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Analysis of Optimal Phase Retardation of a Fringe Field-Driven Homogeneously Aligned Nematic Liquid Crystal Cell

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We studied the optimal cell retardation value that shows the maximal transmittance in a fringe-field-driven homogeneously aligned (HA) nematic liquid crystal (LC) cell. When the LC with positive dielectric anisotropy is used, the transmittance is much higher than that of an in-plane-field-driven HA cell. The unexpected electrooptic behaviors are caused because the transmittance of light from a deformed LC in a white state cannot be explained using only the uniaxial medium model that describes an in-plane-field-driven HA cell. [DOI: 10.1143/JJAP.43.1028]

KEYWORDS: cell retardation value, fringe field, liquid crystal, in-plane field

1. Introduction

Nowadays, the image qualities of liquid crystal displays (LCDs) have been greatly improved by several wide-viewing-angle technologies. Among them are in-plane switching (IPS)[1–4] and fringe-field switching (FFS)[5–10] modes utilizing the concept of an in-plane rotation of the LC director. In both devices, the LCs are homogenously aligned (HA) at the initial state and the electrodes exist only on one substrate. In the IPS mode, the distance (l) between the pixel and the counter electrodes is always larger than that of the cell gap (d) and the width (w) of the electrodes such that an in-plane field is generated with a bias voltage. While in the FFS device, l is either smaller than d and w or zero such that a fringe electric field that has both horizontal and vertical components is generated with a bias voltage. In this way, in the IPS device, the horizontal field drives the HALC molecules to rotate almost in-plane whereas the fringe-field performs this role in the FFS mode. However, the different driving fields in these two devices cause a difference in their electrooptic behavior. The most notable difference is that an FFS device with LCs of negative dielectric anisotropy ($-$LCs) exhibits a very high light efficiency that is comparable to that of the twisted nematic (TN) device. That is, the light transmittance is much higher than that of an IPS device. Also the light efficiency of an FFS device is dependent on the type of LC and the rubbing angle for LCs of positive dielectric anisotropy (+LCs), unlike an IPS device.[9,10] In an FFS device using a $-$LC, the transmittance is higher but the response time is slower than for a device using a +LC. Therefore, recently, an FFS device with a +LC has been commercialized.[11]

In this paper, we studied the optimal cell retardation value that exhibits maximum light transmittance and the results show that an FFS device with a +LC needs a much higher cell retardation value than for a device using the IPS mode. From simulations describing the director distribution and light transmittance, and from experiments, we demonstrate the difference between the two devices.

2. Results and Discussion

In the IPS mode where the uniaxial birefringent medium is under a crossed polarizer, the normalized light transmission is given by

$$T/T_0 = \sin^2(2\phi(V))\sin^2(\pi d\Delta n(V)/\lambda), \qquad (2.1)$$

where ϕ is a voltage-dependent angle between the transmission axis of the crossed polarizer and the optic axis of the LC (or apparent optic axis rotation angle[11]), $d\Delta n$ is the voltage-dependent cell retardation value and λ is the wavelength of incident light. In the off state with no bias voltage, the optic axis of HALC molecules is coincident with the polarizer axis, that is, ϕ is zero so that the cell appears to be black. In the on state with a bias voltage, ϕ starts to deviate from the axes of the crossed polarizers and the cell appears to be white when it is at 45°. The transmittance is also dependent on the cell retardation value $d\Delta n$. If the HALC makes an angle of 45° with the polarizer axis, the $d\Delta n$ should be $\lambda/2$ to exhibit the maximum transmittance, that is, it should be 275 nm with 550 nm incident light. However, in the IPS mode, the cell retardation value is voltage dependent and decreases with increasing voltage. In other words, when a voltage is applied, the whole LC inside a cell cannot rotate in plane since the LC at the surface is strongly anchored, thus it cannot rotate by voltage application. In a previous work,[12] using the uniaxial medium model in which the HALC molecules rotate uniformly accompanied by the change in Δn, an effective birefringence Δn_{eff} was introduced to replace Δn in eq. (2.1) and ϕ was replaced by an apparent optic rotation angle ϕ_{app} in eq. (2.1). Δn_{eff} was found to be $0.8\Delta n$ for the IPS cell to show the maximum transmittance for the +LC, indicating that the cell retardation value should be approximately 343.8 nm for incident light of 550 nm and also the ϕ_{app} is 45° when the transmittance is at maximum.

Now, we investigate the difference between the IPS mode using a +LC and the FFS mode using a +LC by simulation. For simulations, we use the commercially available software "LCD Master" (Shintech, Japan). Figure 1 shows the configuration of the LCs along with the electrode positions and their corresponding transmittance. Here, the width of the pixel electrodes and the distance between them are 3 µm and 4.5 µm, respectively. The surface pretilt angle for both substrates is 2°, the initial rubbing direction is 78° with respect to the horizontal component (E_x) of the fringe electric field, and the cell gap is 4 µm. A LC with physical

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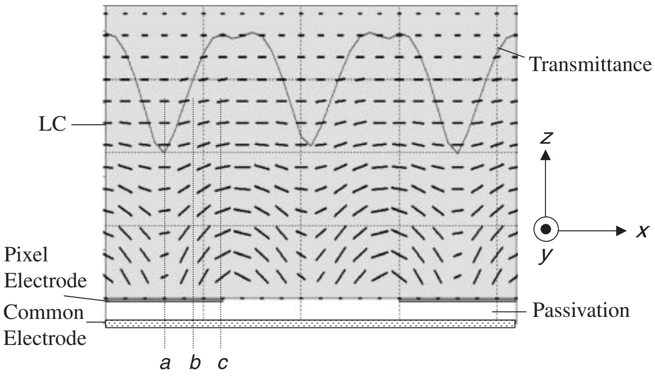

Fig. 1. Configuration of the LC molecules and corresponding transmittance in the white state of the FFS mode using a +LC.

properties (dielectric anisotropy $\Delta\varepsilon = 8.2$, $\Delta n = 0.105$, $K_1 = 9.7pN$, $K_2 = 5.2pN$, $K_3 = 13.3pN$) is used and strong anchoring of the LC to the surface is assumed. From Fig. 1, it is clearly observed that the LC deformation is different depending on the electrode positions and consequently, the transmittance changes along the electrode position and also oscillates periodically. Here *a*, *b* and *c* represent positions at the center, between the edge and the center, and the edge of the pixel electrodes, respectively. Since the transmittance from the center to the edge of the pixel electrode is a repeatable unit that can represent the characteristic of the whole transmittance, investigating the director profile in that distance is required to understand how the light is modulated.

Figure 2 shows the LC director profile for the twist and tilt angles at three different positions *a*, *b*, and *c* when using the +LC in the FFS mode. Interestingly, the LC molecules in *c* are twisted by 68° near $z/d = 0.18$, indicating that a strong horizontal field near the bottom surface causes the LC director to rotate almost parallel to the E_x as shown in Fig. 2(a). As a result, the LC director configuration is similar to that of the low twisted TN device except for strongly anchored LCs near the bottom surface. In *b*, the maximum twist angle for the +LC is approximately 50° at $z/d = 0.25$ while in *a*, the maximum twist angle is only about 33° at $z/d = 0.4$. Considering the tilt angle, the upward tilt angle occurs most strongly in *b* due to the existence of a strong vertical field and the maximum tilt angle in *b* is about 42° whereas it is only about 8° in *a*. Since in the IPS mode, the LC deformation is largest near the mid-director with a low tilt angle along the LC layer, the profile of the LC in the white state with respect to *a* is similar to the IPS mode. Therefore, this indicates that for the FFS device with a +LC, the light transmittance in *a* is low since the ϕ should be 45° to obtain the maximum transmittance according to eq. (2.1). Furthermore, one can understand that the transmittance equation cannot be applied to locations in *b* and *c* where the LC twists maximally below the midlayer with a high degree of tilt angle.

To determine the optimal cell retardation value at each position, we calculated the transmittance as a function of cell retardation value at three positions. There are two ways of obtaining the optimal cell retardation value of the device at which a maximum transmittance is achieved. The first one is to change the cell gap while keeping the LC fixed and the second one is to change the LCs while keeping the cell gap fixed. In a conventional device such as a TN device, the same optimal cell retardation value is shown irrespective of what is changed only if the cell retardation values remain the same. However, in the FFS device, a different value is shown since the transmittance changes with changing cell gap although the cell retardation values remain the same.[13] Here the cell gap is fixed and the birefringence of the LC is varied. As shown in Fig. 3, the maximum transmittance in *a* and *c* occurs when the $d\Delta n$ values are 0.36 µm and 0.44 µm respectively, while the transmittance keeps increasing in *b*

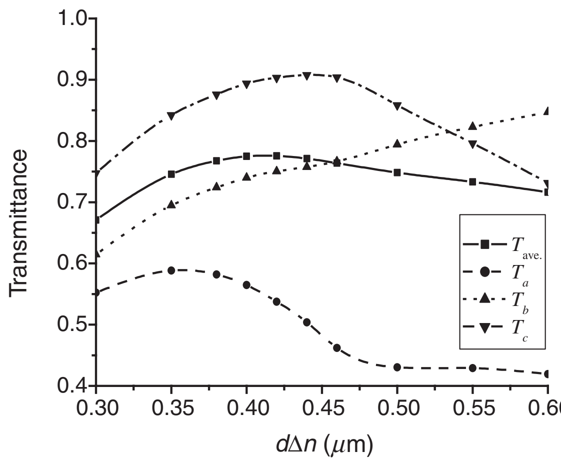

Fig. 3. Calculated transmittance as a function of cell retardation value at three different positions where "AVE" indicates the average value of light transmittance at a distance of 7.5 µm.

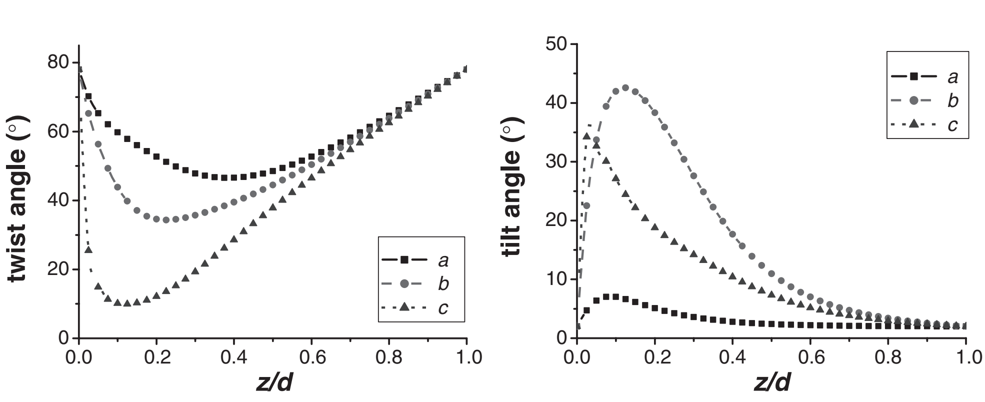

Fig. 2. Distribution of the LC's twist and tilt angles at three different positions in the FFS mode.

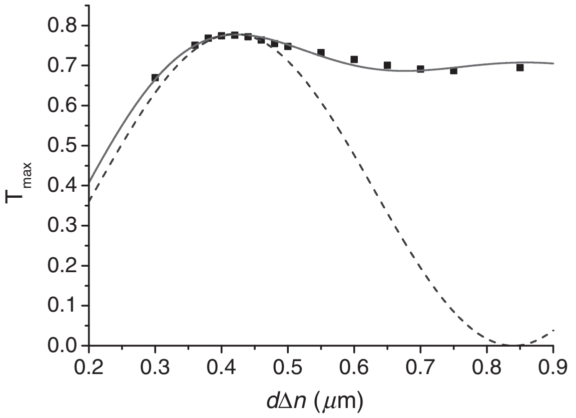

Fig. 4. Calculated maximum transmittance as a function of cell retardation value. The solid lines are fitting results. The solid and dashed lines are fitting results using the transmittance equation of both the IPS and normally white TN modes, and only the IPS mode, respectively.

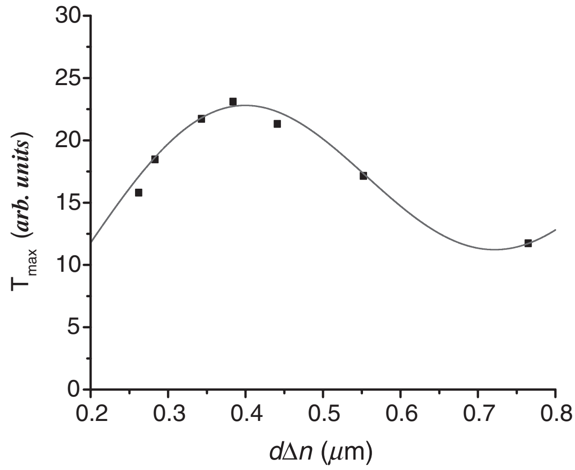

Fig. 5. Measured maximum transmittance as a function of cell retardation value. The solid line is the fitting result.

with increasing $d\Delta n$. The former value is close to that in the IPS mode and the latter is close to the first minimum condition of the TN mode.[14] The average transmittance defined as

$$T_{\mathrm{ave}} = \sum_{x=0}^{x=7.5} T(x)$$

shows that maximum transmittance occurs at a $d\Delta n$ value of 0.42 µm, which is much higher than that of the IPS mode. From the results, one can consider the transmittance behavior intuitively as both the IPS and the TN behavior are mixed with different weight percentages since the transmittance in *c* is higher than that in *a*. Therefore, the transmittance in the FFS mode using a +LC can be described as

$$T/T_0 = A\sin^2(B\pi d\Delta n/\lambda) + C\left(1 - \frac{\sin^2(\pi/2\sqrt{1+(2Dd\Delta n/\lambda)^2})}{1+(2Dd\Delta n/\lambda)^2}\right) \quad (2.2)$$

where *A*, *B*, *C*, and *D* are fitting parameters. The first term and the second term in eq. (2.2) come from eq. (2.1) and the Gooch and Tarry's transmittance equation for the TN mode, respectively. Figure 4 shows the calculated maximal transmittance depending on the cell retardation value, where the maximal transmittance indicates a maximal value in voltage-dependent transmittance curves in which the transmittance is an average transmittance T_{ave} along the electrode. Here, the transmittance is obtained by changing the birefringence of the LC at a fixed cell gap of 4 µm while all other calculated parameters remain the same as described above. The calculated data do not coincide with the fitting curve based on eq. (2.1) (dotted line) where the extinction of transmittance should occur depending on $d\Delta n$ values but matches well with the fitting curve based on eq. (2.2) where *A*, *B*, *C*, and *D* are 0.1, 0.54, 0.7, and 1.16, respectively.

Figure 5 shows an experimental result that shows the maximum transmittance as a function of $d\Delta n$ where the gap is fixed at 3.9 µm. Here, the pixel electrode width is 3 µm, the distance between pixel electrodes is 5.5 µm and the LCs with different birefringence are tested so that the operating voltages for each cell are mutually different. As shown in Fig. 5, the experimental data coincide well with the fitting

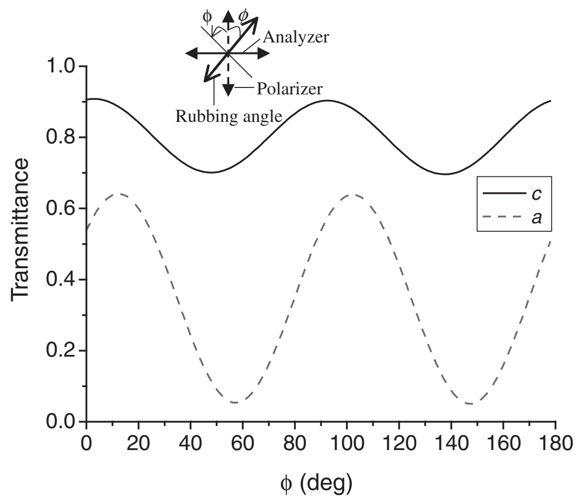

Fig. 6. Transmittance as a function of the rotation angle of the crossed polarizer in the white state of positions *a* and *c*.

curve based on eq. (2.2). Consequently, the results reveal that the transmittance in the device can be described well by eq. (2.2) consisting of the transmittance behavior of both the IPS and the TN modes. Nevertheless, one should understand that *A*, *B*, *C*, and *D* are voltage-dependent, that is, if the cell gap is changed while fixing the LC, the operating voltage that shows a maximal transmittance is changed, indicating that the values of the parameters are changed.

To confirm the results, we calculated the transmittance in *a* and *c* by rotating the axes of the crossed polarizer counterclockwise, as shown in Fig. 6. The simulation conditions are the same as those described above. As indicated, the transmittance in *a* is a maximum at 12° since the maximum twist angle is 33° and follows $\sin^2(\pi d\Delta n/\lambda)$ almost exactly, with extinction of the transmittance every 45°. However, the transmittance in *c* does not show an extinction of light, though it oscillates due to the twist alignment of the LC. That is, in the device, light modulation occurs in two different ways and it is electrode-position dependent.

Finally, Fig. 7 describes the transmittance as a function of

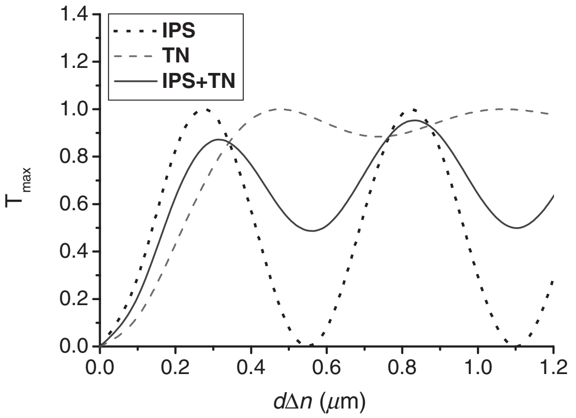

Fig. 7. Calculated maximum transmittance as a function of cell retardation value for the IPS, TN, and TN+IPS modes.

$d\Delta n$ using the equation for the IPS, TN, and IPS plus TN modes with equal weight ratio. This indicates that in a device which modulates light using a mixed IPS and TN mode, the optimal cell retardation value exists between the two first minimum conditions 0.275 µm and 0.48 µm at a wavelength of 550 nm that show the maximal transmittance in eq. (2.1) and the Gooch and Tarry's transmittance equation for the TN mode, respectively, which is $0.275\,\mu m < d\Delta n < 0.48\,\mu m$.

3. Summary

In summary, we studied the optimal cell retardation value that exhibits the maximum transmittance in the FFS mode using a +LC. The results show that two different modes of light modulation, namely, birefringence (IPS) and optical rotation (TN) exist such that to maximize light efficiency, the device requires a higher cell retardation value than that required in the IPS mode but a lower retardation value than that required in the TN mode. This result is very important for the design of a FFS-LCD with high brightness.

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