36 µm. Next, the cell-retardation dependent T_{ave} curve is fitted using Eq. (2) and interestingly, the fitting curve matches well, up to

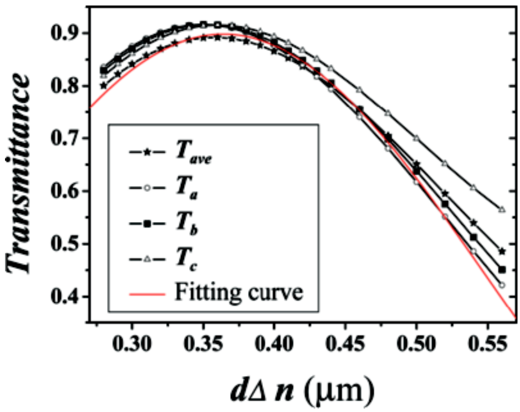

FIGURE 4 Calculated maximum transmittance as a function of cell retardation value at three different positions.

a cell retardation value of about 0.48 μm but larger than that value, the fitting curve starts to deviate from calculated results. This is due to from the LC orientation at position c, as clearly seen in Figure 4, with high twist angle near the bottom substrate where the optic axis does not exist at this position. Nevertheless, the Eq. (2) is valid up to a certain cell retardation value and the fitting results show that A and B are 0.90 and 0.755, respectively, that is, the ratio of $\Delta n_{\mathrm{eff}}/\Delta n$ is 0.755 at 550 nm with light efficiency of 0.9.

To confirm the results, we have fabricated test cells with a cell gap of 3.85 μm and filled the LCs with different birefringences. The voltage-dependent transmittance curves were measured and then the maximum transmittance was plotted as a function of cell retardation values, as shown in Figure 5. The experimental results also show that the B is 0.757, which is in good agreements with the calculated results. If we assume that the other LC physical parameters such as dielectric anisotropy, viscosity, and elastic constants do not affect the transmittance much, we conclude that the measured data can be well fitted by Eq. (2) with the ratio of $\Delta n_{\mathrm{eff}}/\Delta n = 0.757$.

Finally, we have also calculated the optimal cell retardation value as a function of cell gap, as shown in Figure 6. In the FFS mode, the light transmittance decreases with decreasing cell gap [8], which means that the LC orientation changes. The results show that the optimal cell retardation value decreases with increasing cell gap slightly, that is, the ratio of $\Delta n_{\mathrm{eff}}/\Delta n$ approaches about 0.8 like in the IPS mode of 4 μm cell gap [11].

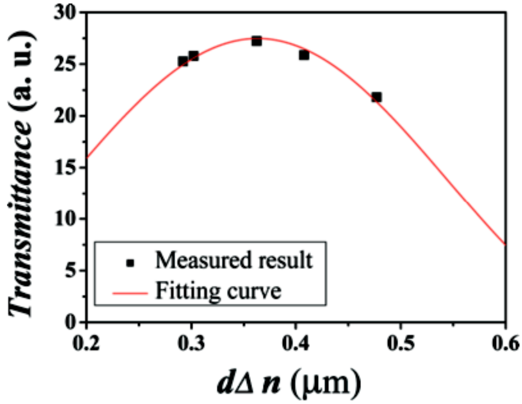

FIGURE 5 Measured maximum transmittance as a function of cell retardation value. The solid line is the fitting result.

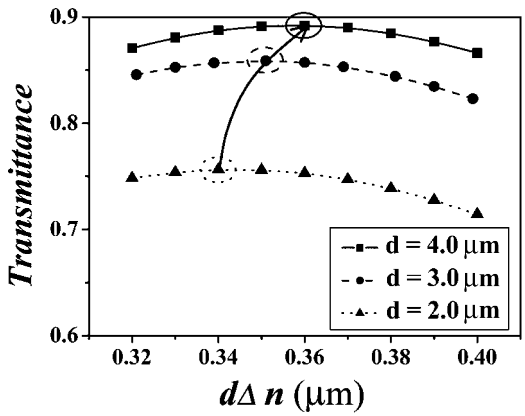

FIGURE 6 Calculated maximum transmittance as a function of cell retardation value at three different cell gaps.

CONCLUSION

We have analyzed the optimal cell retardation value that shows maximum transmittance in the FFS mode using a LC with negative dielectric anisotropy. Unlike in the IPS mode, the LC rotation angle depends on electrode positions such that the LC at the center of electrode does show optic axis in on state while the LC at the edge of electrodes does not show the optic axis. Nevertheless, the results show that the transmittance behavior follows a uniaxial medium model like in the IPS mode up to a certain cell retardation value and the effective birefringence reduces to about 76% of the original value, which is smaller than that in the IPS mode.

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