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Electro-Optic Characteristic of Fringe-Field Switching Mode Depending on Rubbing Direction

Seung Ho HONG, In Cheol PARK, Hyang Yul KIM and Seung Hee LEE*

TFT Process Development Department, LCD SBU, Hyundai Electronics Industries, San 136-1, Ami-ri, Bubal-eup, Ichon-si, Kyungki-do 467-701, Korea

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A recently developed new liquid crystal display, which operates in the fringe-field switching mode, is known to exhibit high transmittance as well as a wide viewing angle unlike the conventional in-plane switching (IPS) mode display. The device shows unique electro-optic behavior, nevertheless the liquid crystal director rotates almost in-plane as in the IPS mode. We found that light efficiency decreases as the rubbing angle with respect to the horizontal component of the fringe field decreases for a liquid crystal with positive dielectric anisotropy, whereas this is not observed for a device driven by the in-plane field. In this paper, the switching mechanism and voltage-dependent transmittance characteristics with respect to rubbing directions have been investigated.

KEYWORDS: liquid crystal display, fringe-field switching, in-plane switching, electro-optic characteristics, rubbing direction

1. Introduction

Over the last four years, there have been great improvements made in the viewing angle characteristic of liquid crystal displays (LCDs). Technologies based on the in-plane switching (IPS) mode[1–4] and fringe-field switching (FFS) mode[5–8] in which the liquid crystal director rotates in-plane are used. The electro-optic characteristics of the IPS mode have been studied intensively. The effects of the rubbing direction on the voltage-dependent transmission curve and response time have also been studied. Previous works show that the transmittance of the IPS device is not dependent on the sign of dielectric anisotropy and rubbing direction within the optimized range because the horizontal field drives the LC molecules; instead, the dynamic range and response time are dependent on the rubbing direction.[9,10] However, in the FFS mode that discards the concept of interdigital electrodes between the pixel and counter one and the in-plane field, the LC molecules are driven by the fringe field and the light efficiency is strongly dependent on the sign of dielectric anisotropy.[11] Furthermore, we found that it is also strongly dependent on the rubbing direction when the liquid crystal with positive dielectric anisotropy is used. This result is important to obtain a fast response time of the FFS mode with high light efficiency because at the present level, the rotational viscosity of the positive LC is much lower than that of the negative one. In this study, the switching mechanism and voltage-dependent transmittance characteristics depending on the rubbing direction compared with those of the IPS mode have been examined by simulation and experiment.

2. Experimental and Simulation Results

Figure 1 shows a cell structure of the FFS mode with fringe-field lines. The indium-tin-oxide (ITO) with a thickness of 400 Å was deposited on the bottom glass substrate at first and then the passivation layer, SiO_2 with 1500 Å thickness was coated by chemical vapor deposition. Finally, the second ITO layer of 400 Å thickness was deposited and patterned as interdigital electrodes. The width of the second ITO electrodes was 3 μm with a distance of 5 μm between electrodes. There is no electrode on the top glass substrate. In this case, the first and second ITO layers perform the role as common electrode and pixel electrode, respectively and there is no horizontal distance between the first and second ITO layers so that fringe field lines are generated instead of the in-plane field in the case of the conventional IPS mode with a bias voltage. The alignment layer from Japan Synthetic Rubber Co. (AL-1051) was coated on both substrates and the rubbing was performed in antiparallel directions. The rubbing angle (α) was defined as the angle made with respect to the horizontal component of fringe field. The pretilt angle generated by the rubbing was 2°. Two glass substrates were then assembled to give a cell gap (d) of 4.0 μm. The liquid crystals with negative dielectric anisotropy ($\Delta n = 0.074$

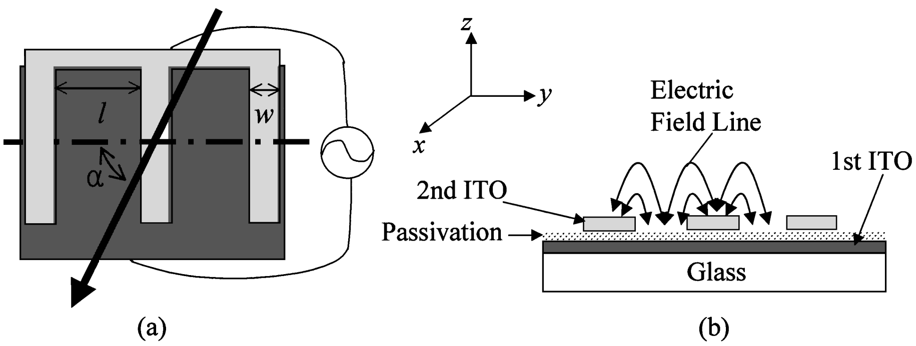

Fig. 1. Schematic diagrams of the cell structure with field lines in the FFS cell. (a) top view and (b) side view of electrodes.

*E-mail address: lsh1@hei.co.kr

at $\lambda = 589\,\text{nm}$, $\Delta\varepsilon = -3.8$) and with positive dielectric anisotropy (birefringence $\Delta n = 0.074$ at $\lambda = 589\,\text{nm}$, dielectric anisotropy $\Delta\varepsilon = 8.0$) from Merck Co., were used for the experiments and simulations. The polarizers crossed each other and one of them was parallel to the rubbing direction. In this case, the normalized transmission of light is

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

where ψ is the angle between the polarizer and liquid crystal director, and T_o is the transmitted light through parallel polarizers. Therefore, the FFS mode is normally black mode, and the transmission becomes maximal when the LC director rotates by 45° with an applied voltage, given the birefringence of the LC medium.

Figure 2 shows calculated voltage-dependent transmittance curves as a function of rubbing direction. For cells with negative LC, the transmission remains about the same though the rubbing angle increases to 30°. However, the transmission is strongly dependent on the rubbing angle for cells with positive LC. The operating voltage at which the transmission becomes maximal also increases as the angle between the rubbing direction and field direction becomes large (smaller) for negative (positive) LC. The relationship between voltage and rubbing angle for a fringe-field-driven cell is the same as that for an in-plane-driven IPS cell.[9] Figure 3 shows experimental results for both cases. The dependence of voltage-dependent transmission on rubbing direction exactly agrees

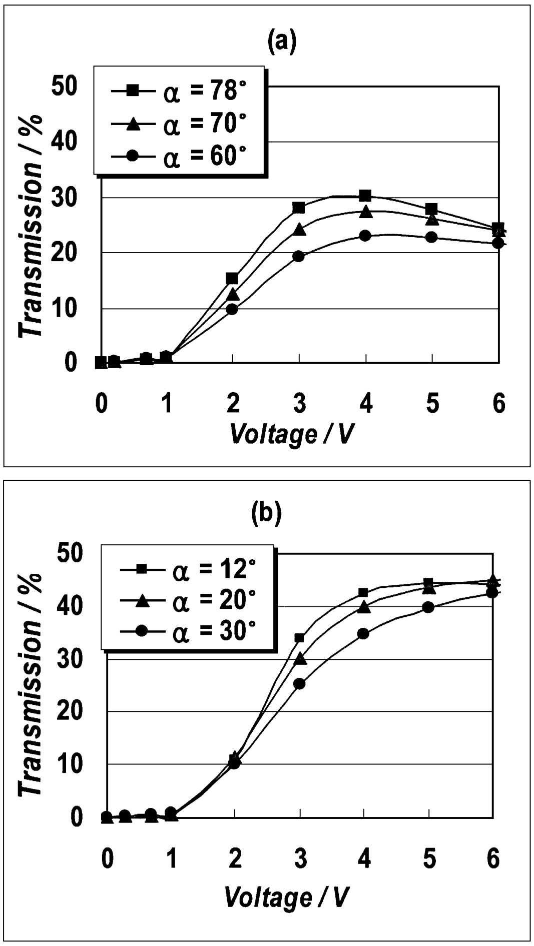

Fig. 2. The calculated result of voltage-dependent transmittance depending on rubbing direction in the FFS mode using (a) positive and (b) negative LCs.

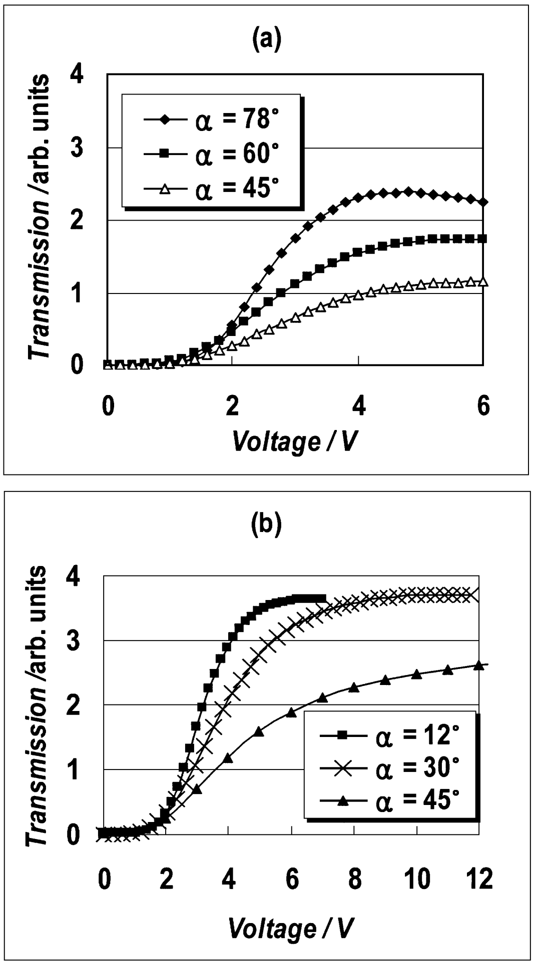

Fig. 3. The experimental result of voltage-dependent transmittance depending on rubbing direction in the FFS mode using (a) positive and (b) negative LCs.

with the simulation result and it is clear that the electro-optic behavior of fringe-field driven cells clearly depends on the dielectric anisotropy of LC, unlike in the case of conventional in-plane driven cells. In addition, when the rubbing angle is 45°, the transmission is also decreased significantly because the maximum rotation of the LC director by an applied voltage is only 45°. However, in this case, the operational voltage becomes too high. These different behaviors directly imply that the distribution of the LC director with a bias voltage is dependent on the sign of dielectric anisotropy and rubbing direction. Therefore, we have investigated the light transmission along the horizontal axis of the FFS cell to understand the origin of the decrease of transmittance with increasing rubbing direction for cells with positive LC by simulation as shown in Fig. 4. As reported in our previous work,[5] in the FFS mode, the dielectric torque, initially, and then the elastic force between neighboring molecules affect the switching of the LC director. Therefore, the distribution of the LC director along the horizontal axis is inhomogeneous, giving rise to alternating transmittance. Similar behavior is also observed in previous works, namely that homogeneously aligned LC molecules assume a hybrid twisted nematic (TN) LC molecular orientation by the electric field generated by the slit-patterned electrode structure.[12,13] Figure 4(a) is a simulation result with resulting light transmission with applied operating voltage where the rubbing angle is 80°. The light trans-

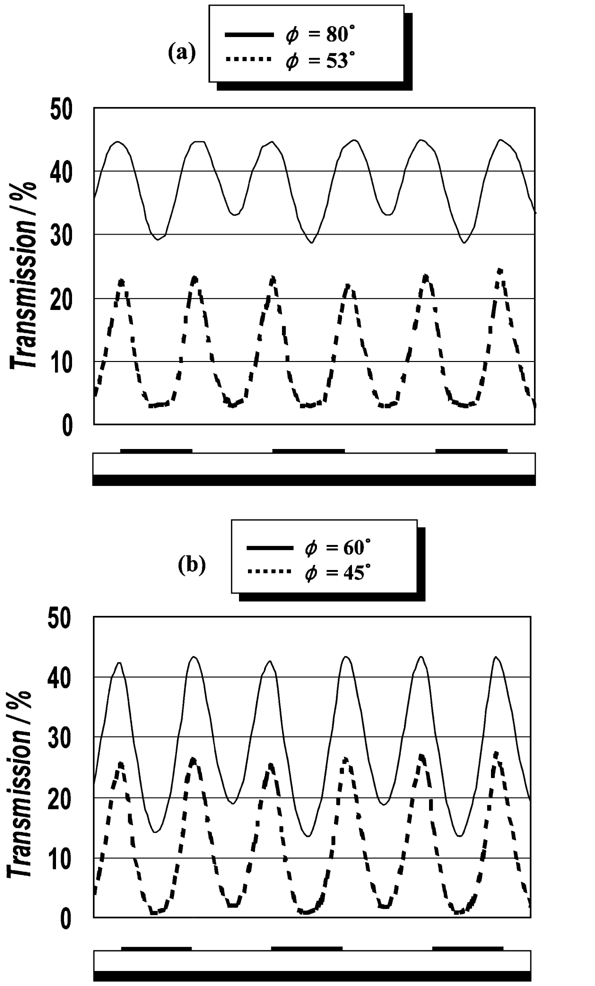

Fig. 4. The simulational result of light transmission along the y axis in a cell when operating voltage is applied and the optic axis of crossed polarizers (ϕ) is rotated to obtain the lowest transmission above the center of electrodes for (a) $\alpha = 80°$, and (b) $\alpha = 60°$.

mission is oscillating and low above the center of the first and second electrodes. The positive LC orients along fringe-field lines, that is, the LC molecules tilt up near the edge of electrodes instead of rotating so that the elastic force causing the LC above the center of electrodes to rotate is weak giving rise to a low transmission. This is the main reason why the positive LC shows lower transmission than the negative one. We have also rotated the optic axis of the crossed polarizers (ϕ) to check the degree of rotation (χ) above the center of electrodes. As can be seen, when we rotate ϕ by 53°, the transmission becomes lowest above the center of the electrodes, indicating that the director rotates only by 27° in that region. Now when the rubbing angle is 60°, the peak transmission near the edge of the second electrodes is about the same as that for the cell with an 80° rubbing angle as shown in Fig. 4(b). However, it decreases rapidly with increasing distance from the edge of electrodes and is lower than that of the 80° rubbed cell above the center of the electrodes. In this case, when ϕ is rotated to 45°, the transmission becomes lowest above the center of electrodes, indicating that the director rotates only by 15° in that region, which is about 12° less than that of the 80° rubbed cell. This explains the decrease of low transmission as the rubbing angle to the horizontal component of fringe-field decreases. We have plotted the degree of rotation above the center of electrodes against the rubbing angle.

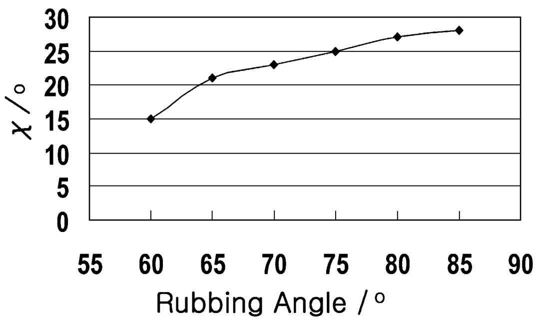

Fig. 5. The degree of rotation of the LC director above the center of electrodes dependent on rubbing angle when the operational voltage is applied.

It is seen in Fig. 5 that the degree of rotation decreases as the rubbing angle decreases, indicating that the light transmission above the center of the electrodes decreases with decreasing rubbing angle. Now we investigate the origin of the low χ value in that region. As can be seen in Fig. 1(b), a strong horizontal electric field exists near the bottom substrate between the region of the edge of the second ITO and first ITO, that is, a strong dielectric torque in that region rotates the LC molecules to be parallel to the field lines overcoming the initial surface boundary condition. This indicates that for a cell with a rubbing angle of 80°, the LC molecules near the edge of the second electrodes are twisted about 80° from the bottom to top substrates. However, away from the edge of second electrodes the intensity of the horizontal field becomes weak and the vertical field becomes strong, and the LCs with positive dielectric anisotropy orient parallel to such field lines. Consequently, the degree of rotation of the LC molecules is less than 80° away from the edge of the second electrodes, and also the LC molecules tilt up so that the transmission decreases away from that region. As a result, when the rubbing angle decreases, the degree of twist of the LC molecules in the edge region of the second ITO decreases and the elastic force required to rotate the neighboring LC molecules becomes weak, giving rise to decreased transmission. We have performed simulations to understand the LC molecular orientation in that region. We have compared a 60° twisted TN cell with the LC orientation of the FFS cell with a rubbing angle of 60° by rotating the optic axis of crossed polarizers up to 90° for a cell of the same retardation. The trend of transmission change is in good agreement for both cases as shown in Fig. 6. This supports the explanation that the LC molecules near the edge of the electrodes are twisted 60° from the bottom to top substrates from the initial homogeneous alignment.

In conclusion, in the FFS mode, the switching occurs by a dielectric torque and elastic force between neighboring molecules. When the positive LC is used, the LC molecules near bottom substrates near the edge of electrodes orient parallel to the horizontal component of the fringe-field such that they are twisted from bottom to top substrates from the initial homogeneous alignment. Away from the edge of electrodes, the horizontal field becomes weak so that the LC molecules tilt up and the degree of twist becomes small, giving rise to decreased transmission. As a result, the degree of twist at the edge of electrodes decreases as the rubbing angle decreases and consequently, the degree of twist at the center of electrodes becomes lower, giving rise to a decreased transmittance, as can be seen in Fig. 5. However, when the negative

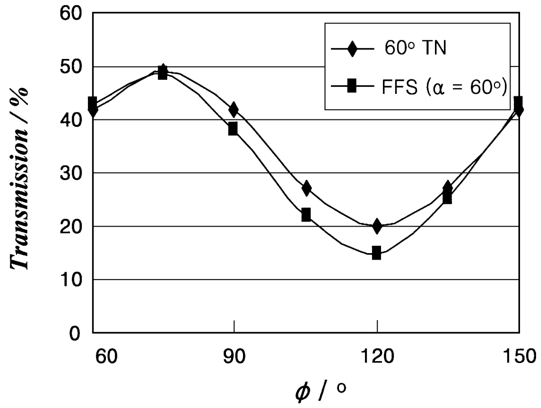

Fig. 6. Comparison of light transmission to predict the LC molecular orientation near the edge of a second electrode as a function of the optic axis of the crossed polarizers between 60° twisted TN cell and 60° rubbed FFS cell.

LC is used, the LC director orients perpendicular to the field direction and does not tilt up, being away from that region, so that such dependency does not occur. Even in the IPS mode, this behavior is not observed. In other words, the intensity of modulated light between electrodes does not depend much on position, because mainly the horizontal field rotates the LC director parallel to the substrate by a dielectric torque and the LC molecules tilt up only slightly near the edge of electrodes, irrespective of the dielectric anisotropy of the LCs.

3. Summary

In summary, we have studied the rubbing direction effects on voltage-dependent transmission characteristics by experiment and calculation. Unlike the conventional in-plane switching mode, the FFS cell shows that the light transmission decreases as the rubbing angle to the horizontal component of the fringe-field decreases for the positive LC. This result arises from the unique electro-optic switching characteristic of the FFS mode, that is, a strong dielectric torque near the edge of electrodes and elastic force controlling degree of twist above the center of the electrodes. This work is important for the design of fast-speed LCDs with high transmission.

1) R. A. Soref: J. Appl. Phys. **45** (1974) 5466.
2) R. Kiefer, B. Weber, F. Windscheid and G. Baur: *Proc. 12th Int. Display Research Conf.* (Society for Information Display and the Institute of Television Engineers of Japan, Hiroshima, 1992) p. 547.
3) M. Oh-e, M. Ohta, S. Aratani and K. Kondo: *Proc. 15th Int. Display Research Conf.* (Society for Information Display and the Institute of Television Engineers of Japan, Hamamatsu, 1995) p. 577.
4) K. Kondo, S. Matsuyama, N. Konishi and H. Kawakami: *Dig. Tech. Papers of 1998 Society for Information Display Int. Symp.* (Society for Information Display, Anaheim, 1998) p. 389.
5) S. H. Lee, S. L. Lee and H. Y. Kim: *Proc. 18th Int. Display Research Conf.* (Society for Information Display and the Korean Physical Society, Seoul, 1998) p. 371.
6) S. H. Lee, S. L. Lee and H. Y. Kim: Appl. Phys. Lett. **73** (1998) 2881.
7) S. H. Lee, S. L. Lee, H. Y. Kim and T. Y. Eom: *Dig. Tech. Papers of 1999 Society for Information Display Int. Symp.* (Society for Information Display, San Jose, 1999) p. 202.
8) S. H. Lee, H. Y. Kim and S. L. Lee: *Proc. 6th Int. Display Workshops* (Society for Information Display and The Institute of Image Information and Television Engineers, Sendai, 1999) p. 191.
9) S. H. Lee, J. G. You, H. Y. Kim, D. S. Lee, S. K. Kwon, H. S. Park and C. K. Kim: *Dig. of Tech. Papers of 1997 Society for Information Display Int. Symp.* (Society for Information Display, San Diego, 1997) p. 711.
10) M. Oh-e and K. Kondo: Liq. Cryst. **25** (1998) 699.
11) S. H. Lee, S. L. Lee, H. Y. Kim and T. Y. Eom: J. Korean. Phys. Soc. **35** (1999) S1111.
12) Z. He, T. Nose and S. Sato: Jpn. J. Appl. Phys. **36** (1997) 1178.
13) Z. He, Z. Ling, T. Nose and S. Sato: Jpn. J. Appl. Phys. **36** (1997) 2128.