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Study of Optimal Phase Retardation According to Electrode Structure in the Fringe-Field Switching Mode Using the Negative Liquid Crystal

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The fringe-field switching (FFS) mode has unique characteristics such as high transmittance and wide viewing angle and its electro-optic characteristics strongly depend on pixel electrode width (w) and distance (l) between them. In this study, optimal phase retardation of the FFS mode using a liquid crystal (LC) with negative dielectric anisotropy depending on pixel electrode structure was investigated based on the simulation. The results shows that when the width of the pixel electrode and distance between electrodes are 3 μm and 4.5 μm, respectively, the cell shows transmittance 0.87 with optimal phase retardation value of LC cell 0.36 μ. As w and l are decreased to 1 μ and 1.5 μ, the cell shows transmittance of 0.90 with optimal phase retardation of LC cell 0.40 μ, indicating that the light modulation method is changed according to electrode structure.

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

INTRODUCTION

In these days, as the application field of the liquid crystal display become wider from a small size such as mobile phone and notebook PC to large size such as LC TV, the image quality and response time

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of the LCDs has been important more and more. There are applied several LC modes such as in-plane switching (IPS) [1], fringe-field switching (FFS) [2–5], and multi-domain vertical alignment (MVA) [6–11]. Among them, IPS and FFS mode have a wide viewing angle intrinsically, because the LCs are aligned homogeneously at an initial state and then in-plane and fringe electric field rotate the LC almost in plane. However, the different driving fields in 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 does not rotate. However, FFS mode driven by a fringe electric field has not only a wide viewing angle but also high transmittance because LCs above electrodes rotate in the low driving voltage [2]. Further, FFS mode utilizes mixed concepts of both polarization rotation and phase retardation effects. Due to many advantages such as wide viewing angle and high transmittance, the FFS mode is being applied to various application fields such as mobile, table PC, notebook, monitor and LC-TVs.

There are many researches to improve the performance of the FFS mode. To improve the light efficiency, the cell gap, pixel electrode width and distance between them reduced [12–13]. When the cell gap decreases, the light efficiency of the LC cell decreases since the more LCs are affected by strong surface anchoring so that the LC above center of electrodes becomes harder to rotate as the cell gap decreases [12]. In case of optimized pixel electrode width and distance between them, transmittance is increased because of strong horizontal field intensity [13].

This paper investigates that how to improve response time and transmittance in the optimal phase retardation according to electrode structures in the FFS mode using a LC with negative dielectric anisotropy of the LC(-LC). And we describe how light modulation varies as electrode structure changes.

Switching Principle and Simulation Conditions

In the FFS mode, the electrodes exist only at the bottom substrate. In general, common electrodes exist as planes and pixel electrodes exist in slit form with suitable gaps (l) between them. With this electrode structure, a fringe-electric field is generated when voltage is applied and, more importantly, a strong horizontal field exists near the bottom surface at the edge of each pixel 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. In the FFS mode using a -LC, the transmittance are mixed both the IPS and the TN behavior due to different transmittance along the electrode positions [14]. 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 voltage-dependent effective birefringence of LC medium, and λ is the wavelength of the incident light.

We performed a simulation using commercially available software "LCD Master" (Shintech, Japan) where the motion of the LC director is calculated based on the Eriksen-Leslie theory and 2×2 extended Jones matrix is applied for an optical transmittance calculation [15]. Under these observations, the LC has physical properties, such as $\Delta\varepsilon = -4.0$, $\Delta n = 0.05 \sim 0.20$, $K_{11} = 13.5$pN, $K_{22} = 6.5$pN, and $K_{33} = 15.1$pN. The strong anchoring at both substrates with anchoring energy much larger than 10^{-3} Jm^{-2} is assumed such that the LCs does not rotate at the interface. The surface pretilt angle for both substrates is 2°, cell gap is 4 µm, and the initial rubbing direction is 10° with respect to the horizontal component (E_y) of the fringe electric field. The calculated LC orientation in this paper is achieved after relaxation time of 100 ms.

Simulation Results and Discussion

To confirm optimal phase retardation along the electrode structures in the FFS mode using a -LC, width of the pixel electrode (w) and distance between pixel electrodes (l) reduced while maintaining the ratio of l/w at 1.5, and Δn of LC is changed from 0.05 to 0.20 for calculating the maximum transmittance according to phase retardation (dΔn). Figure 1 shows the light efficiency according to operating voltage (V_{op}) and dΔn for three different electrode structures. As show Figure 1, when changed the dΔn, transmittance is oscillate and transmittance difference of electrode structure with 1/1.5 µm is less more than 3/4.5 µm. As result of Figure 1, confirmed optimal phase retardation and then transmittance curve according to voltage is performed at the optimal phase retardation. The results show Figure 2 and Table 1. Figure 2 is show voltage dependant transmittance and Table 1 is show numerical data. As shown Figure 2 and Table 1, when electrode structure is decreased, optimal dΔn is increased from 0.36 to 0.40 and transmittance is enhanced from 0.87 to 0.90. This value is almost same transmittance of TN mode, but V_{op} increases to 7.9 V.

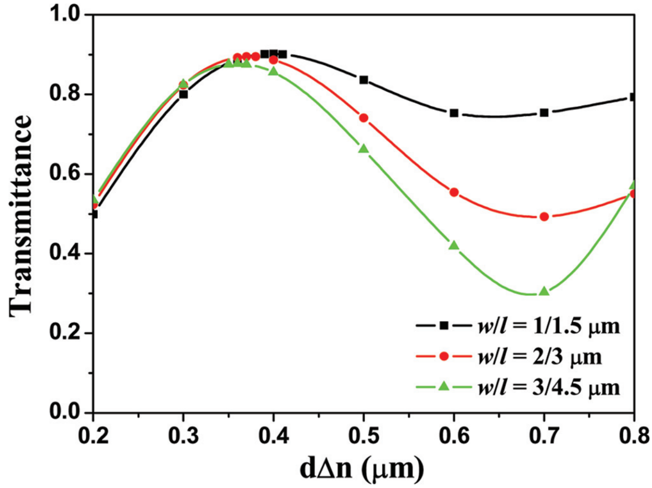

FIGURE 1 Transmittance curve according to phase retardation.

We investigated why the transmittance increases when the w and l decrease. Figure 3 reveals light efficiency and the LC director orientation dependent on electrode position in the white state when the electrode width is vary. In the conventional FFS device, a fringe-electric

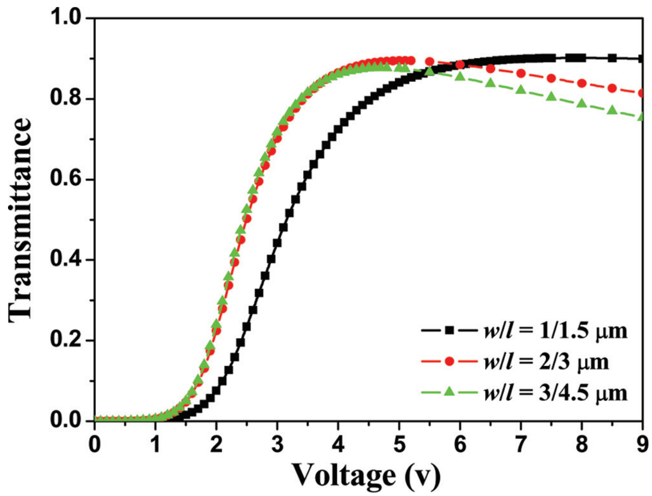

FIGURE 2 Voltage dependent transmittance curve at the optimal phase retardation of respectively different electrode structures.

TABLE 1 Optimal Phase Retardation and Numerical Data of Figure 1

W/l (μm)	Optimal dΔ n	T_{max}	Operating voltage (V)
1/1.5	0.40	0.9018	7.9
2/3	0.37	0.8947	5.1
3/4.5	0.36	0.8769	4.7

field dependent on horizontal and vertical field 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 3c. But when the width of the pixel electrode (w) decreases 2 μm and 1 μm, transmittance is almost same independent of the electrode position. In the conventional FFS mode such as $w = 3$ μm and $l = 4.5$ μm, transmittance takes place over the whole area, creating high transmittance, even though the accompanying degree of deformation of the LC differs depending on electrode position, because of different dielectric torques acting on the LCs. However, the LC at the edge of pixel electrode becomes overtwisted and the LC at the center of pixel electrode becomes properly twisted. Accordingly, the transmittance difference between the two positions is occurred and the transmittance is oscillated. The other hand, when the electrode structure is decreased, occur high transmittance because of decreasing the degree of oscillation. Interestingly, FFS mode is available to light modulation according to electrode structure. We calculated the transmittance in center, between, and edge of pixel electrode by rotating the axes of the crossed polarizer counterclockwise at three different electrode structures, as shown in Figure 4. As indicated, the transmittance at center of pixel electrod is a maximum at 0° and extinction of the transmittance

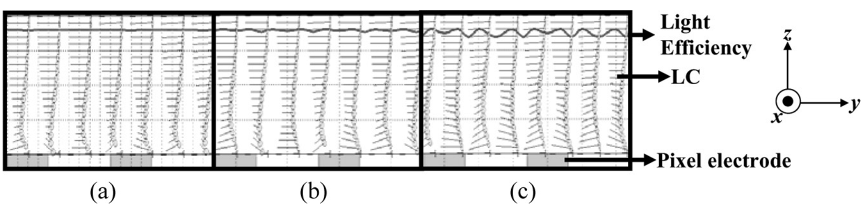

FIGURE 3 Light efficiency and the LC director orientation dependent on electrode position in the white state when the electrode width is (a) 1 μm, (b) 2 μm, and (c) 3 μm.

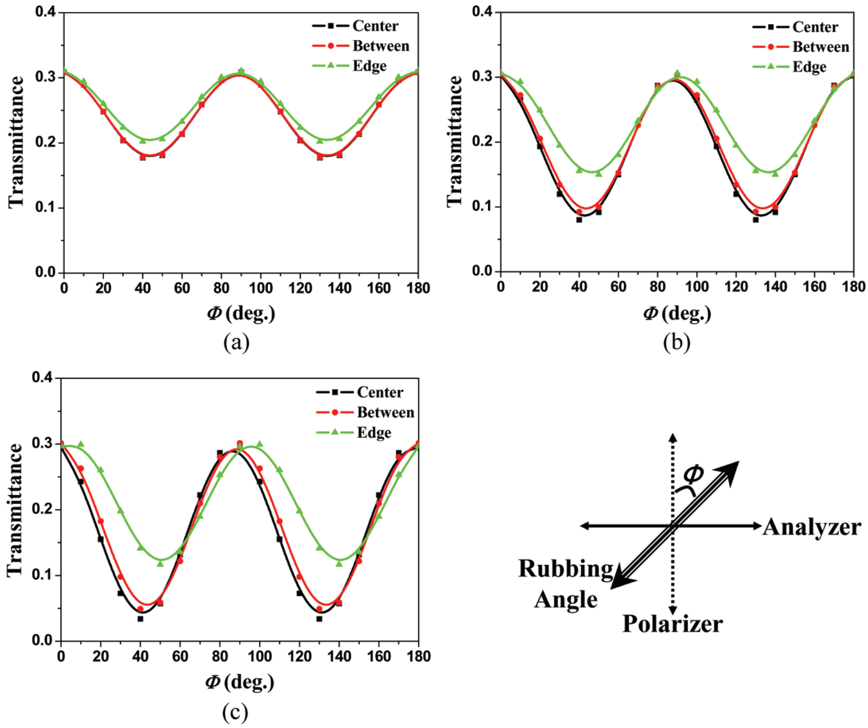

FIGURE 4 Light modulation according to the electrode structures; (a) $w = 1\,\mu m$, $l = 1.5\,\mu m$, (b) $w = 2\,\mu m$, $l = 3\,\mu m$, and (c) $w = 3\,\mu m$, $l = 4.5\,\mu m$.

appears every 40°. But, the transmittance in edge does not show an extinction of light, though it oscillates due to the twist alignment of the LC. First, the light modulation does occur using polarization rotation effect (edge) while in the latter is does occur using phase retardation effect (center). But when w and l decrease, the oscillation of the transmittance at the center is reduced. This means which the light modulation occurs using polarization rotation effect only.

Figure 5 presents calculated LC orientation in a white state at three different electrode positions along the electrode structure. Here, the initial twist angle is 10°. When $w = 3\,\mu m$, the maximal twisted angle from the initial position is strongly dependent on electrode position such that it is about 65° near the bottom substrate at the edge of the electrode and about 45° around the middle of the cell at the center of the electrode. However, the LC orientation becomes almost same irrespective of electrode positions with decreased electrode structure.

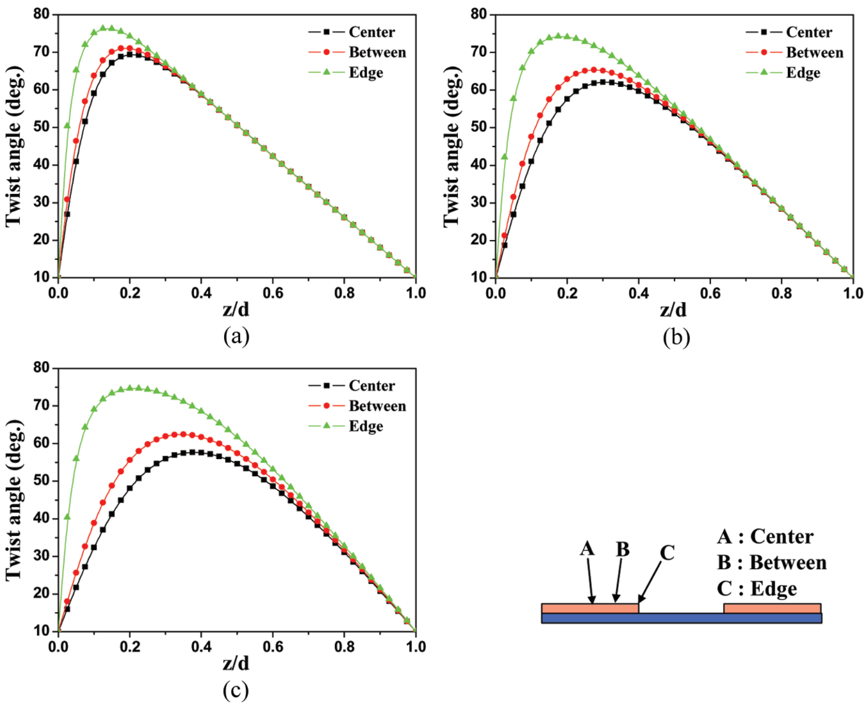

FIGURE 5 Director profile of twist angle at three different electrode positions; (a) $w = 1.0\,\mu m$, $l = 1.5\,\mu m$, (b) $w = 2\,\mu m$, $l = 3\,\mu m$ and (c) $w = 3\,\mu m$, $l = 4.5\,\mu m$.

When w is $1\,\mu m$, the maximal twist angle larger than 55° occurs near bottom below $z/d = 0.2$ substrate at all electrode positions and is larger than those in the cell with $w = 3\,\mu m$ and besides twist angles are about same above $z/d = 0.2$. This means that the twist angle is independent of electrode position for $w = 1\,\mu m$ and $l = 1.5\,\mu m$, resulting in linear transmittance along electrode position. Further, the light efficiency is maximized in all electrode positions.

Next, we calculated the response time characteristic along the electrode structures. As shown Table 2, the decay time is inversely proportional to the elastic constant (K) of the LC. In the FFS mode, decay time is slow because elastic constant of the twist deformation (K_{22}) is lower than that of other deformations such as bend (K_{33}), splay (K_{11}) deformation. When $w = 3.5\,\mu m$, rise time is 28 ms and decay time is 54 ms. However w and l decrease, response time is slightly fast because horizontal electric field intensity increases and the LCs are

TABLE 2 Calculated Response Time Dependent on Electrode Structure

w, *l*		1 *um*, 1.5 *um*	2 *um*, 3 *um*	3 *um*, 4.5 *um*
T_{on} (*ms*)	90%	28	28	28
	80%	20	20	21
T_{off} (*ms*)	90%	52	53	54
	80%	40	41	42
Elastic energy		2.82	2.02	1.69

influenced by strong dielectric torque in all electrode position. Decay time is also improved because highly twisted LC director at the bottom surface relaxes back to high force of restitution due to surface effect.

CONCLUSION

This paper studied electro-optic characteristics at the optimal phase retardation when the electrode structure changes in the FFS mode using -LC. Further, response time is also investigated. When width and distance of pixel electrode decreases from 3, 4.5 μm to 1, 1.5 μm respectively, the transmittance of the 3, 4.5 μm structure becomes dependent on the electrode position, resulting in a lower transmittance due to oscillation of light efficiency by different dielectric torque according to electrode position compared with the 1, 1.5 μm structure. Accordingly, when the electrode structure decreases, the transmittance increases almost same transmittance of TN mode. Also, the response time is slightly enhanced due to strong dielectric torque and high force of restitution. Besides as *w* is larger than 3 μm, phase retardation and polarization rotation effects exist along electrode positions. But, when *w* and *l* is reduced to less than 2 μm, only polarization rotation effect exists.

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