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Influence of the Rubbing Angle on Reflective In-Plane-Switching Liquid Crystal Displays

Yubao SUN and Shin-Tson WU[1]

Department of Applied Physics, Hebei University of Technology, Tianjin 300130, P. R. China
[1]*School of Optics/CREOL, University of Central Florida, Orlando, FL 32816, U.S.A.*

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Rubbing angle effects on the response time of a normally black reflective in-plane-switching homogeneous liquid crystal display were analyzed at different grey scales. As the rubbing angle increases, the rise time is decreased except that the on-state voltage is slightly increased. The optimal rubbing angle is around 30° rather than the conventional 10°.
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KEYWORDS: reflective liquid crystal display, in-plane-switching, rubbing angle effect, response time

The in-plane switching (IPS) mode has been used for large-screen transmissive liquid crystal displays (LCDs) because of its excellent viewing angle.[1–4] Recently, the IPS mode is also considered for reflective liquid crystal displays.[5–8] As expected, the wide viewing angle and high contrast ratio of the R-IPS mode is obtained. However, the response time of the IPS mode is relatively slow as compared to other modes.[9] In the IPS mode, the response time depends on the cell gap, rotational viscosity, twist elastic constant, applied electric filed, and rubbing angle (Φ). Usually, the rubbing angle is about 10° in transimissive IPS mode. In our previous paper,[10] we derived the formulae for response time of a reflective IPS mode under three grey levels. In this paper, we extend the theoretical analyses of the rubbing angle effects on the reflectance, operating voltage, and response time of a reflective IPS LCD.

When backflow and inertial effects are ignored, the dynamics of liquid crystal director rotation is described by the following Erickson-Leslie equation:[5,9]

$$\gamma_1 \frac{\partial \phi}{\partial t} = K_2 \frac{\partial^2 \phi}{\partial z^2} + \varepsilon_o |\Delta\varepsilon| E^2 \sin\phi \cos\phi, \qquad (1)$$

In eq. (1), γ_1 is the rotational viscosity, K_2 is the twist elastic constant, $\Delta\varepsilon$ is the dielectric anisotropy, E is the electric field strength and ϕ is the LC rotation angle. The homogeneous LC layers are assumed to have cell gap d along the z-axis. Under such a circumstance, the turn-off and turn-on times of the R-IPS mode have following expressions:[10]

$$\tau_{\rm off} = \frac{\gamma_1 d^2}{\pi^2 K_2}. \qquad (2)$$

$$\tau_{\rm on} = \frac{\gamma_1}{\varepsilon_o |\Delta\varepsilon| E^2 \left(\cos(2\Phi) \dfrac{\sin(2\bar{x})}{2\bar{x}} + \sin(2\Phi) \dfrac{\cos(2\bar{x})}{2\bar{x}} \right) - \dfrac{\pi^2}{d^2} K_2} \qquad (3)$$

From eq. (2), the relaxation time is governed by the cell gap (d) and the LC visco-elastic coefficient (γ_1/K_2), and is independent of the rubbing angle Φ. While in eq. (3), $\bar{x} = \int_0^{\frac{d}{2}} x \mathrm{d}z$ defines the rotation of the average optical axis of the LC layer.[7,10]

Figure 1 shows the electrode configuration of the IPS mode under study. The following LC cell parameters are used for calculations: $d = 3\,\mu$m, $\gamma_1 = 85$ m Pa·s, $K_2 = 7$ pN, $\Delta\varepsilon = 7.8$, and $\Delta n = 0.06$. The electrode gap is $l \sim 10\,\mu$m and width $\omega \sim 5\,\mu$m. In our simulation for a reflective IPS mode, we have placed the interdigitated indium tin oxide (ITO) electrodes in the top substrate and an aluminum reflector in the bottom substrate. A quarter-wave film is needed between the LC layer and the reflector in order to obtain the normally black mode. For simplicity, the thin film transistor (TFT) aperture ratio was not taken into account. The Jones matrix method[11] is used for calculating the reflectance.

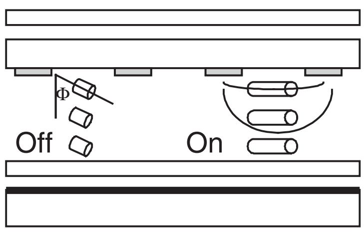

Fig. 1. Device configuration of the proposed reflective IPS display. In the voltage-off state, the LC directors are at an angle Φ with respect to the IPS electrodes.

Figure 2 depicts the voltage-dependent reflectance at $\lambda = 450$, 550 and 650 nm and rubbing angle $\Phi = 30°$. Here, we use the normalized reflectance; all the optical losses from polarizer and glass substrates are ignored. From Fig. 2, the proposed R-IPS mode is normally black. Strictly speaking, the Freedericksz transition threshold exists only for $\Phi = 0$, where the electric field is orthogonal to the LC directors. As the rubbing angle departs from 0, the Freedericksz transition

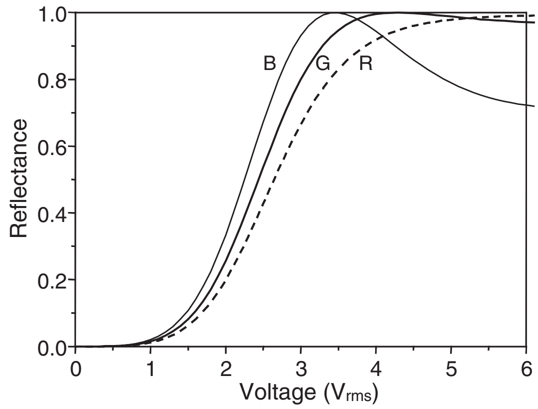

Fig. 2. Voltage-dependent reflectance of the reflective IPS cell at $\Phi = 30°$. $R = 650$, $G = 550$ and $B = 450$ nm.

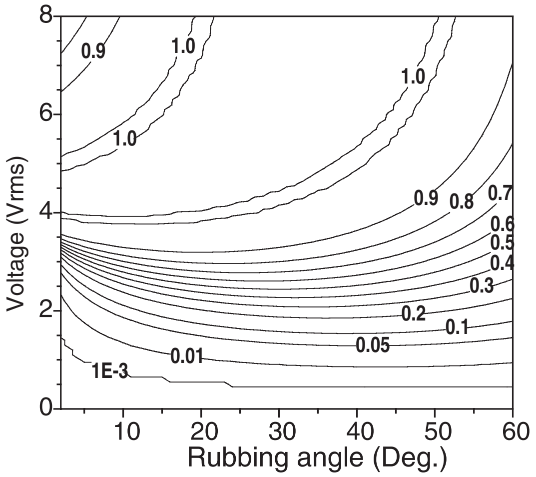

Fig. 3. Voltage-dependent reflectance of the reflective IPS cell at different rubbing angle.

disappears. However, the threshold-like optical transition exists. We define the optical threshold (V_{op}) as the reflectance reaches $R = 0.1$. From Fig. 2, the optical threshold is about 1.5 V_{rms} for the 30° rubbing angle. As the voltage continues to increase, the reflectance increases and reaches unity (for $\lambda = 550$ nm) at 4 V_{rms}. Low operating voltage is particularly desirable for low power TFT-LCD.

Figure 3 plots the voltage-dependent reflectance of the homogeneous LC cell at $\lambda = 550$ nm as a function of rubbing angles. The Freedericksz transition threshold voltage for $\Phi = 0$ occurs at $V_{th} = (\pi l/d)\sqrt{K_2/\Delta\varepsilon}$ which is equal to 3.33 V_{rms}. As the rubbing angle departs from 0, the "threshold" voltage decreases. For a given rubbing angle, say $\Phi = 30°$, the reflectance increases to $R \sim 1$ at $V \sim 4$ V_{rms}, same as that shown in Fig. 2. From Fig. 3, the contour lines of $R \sim 1$ strongly depend on the rubbing angle. If the rubbing angle is larger than 45°, then the required voltage to achieve unity reflectance is quite high. This is because the LC directors need to be reoriented to be completely perpendicular to the substrate surfaces. The small rubbing angle has advantage in lower operating voltage. However, its response time is slower.

The voltage-dependent rotation of average optical axis ($\bar{x}$)

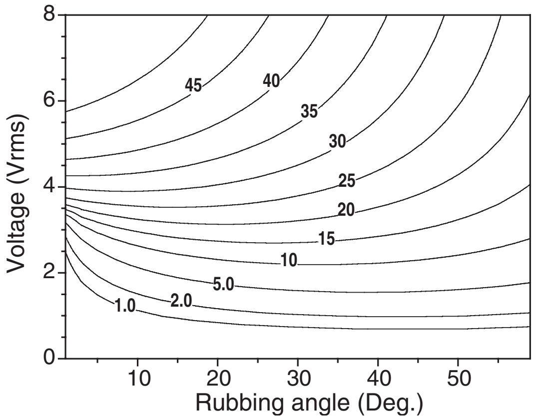

Fig. 4. Voltage-dependent rotation of average optical axis of the reflective IPS LC layer at different rubbing angel (Φ).

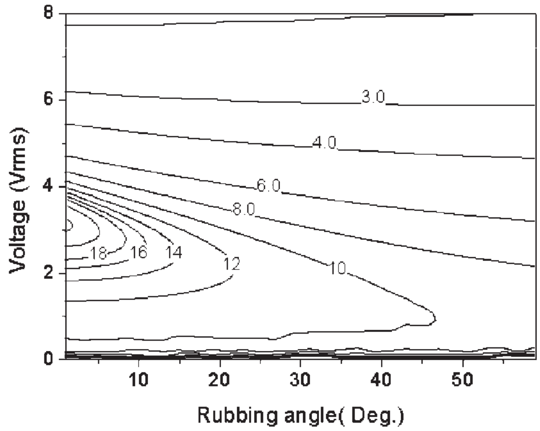

Fig. 5. The calculated rise time at different rubbing angle (Φ) and voltages. Cell gap $d = 3$ μm.

of LC layer is calculated and results are shown in Fig. 4. In comparison with the results plotted in Fig. 3, we found that $\bar{x} \sim 25°$ at the operation voltage corresponding to $R \sim 1$. This result is consistent with the experimental data reported in ref. 7. We also found that $\bar{x} \sim 5°$ for the optical threshold voltage which is defined as $R = 0.1$.

Response time is an important parameter for liquid crystal displays. As shown in eq. (2), the relaxation time is a constant once the cell gap and LC material are chosen. From the LC parameters we used, $\tau_{off} \approx 11$ ms. From eq. (3), the turn-on time depends on the applied electric field (E), rubbing angle (Φ) and rotation of average optical axis ($\bar{x}$). The rotation of average optical axis ($\bar{x}$) can be calculated once the applied electric field is given.

The voltage-dependent turn-on time for different rubbing angle is shown in Fig. 5. At a given voltage, the turn-on time decreases as the rubbing angle increases. From this figure, the turn-on time is less than 12 ms when the rubbing angle is larger than 20°, and the total response time ($\tau_{on}+\tau_{off}$) is less than 16 ms at any gray level. The fast response time of this reflective IPS mode is due to the thin (3-μm) cell gap and low viscosity LC material.

Strictly speaking, eq. (3) holds only in the small signal regime because the distribution of the LC directors does not fit with a sinusoidal curve when the electric filed is too large. However, in our simulation the reflectance does not change too significantly before $\bar{x}$ grows larger than 20°. Therefore, our results are still valid for large signal swings.

In summary, we have calculated the voltage-dependent reflectance, rotation of average optical axis of the LC layer, and response time of a reflective IPS liquid crystal display. The rubbing angle plays a very important role to the response time and operating voltage. Based on our analyses, the optimal rubbing angle is around 30° rather than the conventional 10°.

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