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Electrooptic Characteristics of a Fringe-Field Driven Hybrid Aligned Nematic Liquid Crystal Cell using a Liquid Crystal with Positive Dielectric Anisotropy

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We have fabricated hybrid aligned nematic liquid crystal (LC) cell driven by a fringe electric field using a LC with positive dielectric anisotropy, which is unlike previous cells using a LC with negative dielectric anisotropy. According to experimental and simulational results, the new device still shows high transmittance, low driving voltage, optimal viewing angle and much improved response time, although the driving field is a fringe electric field that has both horizontal and vertical components. [DOI: 10.1143/JJAP.43.637]

KEYWORDS: hybrid aligned nematic liquid crystal cell, fringe electric field, liquid crystal with positive dielectric anisotropy

1. Introduction

The electro-optic characteristics of liquid crystal displays (LCDs) are constantly being improved. Several liquid crystal modes such as in-plane field switching (IPS),[1,2] fringe field switching (FFS),[3,4] and vertical alignment (VA)[5] have yielded wide viewing angle and fast response time in their own ways.. Nevertheless, they have merits and demerits. Recently, we have reported on a hybrid aligned nematic mode using a fringe field (named HAN-FFS).[6–9] This mode, employing only one-side rubbing, shows high luminance and a good viewing angle, when using the LC with negative dielectric anisotropy (−LC). At present, the −LC has a higher rotational viscosity (γ), lower dielectric anisotropic ($\Delta\varepsilon$) value and it is more expensive than the LC with positive dielectric anisotropy (+LC). In an attempt to eliminate the demerits, a new HAN-FFS mode using the +LC was studied. In this paper, the electro-optic characteristics of the HAN-FFS mode using the −LC and the +LC are compared by experimentation and simulation.

2. Cell Structure and Switching Principle of the HAN-FFS with the +LC

Figure 1 shows the cell structure of the HAN-FFS mode with the configuration of the LC director in the on/off state when using the +LC. Like previous devices employing the HAN-FFS mode, pixel and common electrodes exist only on the bottom substrate and the LC has a hybrid alignment. In the device with a uniaxial liquid crystal medium under crossed polarizers, the normalized light transmission is given by

$$T/T_0 = \sin^2(2\psi)\sin^2(\pi d\Delta n/\lambda)$$

where ψ is the angle between the crossed polarizer and the liquid crystal director, Δn the birefringence of the liquid crystal medium, d the cell gap and λ the wavelength of the incident light. In the off state, a rubbing angle (α) on the bottom substrate is coincident with one of the transmission axis of the crossed polarizers and thus the cell appears to be black at normal direction. Here, the rubbing angle is in a range between 89° to 45° against the horizontal component of a fringe electric field. Consequently, when a voltage is applied, a fringe electric field consisting of horizontal and vertical components is generated between the pixel and the common electrode. Between two field components, the strong horizontal field existing near the bottom surface at the edge of the electrodes drives the hybrid aligned LC to rotate to the field direction and causes the cell to appear to be white.

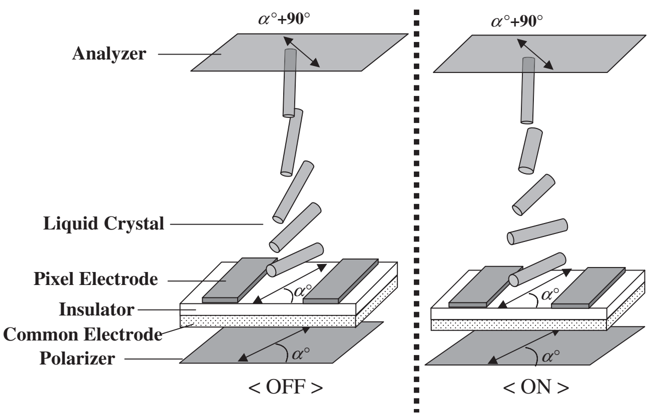

Fig. 1. Cell structure of the HAN-FFS mode in the off and on state using the LC with positive dielectric anisotropy.

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3. Results and Discussions

To fully understand the switching principle when using the +LC and to compare it with the −LC, a simulation was performed at a single wavelength of 550 nm using a software LCD master (Shintech, Japan) based on the 2×2 extended Jones matrix method for optical calculations.[10] Table I shows the simulation conditions for the electrode and the LC parameters. First of all, the transmittance as a function of the cell retardation value ($d\Delta n$) was calculated to investigate the difference in transmittance between the +LC and the −LC, while also comparing the values with the optimal cell retardation value, as shown in Fig. 2. Here, the rubbing angle was 7° and 83° for the −LC and the +LC, respectively. As indicated, the light efficiency using the −LC is higher than that using the +LC and, in addition, the retardation value reveals that maximum transmittance is higher for the +LC than the −LC. Figure 3 shows calculated and voltage-dependent transmittance curves. The calculated results show that the transmittance is higher for the −LC than the +LC

Table I. Simulation conditions for the cell structure and the LC.

Electrode width (μm)		4.5
Electrode distance (μm)		4.5
Cell gap (μm)		5.25
Rubbing angle (°)		83
Pretilt Angle on bottom substrate (°)		2
	K_1	10.3
	K_2	8
LC	K_3	14.9
	Δn at 550 nm	0.099(+LC), 0.089(−LC)
	$\Delta\varepsilon$	+8(+LC), −8(−LC)

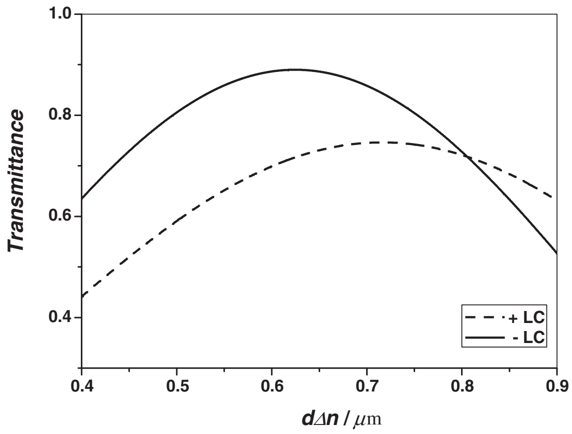

Fig. 2. Calculated result of transmittance as a function of cell retardation value when using +LC and −LC.

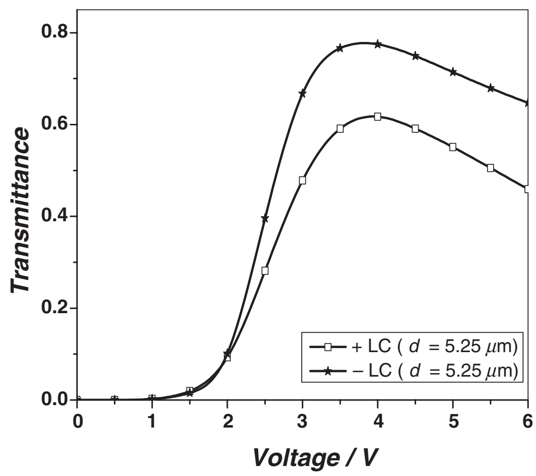

Fig. 3. Calculated voltage-dependent transmittance curves for the −LC and the +LC.

and the operating voltage (V_{op}), which indicates maximum transmittance, is kept below 4 V for both cases. Here, the cell gap of 5.25 μm was chosen, which is the same as that of experimental value, and thus the $d\Delta n$ values are 0.465 μm and 0.519 μm for the −LC and the +LC, respectively. From Fig. 2, we can understand that although the retardation value with the −LC is lower than that with the +LC, the transmittance is still higher for the −LC than the +LC. Test

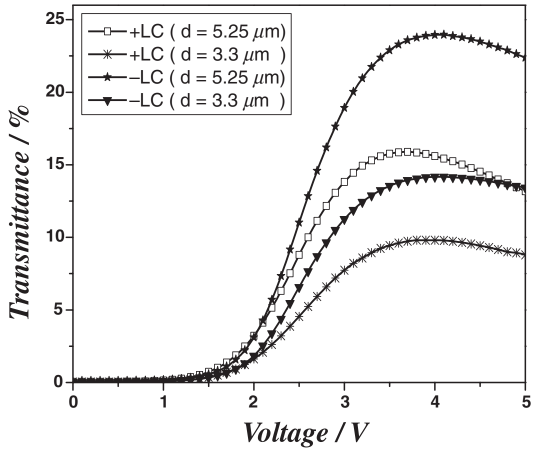

Fig. 4. Measured voltage-dependent transmittance curves as a function of a cell gap for the −LC and the +LC.

cells were fabricated to compare the calculated results for two different cell gaps of 5.25 μm and 3.3 μm, where the electrode structure and the LC's dielectric anisotropy and birefringence are the same as those given in Table I. The experimental results are also similar to the calculated results, and the V_{op} is kept well below 4 V for cells with 5.25 μm as indicted in Fig. 4. In addition, when the cell gap is decreased from 5.25 μm to 3.3 μm, the V_{op} values almost remain the same, indicating the device has an advantage compared with the IPS device[1)] that needs high driving voltage. One of the reasons for its low threshold voltage characteristic is from electrode configuration generating frnge-field[3)] and also from vertical alignment of the LC on top substrate since it allows the LC to rotate in any direction.

Next, electrode position-dependent transmittance for cells with a +LC and a −LC were analyzed to find out the origin of the lower transmittance for the +LC than for the −LC. Figure 5 shows calculated transmittance along the electrode position at three grey levels in which the transmittance is 10%, 50% and 100% of maximum transmittance at a normal direction. For the cell with the +LC, the transmittance is the highest and the lowest at both the edges of electrodes and the center of the pixel and common electrodes, respectively, at 10% and 50% grey levels. With an increase in voltage up to a fully white state, the transmittance is maximal around the edge of electrodes but it remains relatively low above the center of pixel and counter electrodes. However, when using the −LC, the dependence of transmittance along the electrode is low compared with that of the +LC. These results reveal that, due to the central region of electrodes, the light efficiency of the HAN-FFS mode with +LC is lower than that with −LC. To fully understand the electrode-position dependent transmittance, a director profile of the +LC at two electrode positions was calculated, each position showing minimum (A) and maximum (B) transmittance. With respect to the tilt angle (θ), it is slightly increased above the initial values at position A, due to a vertical field existing at the center of electrodes and, further, it has higher values in almost all layers at position A than at position B. Considering a twist angle (φ), the LCs at position B are much more twisted than those at A, that is, the LC at $z/d = 0.5$, which is mid-director, is twisted by about 52° at

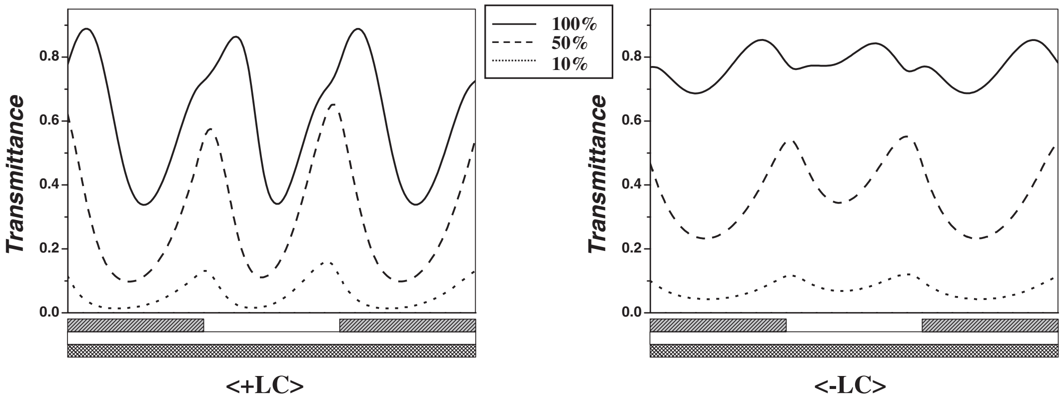

Fig. 5. Light transmittance at three different voltages along a horizontal direction for the +LC and the −LC.

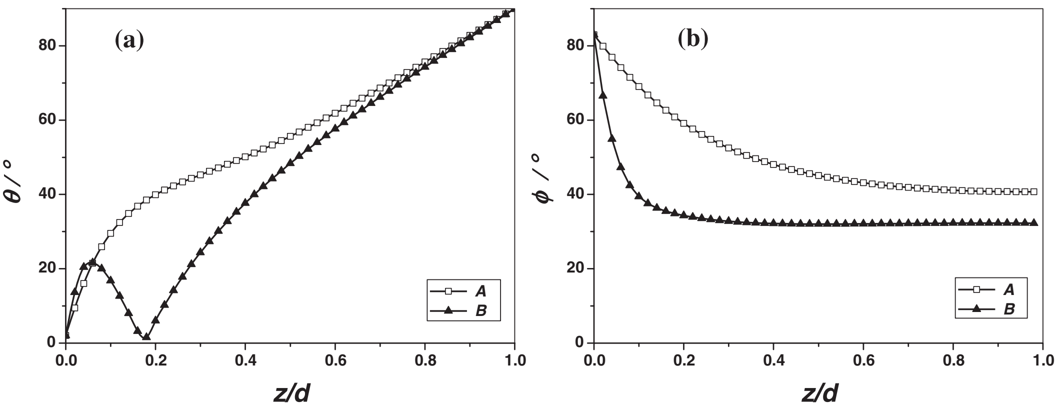

Fig. 6. Director profile of the LC's tilt (a) and twist (b) angles in white state.

the position B while it is only twisted by 40° at position A. The LC deformation with a high tilt angle and a twist angle less than 45° will not induce enough phase difference, like a half-wave plate, giving rise to low transmittance. It can be stated with a high degree of certainty that the reason for low transmittance when using the +LC compared with the −LC is that the transmittance is low at the center of the pixel and counter electrodes. The detailed description of the difference is as follows. In the FFS device, the LC rotates near the edge of electrode at first by strong dielectric torque and then the elastic force between neighboring molecules cause the LC to rotate even at the center of pixel and common electrode where no horizontal field exists. Therefore, the degree of rotation at that region totally depends on twist angle of neighboring molecules existing between the center and the edge of electrode. When using the −LC, the twisting elastic force by neighboring LCs is stronger than that using the +LC because the +LC tilts upward along fringe field, so less twisting elastic force is applied to the LC at the center of electrode. This indicates that the transmittance of the device using the +LC is lower than that using the −LC since it is proportional to $\sin^2(2\psi)$. Nevertheless, the difference in the transmittance between the +LC and the −LC can be reduced with an optimized electrode structure and a cell retardation value, achieving the transmittance as high as 85% (it is 90% when using the −LC).[11] In the third phase of this experiment, simulated viewing angle characteristics were calculated to see how they changed with the +LC. As evidenced

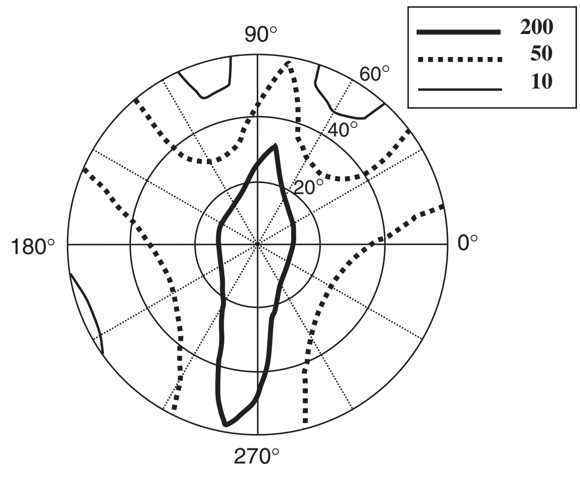

Fig. 7. Iso-contrast contour of the device using the +LC.

in the previous case with the −LC, the discotic film ($nx - nz = 250$ nm, the tilt angle to antiparallel rubbing direction = 40°) has been inserted between the polarizer and the LC cell to control light leakage of the dark state in oblique viewing directions. Here, the calculation was performed in all visible wavelengths. Figure 7 shows the iso-contrast contours, which reveal that a contrast ratio greater than 10 exists at over about 60° of the polar angle in all directions. These results are much superior to that of the

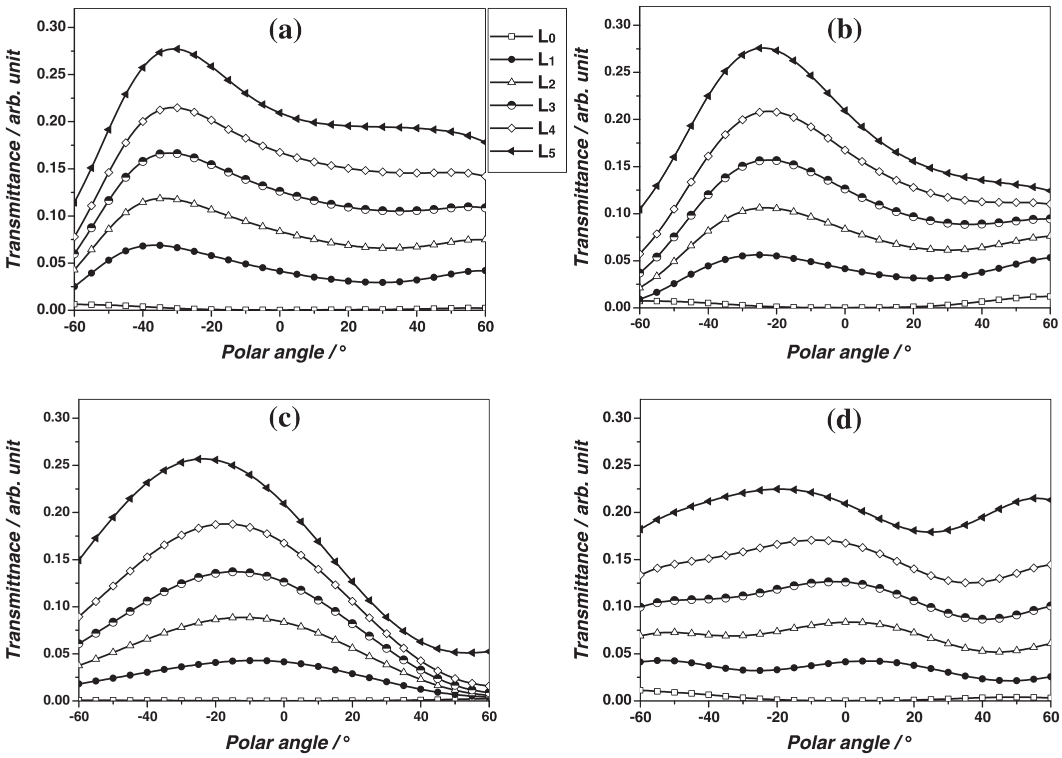

Fig. 8. Luminance change as a function of polar angle at four different azimuthal directions: (a) from 0° to 180°, (b) from 45° to 225°, (c) from 90° to 270°, and (d) from 135° to 315°.

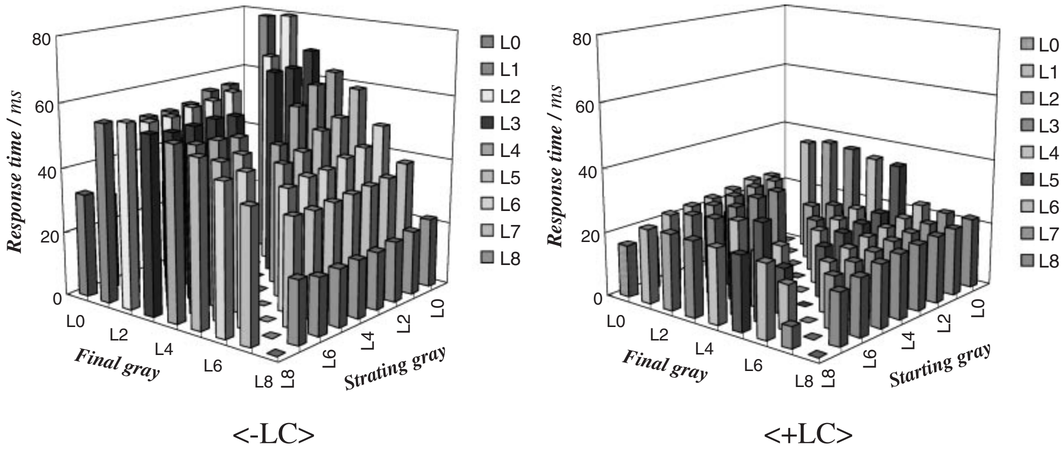

Fig. 9. Comparison of the grey to grey response time for the −LC and the +LC.

twisted nematic mode which is mainly applied to notebook displays. We have also calculated the grey scale inversion for 6 grey levels (obtained by dividing the voltage-dependent transmittance curve at normal direction equally) at horizontal, vertical and two diagonal directions up to 60° of the polar angle. As appeared in Figure 8, grey scale inversion is nonexistent at all directions, though the asymmetry in luminance does exist. However, the asymmetry of iso-luminance in oblique viewing directions can be improved by employing a wedge shaped electrode since the LC director rotates in two opposite directions.[7] Finally, a response time for the +LC and −LC was also measured. Here, the rotational viscosities of the +LC and the −LC are 78 mPa·s and 110 mPa·s, respectively such that the response time with the +LC is inherently superior to that of the −LC. When the d is 3.3 μm, the rising time is 19 ms for both LCs while the decay time is 14 ms and 25 ms for the +LC and −LC, respectively. In general, the rising time depends on applied voltage, dynamics of the LC and rotational viscosity. Therefore, the rising time could be the same for both cells since the applied voltage is different each other. The decaying time strongly depends on the cell gap and the rotational viscosity. Here, the low rotational viscosity of the +LC affects only the decay response time and, as a result, the total response time of the cell with the +LC is 33 ms, which is acceptable for normal applications. Figure 9 shows response times including grey to grey transitions when d is 3.3 μm. Here, we have divided the V–T curve into 9 grey levels equally from black ($L0$) to white ($L8$), i.e., the transmittance intervals, $T(n+1) - T(n)$, are constant where

$T(n)$ is the transmittance for n-th level. When the +LC is used, most grey to grey response times are within 30 ms, whereas they are over 30 ms for the −LC. Consequently, the results suggest that the response times of the device are greatly improved when using the +LC.

4. Summary

In summary, a computer simulation was performed and the HAN-FFS mode using the LC with positive dielectric anisotropy was fabricated. The device has a low driving voltage of less than $4V$ and much faster response times than devices with the −LC. In addition, the viewing angle is larger than 60° in all directions. The application field of the new device is the small and medium-size LCDs that need better viewing angles than those using the twisted nematic mode and a proper response time with low power consumption.

Acknowledgements

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