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Analysis of Light Efficiency in Homogeneously Aligned Nematic Liquid Crystal Display with Interdigital Electrodes

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A homogeneously aligned nematic liquid crystal display with interdigital electrodes has been known to exhibit wide viewing angle due to in-plane rotation of liquid crystal director with applied voltage, and low transmittance due to no twist deformation of liquid crystal director above electrodes. The transmitted light of the device depends on the ratio of cell gap, the distance between electrodes, the width of electrodes and the dielectric anisotropy of the liquid crystal. Recently we have found that light efficiency is much more effective for fringe-field driven device than in-plane field driven one. This paper reports simulational and experimental studies on the light efficiency depending on electrode design and liquid crystal in detail.

I. INTRODUCTION

Liquid crystal displays (LCDs) utilize the anisotropic properties of liquid crystal molecules, organic chemicals, in refractive index and dielectric permittivity. However, the birefringence of LCs has viewing angle and wavelength dependence such that the limited viewing angle is an intrinsic problem in most LCDs. As the size of LCDs becomes large enough to replace CRT monitors and even TVs, this problem needs to be solved. Recently, several new approaches minimizing viewing angle dependency have been introduced. Among them are in-plane switching (IPS) [1], multi-domain vertical alignment (MVA) [2], and film compensated twisted nematic (TN) [3] modes. The IPS mode with interdigital electrodes can realize wide viewing angle due to in-plane orientation of LC director without further using optical compensation film. However, the demerit in the IPS is low transmittance ratio because the light does not transmit above electrodes. The MVA mode also has low transmittance problem due to the existence of disinclination lines in light-transmitted area. The light efficiency in LCDs is also a key issue because it is directly related to the power consumption of the display. Unfortunately, previously described modes do not satisfy both high transmittance and wide viewing angle characteristics at the same time. However, recently we have developed a breakthrough in technology called "fringe-field switching (FFS)" [4,5]. In the FFS device, the LC director twists in plane in the areas between electrodes and even above electrodes. These characteristics of the device make it realize both high transmittance and wide viewing angle at the same time.

In this paper, we study the dependence of the light transmittance on the design of electrodes and dielectric anisotropy of the liquid crystal by simulation and experiment, describing how it can be changed from utilization of in-plane field to a fringe one.

II. SWITCHING PRINCIPLE OF FRINGE-FIELD SWITCHING

Fig. 1 shows schematic drawing of cell structures with field lines generated by interdigital electrodes existing on bottom substrates. Three kinds of cell structure with interdigital electrodes are possible. The first case is when the distance (l) between common and source electrodes is larger than the cell gap (d) and the width of electrodes (w), structure for the conventional IPS. The second one is that l is smaller than d and w. The third one l is ze-

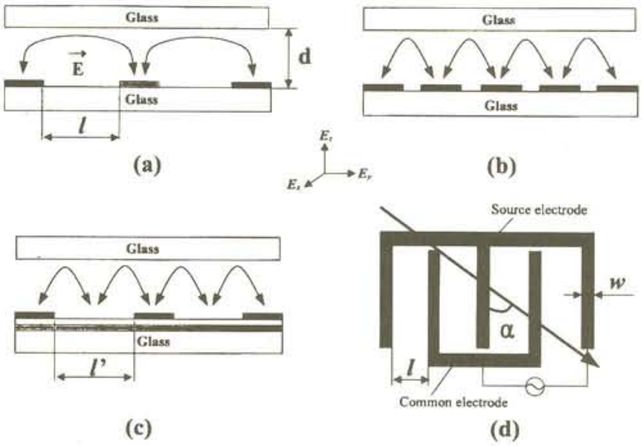

Fig. 1. Schematic diagrams of the cell structure with field lines. (a) l/w and $l/d > 1$; convention IPS cell, (b) l/w and $l/d < 1$, (c) $l = 0$; FFS cell, (d) top view of electrodes.

ro but with distance (l') between source electrodes. The latter two are for the FFS. In the conventional IPS mode, the horizontal component of an electric field is dominant in the range between electrodes for $l > d$ and $l > w$, as shown in Fig. 1(a). However, in the FFS mode where $l/d < 1$ or $l = 0$, the vertical as well as horizontal components of an electric field exist above electrodes, as shown in Figs. 1(b) and 1(c).

In the IPS and FFS cells, the liquid crystal is homogeneously aligned throughout the cell gap by antiparallel rubbing of polyimides coated on above electrodes of bottom glass and top bare glass. The transmission axis of the polarizer is oriented along the rubbing direction at the bottom plate and the analyzer perpendicular to the polarizer. In the IPS cell, the normalized transmission of light is

$$T/T_o = \sin^2(2\Psi)\ \sin^2(\pi d\Delta n/\lambda) \qquad (1)$$

where Ψ is an angle between polarizer and the liquid crystal director, Δn the birefringence of liquid crystal medium, λ the wavelength of the incident light and T_o the transmitted light through parallel polarizers. Therefore, in the voltage-off state, the Ψ is zero and the cell appears to be black. With bias voltage larger than Freedericksz transition threshold, V_{th}, the LC molecules are twisted along (perpendicular to) the field direction when a liquid crystal with positive (negative) dielectric anisotropy is present in the cell, and thus the value of Ψ deviates from zero, giving rise to transmission of the incident light. In the IPS cell, the electric field lines parallel to the substrate mainly exists in the area between electrodes so that only twist deformation of liquid crystal director between them occurs, giving rise to transmission of the incident light. However, the liquid crystal molecules above electrodes do not experience twist deformation due to equipotential surface of electrodes themselves. Consequently the light can be transmitted only in the area between electrodes, resulting in low transmittance compared with that of TN mode in which the light transmits in the whole electrode area. In the FFS cell, l is smaller than d and w so that the electric field parallel to the substrate can not be formed but instead the electric field lines of paraboliclike form are formed in the whole area. In other words, such field lines having vertical components as well as horizontal ones exist throughout the cell and the dielectric torque applies to the liquid crystal medium even above electrodes, resulting in light transmission in the whole area.

III. SIMULATIONAL AND EXPERIMENTAL RESULTS

Using commercially available simulation software (2 dimmos from autronic-Melchers, Germany), the simulations were performed. Table 1 shows the simulational condition and physical parameters of liquid crystals. The difference between LC1 and LC2 is only dielectric anisotropy. For the simulation, the cell gap was 4 μm. Fig. 2 shows simulational results of three cases describ-

Table 1. Physical parameters used for simulation.

Physical Parameters	LC 1	LC2
Δn at 550 nm	0.075	
$\Delta\varepsilon$	8.0	−4.0
Rubbing Direction (α)	12°	78°
K11 (1E-12 N)	11	
K22 (1E-12 N)	6	
K33 (1E-12 N)	13	
Pretilt Angle	1°	

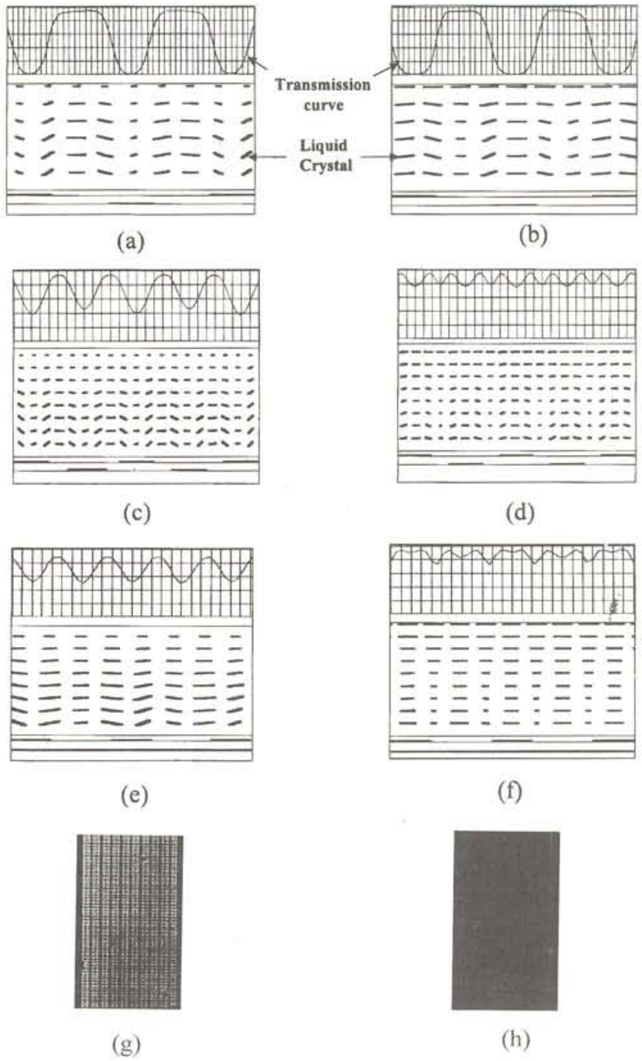

Fig. 2. Simulation results describing the light transmission dependent on the electrode structures and the dielectric anisotropy of LCs: l/w and $l/d > 1$ with LC1 (a) and LC2 (b); l/w and $l/d < 1$ with LC1 (c) and LC2 (d); $l = 0$ and $l'/w > 1$ with LC1 (e) and LC2 (f). Photos of test cells with transmission: (g) with condition (e) and (h) with condition (f).

ing the light transmission dependent on the cell structure and the dielectric anisotropy of liquid crystal. In the IPS case of (a) and (b), the light transmits only in the area between pixel and common electrodes because the LC molecules do not twist deformation above electrodes due to the equipotential surfaces of electrode themselves. The anisotropy dependence of LC is negligible except the director configuration near the edge of electrodes due to different behavior to applied field, *i.e.*, LC with positive (negative) dielectric anisotropy orients along (perpendicular to) field direction. In the FFS case of l/d and $l/w < 1$, the total transmission is increased compared with that of the IPS cell owing to the light transmission even above the electrodes. The dielectric anisotropic dependence on the transmission is also clearly different as shown in Figs. 2(c) and 2(d). In this case, field lines having vertical components (E_z) as well as horizontal ones (E_y) exist throughout the cell. The dielectric torque applied between E_y and the LC director causes twist deformation of the LC, resulting in light transmission in the whole area. Especially, the intensity of E_y varies depending on the position of electrodes, meaning that the degree of twist of LC director periodically changes along the horizontal axis, giving rise to alternating transmittance. In the positive LC, the transmission oscillates with amplitude larger than that of negative one so that the total transmission is higher for negative LC than the positive one. This is due to the fact that the LC molecules tilts up near electrode edges along the field direction for the positive one so that the degree of twist above electrodes is less compared with that between electrodes, thus giving rise to less transmission. However, for the negative LC, the interaction probability between E_z and director is almost zero because the tilt angle is only 1°, so that the twist of LC director occurs even above electrodes by interaction between E_y and LC director, resulting in light transmission in whole area. With further increasing voltage, the maximum point of transmission will be decreased by over twist of LC director, *i.e.*, Ψ greater than 45° whereas the minimum point of transmission is becoming peak, *i.e.*, the director twists toward 45°. In the FFS case of $l = 0$, as shown in Figs. 2(e) and 2(f), the results are similar to the previous case. However, for the positive one, the oscillation period in transmission is shorter than case (c) though the total transmission is about the same. This is also from the oscillation of electric field intensity of E_y. For the negative LC, the total transmission is higher than the positive one as expected but the transmission shape is unlike the previous one (no more kind of cosine function). In this case, the maximum and minimum point of transmission can be reversed with further Ψ increasing of voltage, and more further increasing will decrease the total transmission because the value of Ψ exceeds 45° in the whole area. Figs. 2(g) and (h) shows photos of real test cells of cases (e) and (f). As can be seen, the cell with positive LC shows clearer bright- and less bright-striped pattern than that with negative ones, indicating that the negative LC is more effective in transmission than the positive one. The black spots indicate the location of spacers necessary for cell gap. Fig. 3 shows dependency of light transmission with varying l and l' for different electrode widths and LCs. With increasing l, the transmission decreases linearly and the electrode width of 4 μm gives better transmission than that of 6 μm. The efficiency of light transmission with given electrode width w_c for both positive and negative LCs in case 2 as follows:

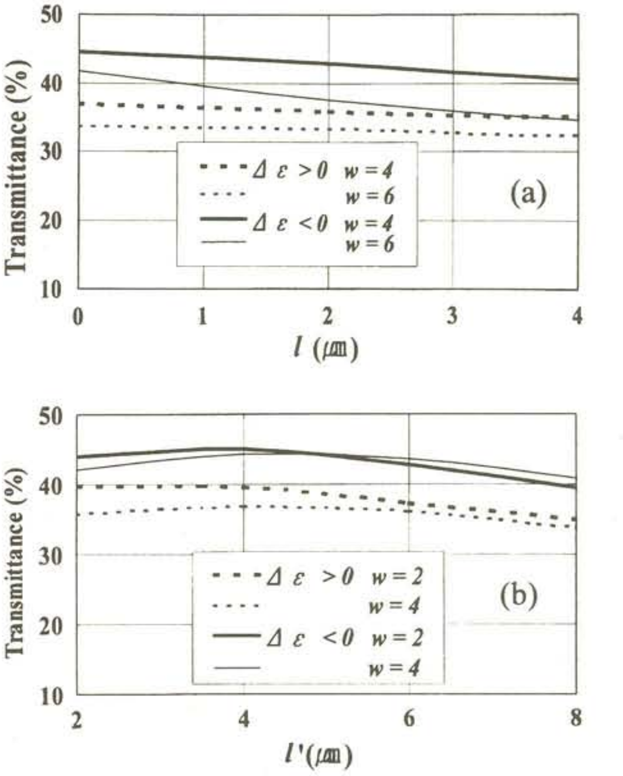

Fig. 3. Simulational results of (a) l and (b) l'-dependent transmission.

$$\eta \propto (l/w_c)^{-1} \tag{2}$$

In conclusion, η is highly effective for $l/w_c < 1$. In the third case of $l = 0$ but with varying l', the light transmission is not linearly decreasing with increasing l' within in the previous case, instead, it has an optimal range. The light efficiency is maximum when the ratio, l'/w_c is in range of 0.25 and 2, particularly 1.2 with $w = 4$ and when the electrode width is 2 μm, it still shows light transmission more than 40 % even when the ratio $l'/w_c = 4$. However, when the positive LC is used, the maximum transmittance is about 37 % for w=4 μm and $l = 0$, which is less than the negative one. But the behavior is similar. Therefore, the efficiency of light transmission with critical distance l'_c showing maximum transmittance as follows:

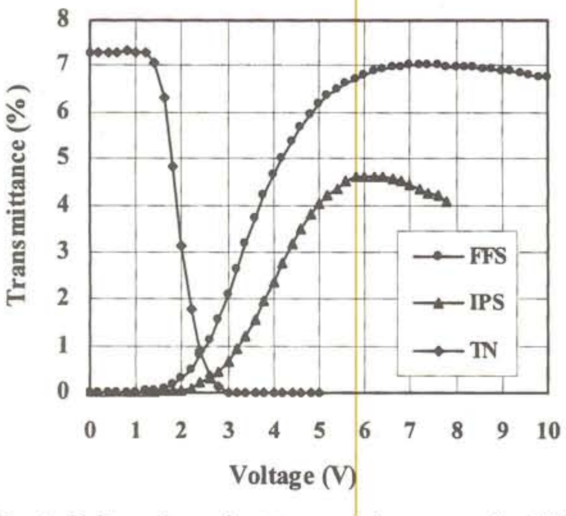

Fig. 4. Voltage-dependent transmission curves for different display modes.

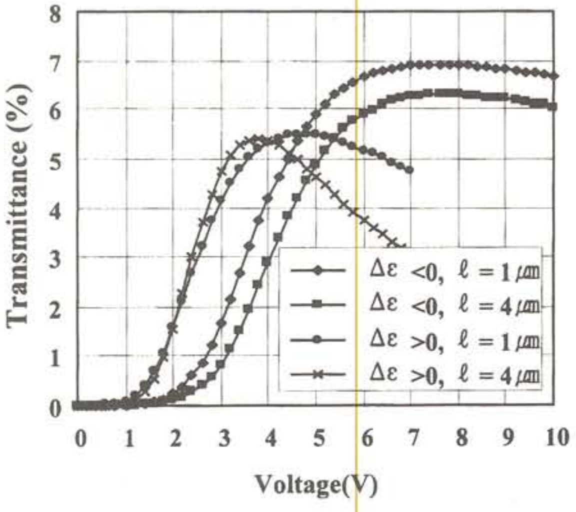

Fig. 5. Voltage-dependent transmission curves depending on dielectric anisotropy of LCs.

$$\eta \propto \{l'_c/w_c - (|l' - l'_c|/w_c)\} \tag{3}$$

With this type of pixel design, η is highly effective for narrow w_c and l'_c.

For the experiments, we have fabricated the actual 12.1" SVGA thin-film-transistor (TFT)-LCD panel for the TN, IPS, and FFS modes. Fig. 4 shows the voltage-dependent transmission curves for three different modes. In transmittance efficiency, the TN mode is best and the IPS mode shows about 4.5 %, about 3 % less than the TN mode. However, the FFS mode shows comparable values to the TN mode. The transmittance also depends on the type of dielectric anisotropy, as shown in Fig. 5. As can be seen, when the ratio l/w is smaller than 1, the difference in transmission between positive and negative LCs is clear but as l/w becomes greater than 1, the difference becomes smaller. These results are in good agreement with simulational results.

IV. CONCLUSIONS

We have studied on the light efficiency of the device driven by in-plane field and fringe-field by simulation and experiment. The device of the FFS shows much better efficiency of light transmission than the IPS device. The study shows that the efficiency is effective when $l/w < 1$ and $l/d < 1$, and narrow w and l' for $l = 0$. Further, the narrow electrode width is required in order for LC to twist even above electrodes giving rise to transmission. This novel device overcomes a demerit of the conventional IPS cell with interdigital electrodes, exhibiting high transmittance and wide viewing angle at the same time. We believe that this is one of the most promising candidates for high quality active matrix LCD, irrespective of panel size and uses.

REFERENCES

[1] K. Kondo, S. Matsuyama, N. Konishi and H. Kawakami, *Dig. of Tech. Papers of 1998 Soc. for Inf. Disp. Int'l Symp.* (Society for Information Display, Anaheim, 1998), p. 389.

[2] A. Takeda, S. Kataoka, T. Sasaki, H. Chida, H. Tsuda, K. Ohmuro, Y. Koike, T. Sasabayashi and K. Okamoto, *Dig. of Tech. Papers of 1998 Soc. for Inf. Disp. Int'l Symp.* (Society for Information Display, Anaheim, 1998), p. 1077.

[3] N. Watanabe, M. Hirata and S. Mizushima, AM-LCD '97, 45 (1997).

[4] S. H. Lee, S. L. Lee and H. Y. Kim, *Proc. of the 18th Int'l Disp. Research Conf.* (Society for Information Display and the Korean Physical Society, Seoul, 1998), p. 371.

[5] S. H. Lee, S. L. Lee and H. Y. Kim, Appl. Phys. Lett. **73**, 2881 (1998).