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Color Tracking Analysis of the Fringe-Field-Switching Cell Using a Liquid Crystal with Negative Dielectric Anisotropy

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Color tracking in a fringe-field driven homogenously aligned nematic liquid crystal cell [named fringe-field switching (FFS)] has been investigated. In the in-plane switching (IPS) device and the FFS device using liquid crystals (LCs) with negative dielectric anisotropy (−LC), the LCs rotate almost in plane except for surfaces where the color tracking occurs for cell retardation value that shows a maximal transmittance. In the IPS device, authentic color appears at a very low cell retardation value that exhibits a low transmittance and bluish white. However, the FFS device shows authentic color even at a relatively high cell retardation value 0.30 µm so that high transmittance and greenish white are kept. [DOI: 10.1143/JJAP.44.225]

KEYWORDS: color tracking, fringe-field switching, liquid crystal, authentic color

1. Introduction

Nowadays, the application range of liquid crystal displays (LCDs) has expanded a lot from small size ones for use in mobile phones to large size ones for use in monitors and LC TV. In addition, high quality color reproduction for the LCDs is in high demand to extend to applications by realizing real pictures. Especially, for TV application the LCDs should show a high image quality like in the cathode-ray-tube (CRT) display. In order to realize such image quality, the color tracking that is defined as a change of a color chromaticity as the grey scale changes should not occur (in such a case, the cell is called to show an authentic color) and the gamma curves should not be changed as the viewing direction changes without a color shift.[1–3]

Recently, the image quality of the LCDs has been greatly improved with the development of the new LC modes. Among them are both in-plane field switching (IPS)[4,5] and the fringe-field switching (FFS)[6–8] modes that utilize the concept of in-plane rotation of the LC director. However, since the driving field is different in each mode, the electro-optic characteristics of both modes are different from each other. Especially, the FFS mode shows a much higher transmittance than that of the IPS mode. Further, both modes have a relatively good uniformity in all grey levels of transmittance compared with that of the twisted nematic (TN) mode, owing to the in-plane rotation of the LC director. Nevertheless, both modes reveal a color tracking at a normal direction such that the color chromaticity is changed as the grey scale changes, since the LC director near the substrates does not fully rotate.[1] In order to overcome such a problem in the IPS mode, a cell with very low retardation value 0.23 µm that did not reveal the color tracking was suggested.[2] However, the authentic-color IPS cell becomes bluish at all gray scale levels and causes a decrease of transmittance by about 15%, and thus the cell requires an adjustment of the light source.

In this paper, we have analyzed the color tracking of the FFS mode using LC with negative dielectric anisotropy (−LC). From simulations describing the director distribution and light transmittance, and from experiments, we demonstrate an authentic-color FFS cell using a −LC, showing greenish white and high transmittance.

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2. Results and Discussion

In the FFS mode, the LCs are homogeneously aligned with an optic axis coincident with one of the crossed polarizers. Therefore, the normalized light transmission of the cell can be described by:

$$T/T_0 = \sin^2(2\psi(V))\sin^2(\pi d\Delta n_{\rm eff}(V)/\lambda)$$

where ψ is an angle between one of the transmission axis of the crossed polarizers and the LC director, d is a cell gap, $\Delta n_{\rm eff}$ is the effective birefringence of the LC medium, and λ is the wavelength of an incident light. From the equation, one can understand that ψ is a voltage dependent value, that is, without a bias voltage (off state), ψ is zero and the cell shows a dark state. With bias voltage (on state), the ψ starts to deviate from the polarizer axis, showing light transmittance. Further, in both IPS and FFS devices $\Delta n_{\rm eff}$ is also a voltage-dependent value since the LCs near both the top and bottom surfaces will not fully rotate with bias voltage due to having a strong surface anchoring. Nevertheless, this problem can be solved by adjusting the cell retardation value, whilst in the TN device this cannot be solved since the LC director tilts upward along a vertical field so that the $\Delta n_{\rm eff}$ is rapidly varied by applying the voltage.[2]

To investigate the color tracking of the device, we performed a simulation using a “LCD Master” (Shintech, Japan) where the motion of the LC director is calculated based on the Eriksen–Leslie theory and 2×2 Jones Matrix is applied for an optical transmittance calculation. Here, the LC with physical properties (dielectric anisotropy $\Delta\varepsilon = -4$, $K_1 = 13.5$ pN, $K_2 = 6.5$ pN, $K_3 = 15.1$ pN) is used and strong anchoring of the LC to the surface is assumed. The surface pretilt angle for both substrates is 2°, the initial rubbing direction is 12° with respect to the horizontal component (E_x) of the fringe electric field, and the cell gap is 4 µm. The transmittance of single and parallel polarizers is assumed to have 45% and 35%, respectively.

Figure 1 shows a cell structure of the FFS mode with an orientation of the LC directors at white state, in which the electrodes only exist on the bottom substrate with a plane type of common electrode and an inter-digital type of pixel electrode with a width 3 µm and a distance between them

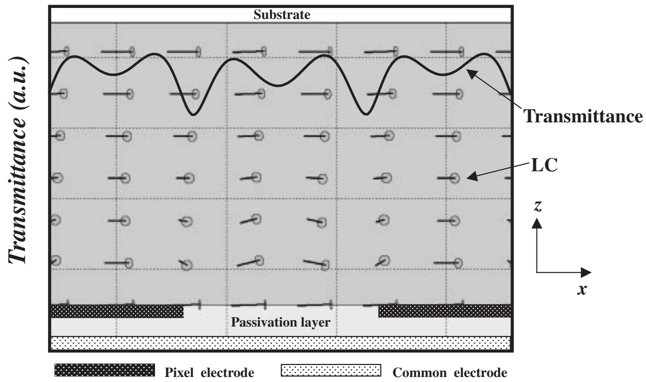

Fig. 1. Cell structure and transmittance profile dependent on the electrode position at white state.

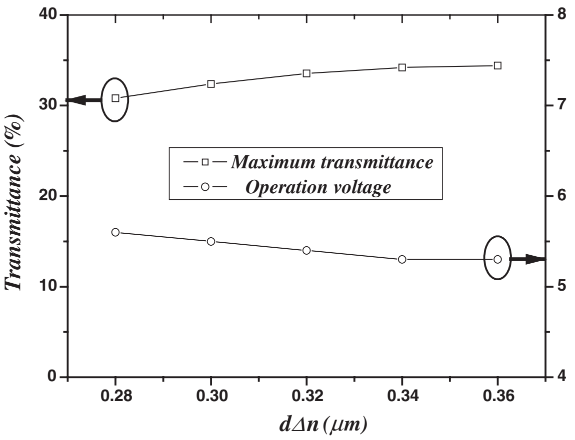

Fig. 2. Maximum transmittance and operation voltage as a function of $d\Delta n$.

4.5 µm. With bias voltage, a fringe-electric field is generated so that a dielectric torque on the LC director is horizontally-position dependent, resulting in different rotating angles of the LC director along the electrode position and thus alternating the light transmission, as shown in Fig. 1. First of all, the light transmittance and the operating voltage are calculated as a function of the cell retardation value ($d\Delta n$) given fixed cell gap, as shown in Fig. 2. When the $d\Delta n$ is 0.36 µm, the cell shows maximum transmittance with the operational voltage of 5.4 V. Next, the wavelength dispersion for six gray levels from the transmittance of 1% to 100% has been investigated for the FFS cell with the $d\Delta n = 0.36$ µm. As shown in Fig. 3, the peak wavelength shifts from 500 nm at the transmittance of 1% to 550 nm at the transmittance of 100%. This indicates that a color looks different when the gray level changes. Figure 4 shows the color chromaticity in $u'v'$ coordinates,[9] and the results show the color tracking. The calculated $\Delta u'v'$ is 0.013, which exceeds the value 0.011 of the cathode-ray-tube (CRT) display. Again, the wavelength dispersion is calculated while changing the cell retardation values and the result for a cell with the $d\Delta n = 0.30$ µm is shown in Fig. 5. The peak wavelength shifts from 490 nm at the transmittance of 1% to 520 nm at the transmittance of 100%, indicating that the degree of shift is less than that for the cell with $d\Delta n = 0.36$ µm. Figure 6 shows that there is a shift of color

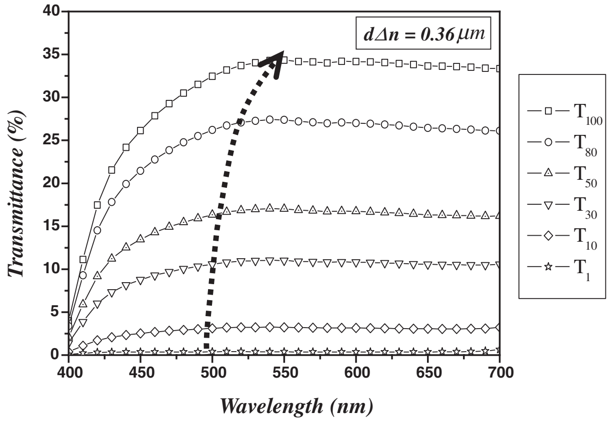

Fig. 3. Wavelength dependent-transmittance of each gray scale in the FFS cell of which the $d\Delta n$ value is 0.36 µm.

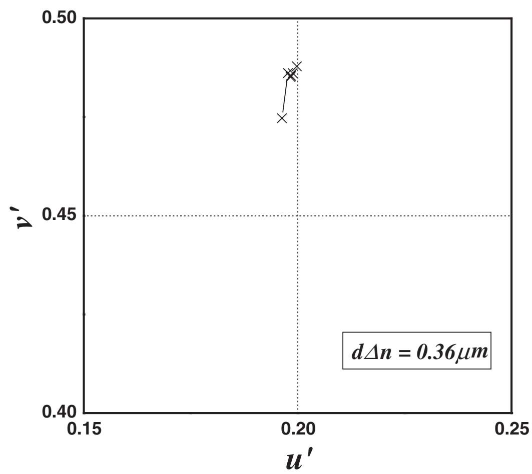

Fig. 4. Color tracking of the FFS cell when the $d\Delta n$ value is 0.36 µm.

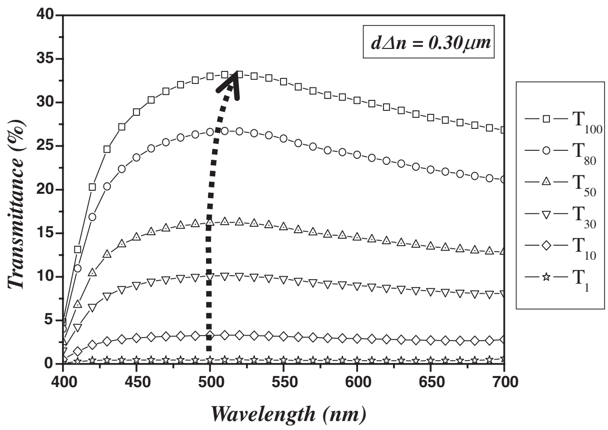

Fig. 5. Wavelength dependent-transmittance of each gray scale in the FFS cell of which the $d\Delta n$ value is 0.30 µm.

chromaticity according to the gray levels. As indicated, the degree of shift is reduced when compared to the high $d\Delta n$ cell and the calculated $\Delta u'v'$ is 0.011, which is the same value in the CRT. In other words, an authentic color is realized by reducing the FFS cell retardation value to $d\Delta n = 0.30$ µm. According to the previous report,[2] the IPS

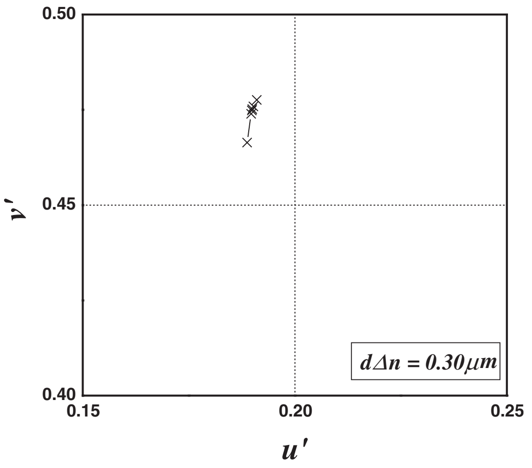

Fig. 6. Color tracking of the FFS cell when the $d\Delta n$ value is 0.30 μm.

cell shows the maximal transmittance around the $d\Delta n =$ 0.32 μm but the authentic color appears when the $d\Delta n$ is 0.23 μm, resulting in transmittance decrease of about 15% and change in white color from greenish to bluish. However, in the authentic FFS cell, the transmittance decrease is only 4% and the greenish white is kept.

Now, the question arises why the FFS mode should show the authentic color at a relatively high cell retardation value without sacrificing much in light transmittance. The major difference between the FFS and IPS modes is that in the FFS mode, the transmittance occurs above the whole electrode surface and is alternating along a horizontal axis, as shown in Fig. 1. In other words, the orientation of the LC director is dependent on the position of the electrode. Since it is periodically alternating, we investigated the color tracking when the $d\Delta n$ is 0.30 μm and the LC director orientation in three electrodes positions; above center (A), between center and electrode edge (B), and near the electrode edge (C), as shown in Fig. 7. For the LC director orientation, the twist and tilt angles as a function of applied voltage have been calculated. At position A, the twist deformation occurs mainly without changing the tilt angle much and the biggest twist angle occurs around $z/d = 0.4$ with a maximum twisted angle of 45° from an original orientation 12°. The LC director deformation is quite similar to that in the IPS mode except for that the biggest twist angle occurs below the mid-LC layer while in the IPS mode it occurs at $z/d = 0.5$. At position B, the tilt as well as twist deformation occurs with the maximum twist angle around $z/d = 0.35$. Although the maximum tilt angle is about $-8°$, where $-$ indicates the tile deformation occurs to the direction opposite to the initial tilt direction, one can notice that it occurs in whole LC layers. At position C, the biggest twist deformation occurs near the bottom surface, that is, at $z/d = 0.22$ with a maximum twisted angle of 65° from an original orientation 12° and decreases continuously as it approaches the top surface. The strong tilt angle in the white state, about $-16°$, occurs at $z/d = 0.05$ but decreases rapidly as it approaches the top surface. Comparing the tilt angles in the white state at B and C, it is $-4°$ and $-1.8°$ at $z/d = 0.4$, respectively, indicating that the average tilt angle is larger at B than at C. From the LC director configuration, one can understand that the vertical position at which the maximum twist angle occurs moves to the bottom surface as the electrode position moves from the center to the edge of the electrodes, and the biggest tilt deformation occurs at electrode position B. Next, the degree of color tracking has been calculated at each

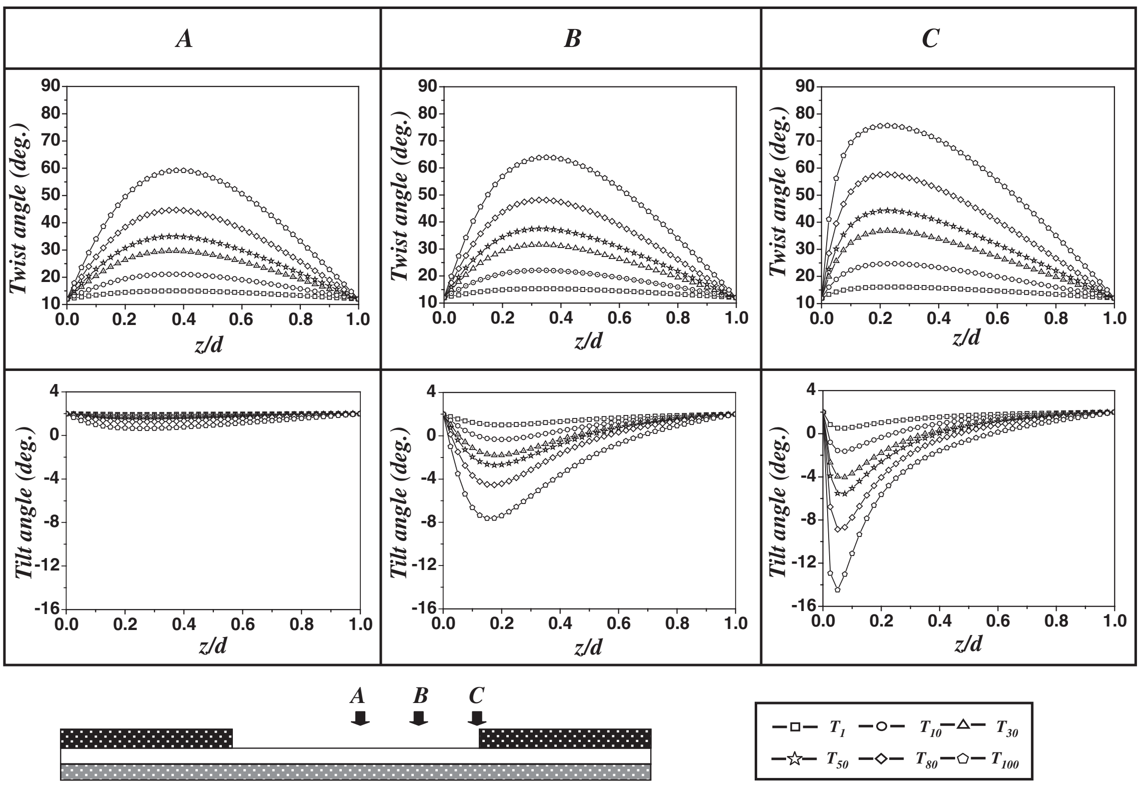

Fig. 7. Voltage-dependent director profile of twist and tilt angles at three different electrode positions.

Table I. Degree of color shift at three different electrode positions.

	$\Delta u'v'$
A	0.0114
B	0.0151
C	0.0080

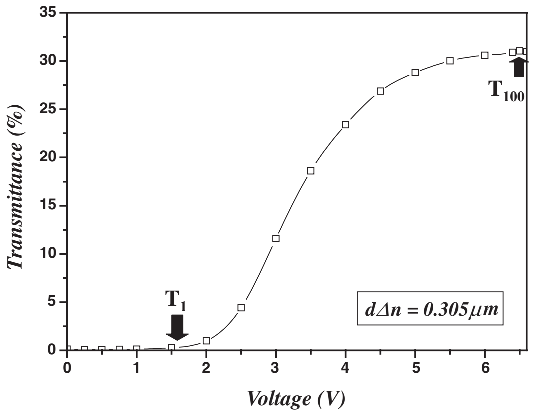

Fig. 8. Measured voltage-dependent transmittance curve when the $d\Delta n$ is 0.305 μm.

electrode position. As shown in Table I, we found that the degree of color tracking is different depending on the electrode positions such that the $\Delta u'v'$ is 0.0114, 0.0151, and 0.0080 at electrode positions *A*, *B*, and *C*, respectively. This implies that the color tracking can be reduced as long as the strong twist deformation occurs near the bottom substrate without generating the tilt angle with increasing the voltage. Consequently, in the FFS device all electrode positions contribute to the transmittance, so that the average color tracking of the whole electrode surface results in $\Delta u'v' = 0.011$ when the cell $d\Delta n$ is 0.30 μm.

Finally, a test cell was fabricated to confirm the calculated results. Here, the cell structures are almost the same as those in the calculated results. Figure 8 shows a voltage-dependent transmittance curve when the cell $d\Delta n$ is 0.305 μm. This curve is divided into 6 grey levels and the wavelength dispersion is measured using the spectrophotometer (MINOLTA, Japan), as shown in Fig. 9. The result shows that the peak wavelength shifts from 480 nm at the transmittance of 1% to 510 nm at the transmittance of 100%, which is in good agreement with the calculated results. This indicates that the white still exhibits a greenish color. Next, the color chromaticity is measured by changing the gray levels. As shown in Fig. 10, the shift of the color chromaticity changes slightly and the measured $\Delta u'v'$ is only 0.0105.

3. Summary

The color tracking is investigated in the FFS mode using the LC with negative dielectric anisotropy. The FFS cell shows the authentic color at a relatively higher cell retardation value 0.30 μm than 0.23 μm in the IPS cell so that the transmittance decreases by only 4% and a greenish white is kept. This originates from that in the FFS mode the deformation of the LC directors changes periodically along the electrode position, and the LCs at the edge of electrode twist strongly near the bottom surface without generation of a high tilt angle.

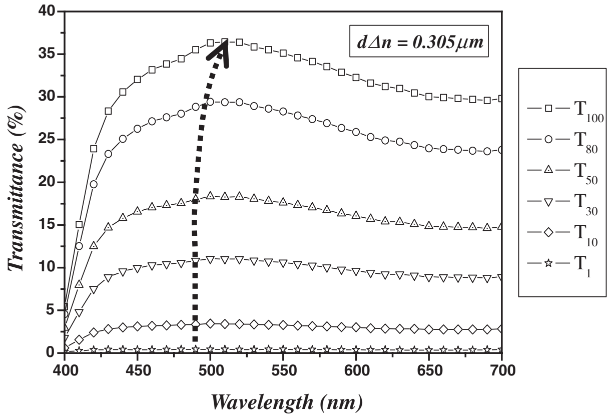

Fig. 9. Measured wavelength dependent-transmittance of each gray scale in the FFS cell of which the $d\Delta n$ value is 0.305 μm.

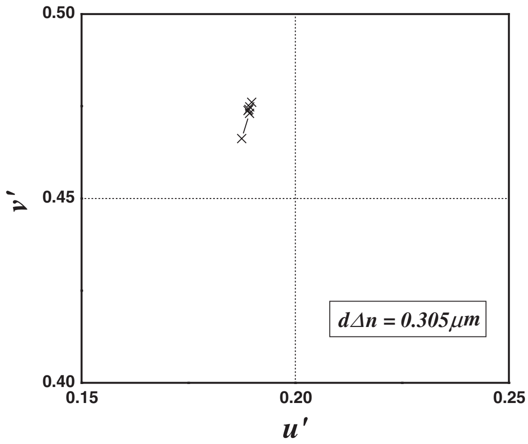

Fig. 10. Measured color tracking of the FFS cell when the $d\Delta n$ value is 0.305 μm.

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