# Rubbing Angle Effects on the Electro-Optic Characteristics of In-Plane Switching Liquid Crystal Display

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We have studied the influence of rubbing angles with respect to in-plane field direction on electro-optic characteristics of in-plane switching (IPS) liquid crystal display. The results show that the threshold voltage increases and the operational voltage decreases as the rubbing angle increases. Further, the total response time and also response times associated with grey-to-grey transitions become fast as the rubbing angle decreases.

*Keywords* : IPS mode, rubbing direction, electro-optic characteristics, threshold voltage, response time

## 1. INTRODUCTION

Liquid crystal displays (LCDs) with twist nematic (TN) mode has been dominant for an application of active matrix LCDs to notebooks and monitor uses up to 17". However it has an intrinsic problem in viewing angle, which restricts its application to large-size LC displays. Recently, there has been a great progress in improving viewing angle comparable to the color CRT with development of TFT-LCDs such as in-plane switching (IPS)[1-3], fringe-field switching (FFS) [4-7] and multi-domain vertical alignment (MVA) [8] modes.

The reason that LCD cells with the IPS mode have superior viewing angle characteristic is that the liquid crystal molecules rotate in parallel to glass substrate with bias field so that change of optical characteristics with viewing angle is very small. However it also has some disadvantages in physical properties such as driving voltage and response time, which mainly depend on liquid crystals, cell gap, and rubbing direction. Recently, the response times associated with grey-to grey transition were reported in the IPS mode [9], but the relationship between the response time and the rubbing angle has not been studied yet.

Understanding of the effects of rubbing direction is of importance in order to have TFT-LCDs to be optimized [10]. In this study, we investigate the electro-optic characteristics such as voltage-dependent transmittance (*V-T*) and response times of test cells by changing rubbing directions with respect to electric field for LCs having positive and negative dielectric anisotropy.

## 2. CELL STRUCTURES and SWITCHING PRINCIPLE

Figure 1 shows cell structures of the IPS mode in cross-sectional and top views. Interdigital electrodes with MoW metal on bottom substrate were patterned as shown in Fig. 1 and the rubbing was done in antiparallel directions to give a pretilt angle of 1° after polyimide coating on top and bottom substrates. The distance between electrode is 20$\mu m$ with electrode width of 10$\mu m$. In this way, the LCs are homogeneous aligned. The cell

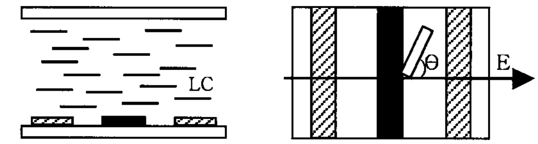



Fig.1. Schematic diagram of cross-sectional (a) and top (b) views of the IPS cell with interdigital electrodes.

gap ($d$) is 4.2$\mu$m. Since the electrode distance is lager than the electrode width and the cell gap, the in-plane field is generated between electrodes when a voltage is applied.

In the IPS mode that the uniaxial LC medium exists under crossed polarizers, the normalized light transmittance is defined by

$$T/T_0 = \sin^2(2\chi)\sin^2(\pi\Delta nd/\lambda) \qquad (1)$$

where $\chi$ is an angle between transmission axis of a polarizer and optical axis of LC molecules, $\Delta n$ is birefringence of the LC and $\lambda$ is a wavelength of an incident light. In the absence of an electric field, the optical axis of LC molecules coincides with polarizer so that the polarization state of incident light through nematic LC layer is not changed. Therefore, the transmitted light is blocked by analyzer in off state. With bias voltage the optical axis of LC molecules deviates from the transmission axis of polarizer by in-plane field so that the polarization state of incident light becomes elliptic before facing analyzer and thus partial light can transmit. In addition, the transmission depends not only on the angle of $\chi$ but also on the phase retardation of the LC medium.

## 3. RESULTS AND DISCUSSION

First, we have performed a computer simulation to investigate voltage-dependent transmittance ($V$-$T$) characteristics as a function of rubbing angles with respect to in-plane field direction, as shown in Fig. 2. For the simulation, we have used the commercially available software "LCD Master" (Shintech, Japan), where the motion of the LC director is calculated based on the Eriksen-Leslie theory and 2x2 Jones matrix is applied for optical transmittance calculation. The simulation conditions are given in Table 1.

Table 1. Simulation condition for the cell structure and the LC.

| | | |
|---|---|---|
| Cell gap ($\mu$m) | | 4 |
| Pretilt angle ( °) | | 1 |
| LC | $K_1$ (pN) | 9.7 |
| | $K_2$ (pN) | 5.2 |
| | $K_3$ (pN) | 13.3 |
| | $\Delta n$ at 590nm | 0.085 |
| | $\gamma$ (mPa.s) | 78.0 |
| | $\Delta\varepsilon$ | 8.2 |

The calculated results show that the threshold voltage ($V_{10}$) increases and the operation voltage ($V_{op}$) at which the maximum transmittance occurs decreases with increasing rubbing angle. In other words, the $V$-$T$ curves become steep with increasing rubbing angle. The maximum transmittance remains about the same although the rubbing angle changed from 83° to 63°. Next, experiments were performed to confirm the calculated results. For experiments, the LC material with positive dielectric anisotropy was used [$\Delta n$ = 0.0752 at 20 °C and 589 nm, dielectric anisotropy $\Delta\varepsilon$ = 8.7 (20 °C, 1 kHz), rotational viscosity $\gamma$ = 87 mPa.s, twist elastic constant $K_2$ = 5.4 x $10^{-12}$ N at 20 °C]. For electro-optic measurement, the halogen lamp was used as a light source and a square wave of 60 Hz voltage source from a function generator was applied to the sample cell. The light passed through the cell was detected to the photomultiplier tube.

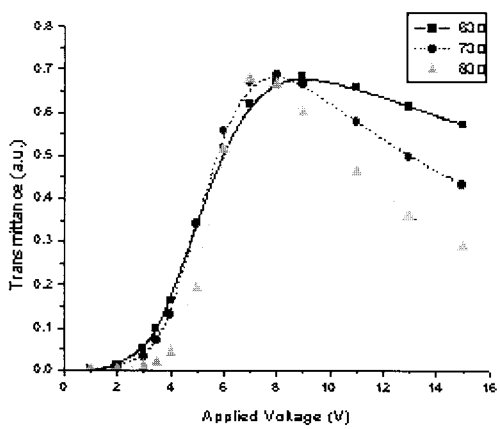



Fig. 2. Calculated voltage-dependent transmittance as a function of rubbing angle.

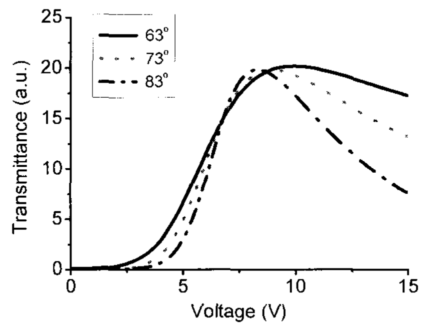
Figure 3(a) shows experimental $V$-$T$ curves and Fig. 3(b) shows a change of $V_{10}$ and $V_{op}$ as a function of rubbing angles. The $V_{10}$ increases and $V_{op}$ decreases as the rubbing directions change from 63° to 83°, and the voltage difference between $V_{10}$ and $V_{op}$ becomes smaller with increasing rubbing directions and the maximum transmittance given different rubbing direction remains almost the same. The results are in good agreements with the simulated results. The relationship between the rubbing angle and the $V_{10}$ can be explained by applying concept of the dielectric torque $N$ on the polarization of nematic LC medium defined as

$$N = \left|\Delta\varepsilon(n \cdot E)\, n \times E\right|$$

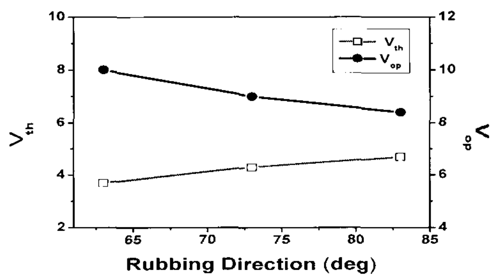
$$= \Delta\varepsilon E_0^2 \sin 2\phi \qquad (2)$$

where **n** is a unit vector of the LC director, **E** is electric field vector, $E_0$ is than that for the 63° rubbed cell although the $V_{10}$ of the first is higher than that of the latter.

Now, we hàve studied the response time to understand whether the rubbing angle affects it or not. Fig. 4 indicates on and off behaviors intensity of electric field and $\phi$ is an angle between the LC director and field direction. Given a bias field $E_0$, the torque is minimum at $\Phi$ = 0° or 90° and maximum at $\Phi$ = 45° so that the liquid crystal director with rubbing direction of 63° will be twisted causing light leakage faster than that of the 83° rubbed cell. For $V_{op}$, as realized from the eqn. (1), the maximum transmittance can be obtained when the director of LC molecules makes an angle of 45° with transmission axis of the polarizer. Thus the maximum transmittance depends on the driving voltage to rotate the mid-layer of the LC by 45° approximately and according to the simulation and measured results, the rubbed cell by 83° requires lower driving voltage than others. This indicates that for the 63° rubbed cell the mid-director rapidly approaches an angle of 45° to the field direction with increasing voltage but with further increasing voltage the angle of it passes over 45°, which starts to reduce the $N$. However, for the 83° rubbed cell the mid-director makes larger angle than 45° to the field direction, causing slow response to the field but as an applied voltage increases the angle of it is toward 45° to the field direction, meaning that with increasing voltage the LC director feels stronger the $N$ than that at low voltage. This causes lower $V_{op}$ for the 83° rubbed cell when the transmittance switches from a black to white state or vice versa as a function of rubbing directions,




(a)




(b)

Fig. 3. (a) Voltage-dependent transmittance for different rubbing directions and (b) $V_{10}$ and $V_{op}$ plotted as a function of rubbing angles.

where $\tau_{on}$ and $\tau_{off}$ are defined in which the transmittance changes from 10% to 90% and from 90% to 10% of maximum transmittance, respectively. $\tau_{off}$ is independent of rubbing angles although the $V_{op}$s are different from each other because the director of 45° twisted just restores the initial state by elastic torque. However $\tau_{on}$ increases from 23 ms to 62 ms, much more than twice as the rubbing angle changes from 63° to 83°, although the driving voltage differs only by about 1V. Consequently, the total response time ($\tau_{total}$) increases with increasing rubbing angle. The increase of $\tau_{on}$ with increasing rubbing angle seems to be reasonable since the rising time is proportional to $1/(E^2 - E_{10}^2)$ where the difference between $E$ and $E_{10}$ becomes decreased as the rubbing angle increases. Several tests for the LCs with

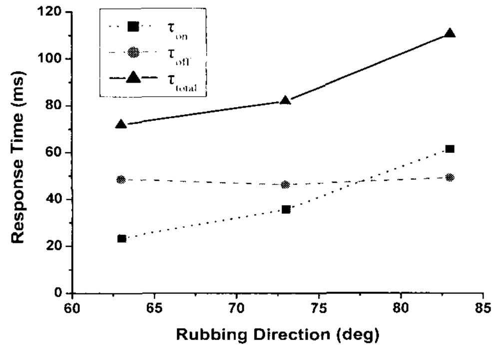
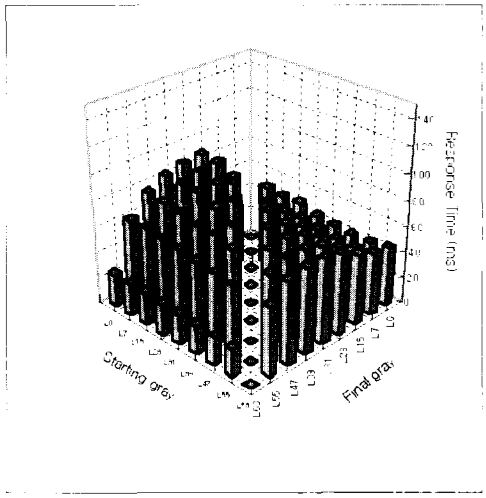
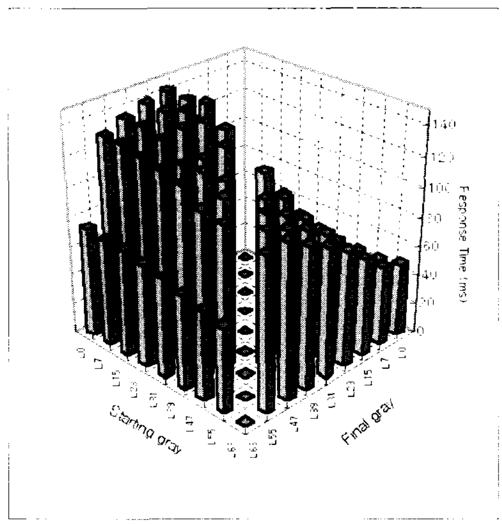



Fig. 4. $\tau_{on}$, $\tau_{off}$, and $\tau_{total}$ plotted as a function of rubbing angles.

different $\Delta n$'s and negative dielectric anisotropy were performed, revealing similar trends [11]. Finally, we have measured the response times including all grey-to-grey transitions. First, we have divided the *V-T* curve into 64 gray levels from black ($L_0$) to white ($L_{63}$) with gamma correction value of 2.2 and the transmittance intervals, *T* (n+1)-*T* (n), are constant for different cells where *T* (n) are the transmittance for n-th level. And then we have measured the response time by applying and reducing a voltage with a minimum jump of 8 gray levels for two cells, as shown in Fig. 5. In case of the $\tau_{on}$s, for the 83° rubbed cell they are mostly over 100 ms whereas they are less than 90 ms for the 63° rubbed cell. In case of the $\tau_{off}$s, although the response time from a white to black state remains about the same irrespective of rubbing angle, $\tau_{off}$s at grey scales are in ranging between 42 ms and 67 ms for the 63° rubbed cell while they are between 45 ms and 107 ms for the 83° rubbed cell. This informs that the rubbing angle strongly affects the response time between grey levels. Therefore, the rubbing angle in the IPS mode should be designed in the viewpoints of not only the driving voltage but also the response time.



(a)



(b)

Fig. 5. Measured response times between grey levels when the rubbing angle is (a) 63° and (b) 83°.

## 4. CONCLUSION

We have investigated the dependence of electro-optic characteristics of the LCD cells associated with IPS mode on the rubbing directions. Both experimental and numerical results show that the driving voltage decreases as the rubbing direction with respect to electric field increases whereas threshold voltage increases with increasing rubbing angle.

The total response time increases as the rubbing direction changes from 63° to 83°. We emphasize that the optimization of the rubbing directions in the IPS mode is indispensable to have best performance of TFT-LCD.

## ACKNOWLEDGMENTS

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