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Rubbing angle effect on in-plane switching liquid crystal displays

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The rubbing angle effect on transmissive in-plane switching liquid crystal displays is analysed by the Jones matrix method. Simulation results show that the optimum rubbing angle is around 30°–40°; the cell gap/birefringence product ($d\Delta n$) is about 0.33 µm. Increasing the rubbing angle can shorten the rise time and enlarge the grey scale voltage intervals. The optical characteristics are similar in two cells with different rubbing angles. These effects are particularly attractive for liquid crystal TV applications.

1. Introduction

Liquid crystal display (LCD) has become the dominant flat panel display technology for notebook and desktop computers [1]. The replacement of cathode ray tube television by LCD is now taking place. For television applications, wide viewing angle, fast response time and high brightness are essential. To achieve wide viewing angle, in-plane switching (IPS) [2–5] and multi-domain vertical alignment (MVA) [6–8] have been commonly utilized. Each approach has its own advantages and disadvantages. For example, the MVA mode exhibits a high contrast ratio and fast response time, however, it requires a biaxial phase compensation film and two circular polarizers. On the other hand, the IPS mode uses linear polarizers and does not require a compensation film, but its response time is too slow to display fast moving objects.

The response time of an IPS LCD is mainly determined by the LC cell gap, rotational viscosity, twist elastic constant and rubbing angle. Reducing the cell gap is an effective approach to shorten the response time; however, manufacturing yield could be reduced. The development of low viscosity LC materials is always highly desirable, but remains a challenging task for molecular engineering. On the other hand, to change the rubbing angle is quite straightforward and is a simpler approach. Lee *et al*. [9] studied the rubbing angle effect and found that as the angle increases from 7° to 17°, the rise time is halved. However, further increase from 17° to 22° produces negligible improvement. These results are questionable and deserve a more detailed investigation.

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In this study, we have re-examined the rubbing angle effect using the Jones matrix method and found that the optimal rubbing angle actually occurs at $\Phi \sim 30°$. By changing the rubbing angle from 10° to 30°, the rise time is improved by a factor of 3 and the grey scale voltage interval is widened. A disadvantage is the slightly higher operating voltage.

2. Simulation and results

Figure 1 shows the cell and electrode configuration of the IPS mode under study. The electrode gap is $\ell \sim 10\,\mu m$ and width $\omega \sim 5\,\mu m$. In the IPS mode, the interdigitated electrodes are usually in the bottom substrate. The two-dimensional voltage distribution was shown in a previous paper [10], but we assume that the variation of electrical potential is uniform in the LC layer, which is between the electrodes, when we calculate the director distribution using a one-dimension model. The polarizer axis is parallel to the rubbing direction and the analyser is crossed so that the display has a normally black mode. For simplicity, the TFT aperture ratio is not taken into consideration. Thus, the optical properties of the IPS cell are determined mainly by three parameters: the rubbing angle (Φ) between the rubbing direction and the electrodes, voltage, and the cell gap-birefringence product $d\Delta n$. If we fix a parameter, then the cell transmittance can be plotted in a two-dimensional (2D) contour diagram. Under such circumstances, the normalized transmittance (T; by ignoring the optical losses from the polarizer and substrates) of such a display is expressed as:

$$T = \left| (\cos\alpha, \sin\alpha) \cdot M \cdot \begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix} \right|^2 \qquad (1)$$

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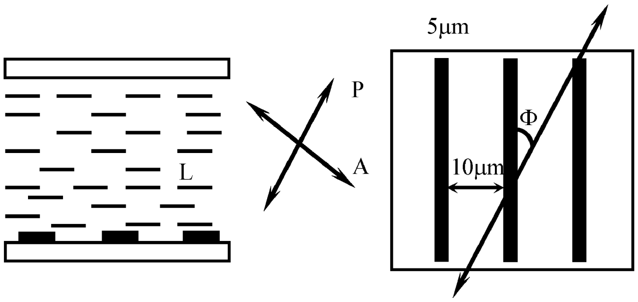

Figure 1. Side view (left), top view (right) and polarizer/analyser configuration of the IPS LCD with inter-digitated electrodes. Φ is the rubbing angle; electrode gap=10 μm and electrode width=5 μm.

where α is the angle between the polarizer axis and the optical axis of the LC layer, and M is the Jones matrix for the LC cell [10]. In the $V=0$ state, $\alpha=0$ so that $T=0$; this is the normally black mode. As the voltage exceeds the Freederisckz transition threshold, twist deformation occurs and the LC director distribution is governed by the following equation:

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

where, γ_1 is the rotational viscosity, $\boldsymbol{E}$ is the electric field strength which is related to voltage V as $\boldsymbol{E}=V/\ell$ (ℓ is the electrode gap), ϕ is the LC rotation angle, K_2 is the twist elastic constant, and $\Delta\varepsilon$ is the dielectric anisotropy. The homogeneous LC layers are assumed to have cell gap d along the z-axis. As the voltage exceeds the Freedericksz transition threshold, the LC directors are reoriented by the electric field, resulting in transmittance of light through the crossed polarizers, according to:

$$T = \sin^2(2\alpha)\sin^2\left(\frac{\pi d \Delta n(\phi)}{\lambda}\right) \qquad (3)$$

where $\Delta n(\phi)$ is the effective LC birefringence in the voltage-on state and λ is the incident wavelength. In our simulations, we chose a Merck LC mixture MLC-16000-100 as an example. The relevant parameters are $\Delta n=0.0908$, $\gamma_1=0.086$ Pa s, $K_2=7$ pN and $\Delta\varepsilon=8.2$.

Figure 2 shows the voltage-dependent transmittance contours of the homogeneous IPS cell as a function of $d\Delta n$ at $\lambda=550$ nm and rubbing angles $\Phi=10°$ and $\Phi=30°$. As shown in figure 2 (a), the maximum transmittance ($T=1$) for the $\Phi\sim10°$ IPS cell occurs at $V\sim3.5\,V_{rms}$ and $d\Delta n\sim340$ nm. As the rubbing angle increases to 30°, figure 2 (b), the on-state voltage increases to $\sim4.5\,V_{rms}$ while $d\Delta n$ stays at ~330 nm. By contrast, the dark state (let us compare at $T=0.01$) voltage drops from 1.2 (for $\Phi=10°$) to $0.9\,V_{rms}$ (for $\Phi=30°$). Thus, the IPS cell with $\Phi=30°$ not only has a lower optical threshold but also

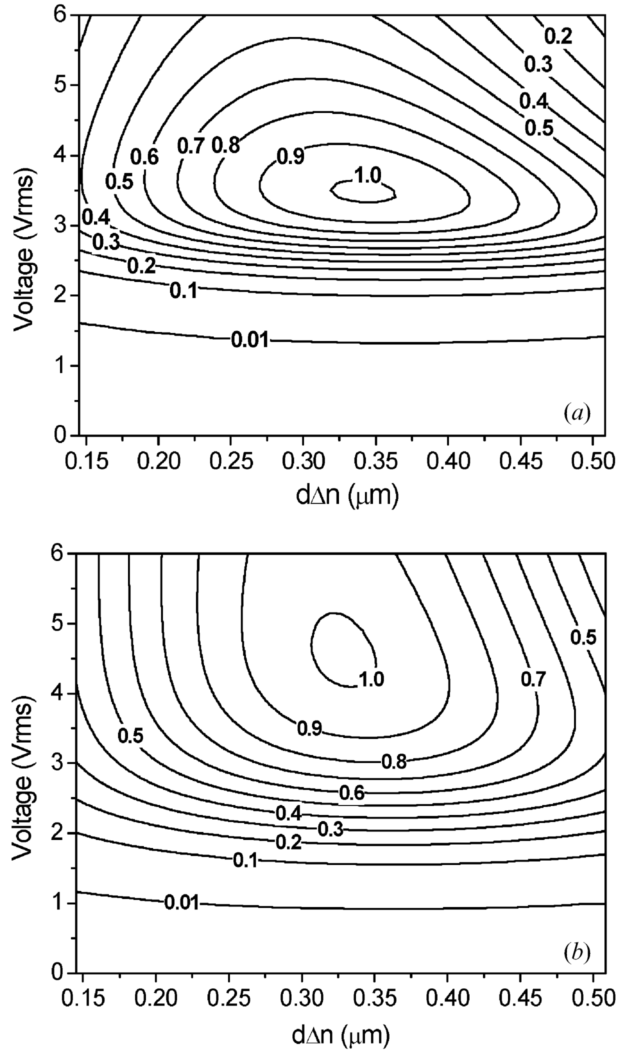

Figure 2. The effect of $d\Delta n$ on grey scale voltage for (a) $\Phi=10°$, (b) $\Phi=30°$.

has a higher on-state voltage than the corresponding cell with $\Phi=10°$. This indicates that the voltage-dependent transmittance for the $\Phi=30°$ curve is shallower (or grey scale interval is larger) than that of $\Phi=10°$.

The rubbing angle effect on the grey scale voltages is simulated using a 3.63 μm IPS cell. For simplicity, we only compute the results for $\lambda=550$ nm. The simulated results are depicted in figure 3, where, the rubbing angle is varied from 1° to 60°. The Freedericksz transition threshold voltage for $\Phi=0°$ occurs at $V \sim \pi l/d \big/ (K_2/\Delta\varepsilon)^{\frac{1}{2}} \approx 2.93\,V_{rms}$. Strictly speaking, the Freedericksz threshold voltage no longer exists as the rubbing angle departs from 0°. The observed 'threshold-like' behaviour is called the optical threshold (V_{op}). For comparison purposes, let us define V_{op} at $T=0.1$. From figure 3, the $T=0.1$ contour line decreases as the rubbing angle increases, saturates in the 30–45° range

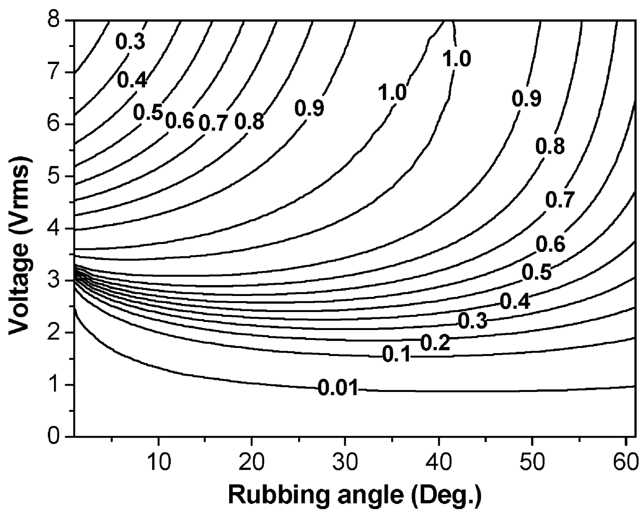

Figure 3. Rubbing angle effect on grey scale voltage for $d\Delta n=0.33\,\mu m$.

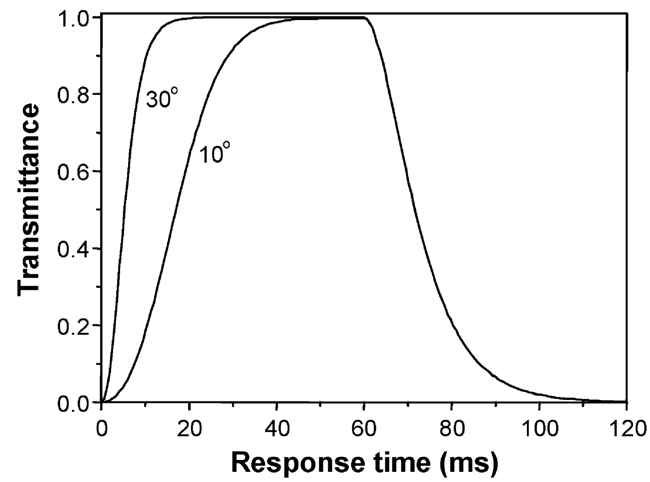

Figure 4. Comparison of rise and decay time at $\Phi=10°$ and 30°; $d=3.63\,\mu m$.

and then slowly returns. On the other hand, the $T=1$ contour line increases substantially as the rubbing angle increases. From equation (3), to achieve $T=1$ all the LC directors including boundary layers must be rotated by 45°. If the rubbing angle approaches $\Phi\sim45°$, the driving voltage for achieving $T\sim1$ would be too high to be practical. If the maximum voltage of the amorphous silicon thin film transistor is $6.0\,V_{rms}$, then the rubbing angle can be stretched to 40°.

Response time is an important parameter for liquid crystal displays. In the IPS mode, the LC free relaxation time is governed by the relationship $\tau_{off}=\gamma_1 / d^2 / K_2\pi^2$. From the LC parameters used, $\tau_{off}\sim16.4$ ms. On the other hand, the turn-on time depends on the applied electric field (E), rubbing angle (Φ) and average twist angle ($\bar{x}$) as follows [11, 12]:

$$\tau_{on}=\frac{\gamma_1}{\varepsilon_o|\Delta\varepsilon|\boldsymbol{E}^2\left[\cos(2\Phi)\frac{\sin(2\bar{x})}{2\bar{x}}+\sin(2\Phi)\frac{\cos(2\bar{x})}{2\bar{x}}\right]-\frac{\pi^2}{d^2}K_2} \quad (4)$$

where $\bar{x}=\frac{2}{d}\int_0^{\frac{d}{2}} x\,dz$ defines the rotation of the average optical axis of the LC layer. Note that the rise and decay times described here are director reorientation times, not optical. In experiments, we often define the rise time as transmittance change from 10 to 90% and decay time from 90 to 10%.

Figure 4 plots the voltage-dependent rise and decay times for the $3.63\,\mu m$ IPS cell with 10° and 30° rubbing angles. The wavelength used for simulations is $\lambda=550$ nm. From figures 2(*a*) and 2(*b*), the on-state voltage is 3.5 and $4.5\,V_{rms}$ for the $\Phi=10°$ and 30° rubbing angles, respectively. Owing to the higher on-state voltage and lower optical threshold, the rise time of the $\Phi=30°$ cell is ~7 ms, while that of the $\Phi=10°$ cell is ~21 ms. The improvement is a factor of three. Increasing the rubbing angle to 40° will further shorten the rise time, although except that the operating voltage is increased to $6\,V_{rms}$, as shown in figure 3. The faster rise time also enhances the display brightness because more light is transmitted in the first few milliseconds.

The wavelength effect of the IPS cells is plotted in figure 5(*a*) and 5(*b*) for $\Phi=10°$ and 30°, respectively. The three primary wavelengths used for calculations are R=650, G=550 and B=450 nm. The cell gap is $d=3.63\,\mu m$. As shown in figure 5(*a*), the transmittance starts to increase at $\sim1.2\,V_{rms}$ and reaches $T=1$ at $\sim3.5\,V_{rms}$. In figure 5(*b*), the transmittance starts to climb at $\sim0.9\,V_{rms}$ and reaches $T=1$ at $\sim4.5\,V_{rms}$. Thus, the larger rubbing angle requires a larger voltage, leading to a larger grey scale voltage interval and faster rise time. However, a drawback is that its power consumption is increased owing to the higher operating voltage. On the other hand, a reduction in the cell gap, increasing the birefringence and dielectric anisotropy, would achieve a faster switching speed (for rise, and decay), lower colour shift and no higher an operating voltage. The development of an LC material with low rotational viscosity would always be a direct way to shorten response time, but remains a challenging task in molecular engineering.

The colour shifts of cells with different rubbing angles under different voltages are shown in figure 6 (plotted in the CIE 1931 chromaticity diagram). The colour shift of the cell with rubbing angle 10° approaches that of the cell with rubbing angle 30°. CIE-D65 is the light source in the simulation. The viewing angle of the IPS displays is independent of the rubbing angle except that its horizontal and vertical viewing axes are rotated with the rubbing angle. The Dr. Lu's simulated iso-contrast contour plots by Lu *et al.* confirm this result [13, 14].

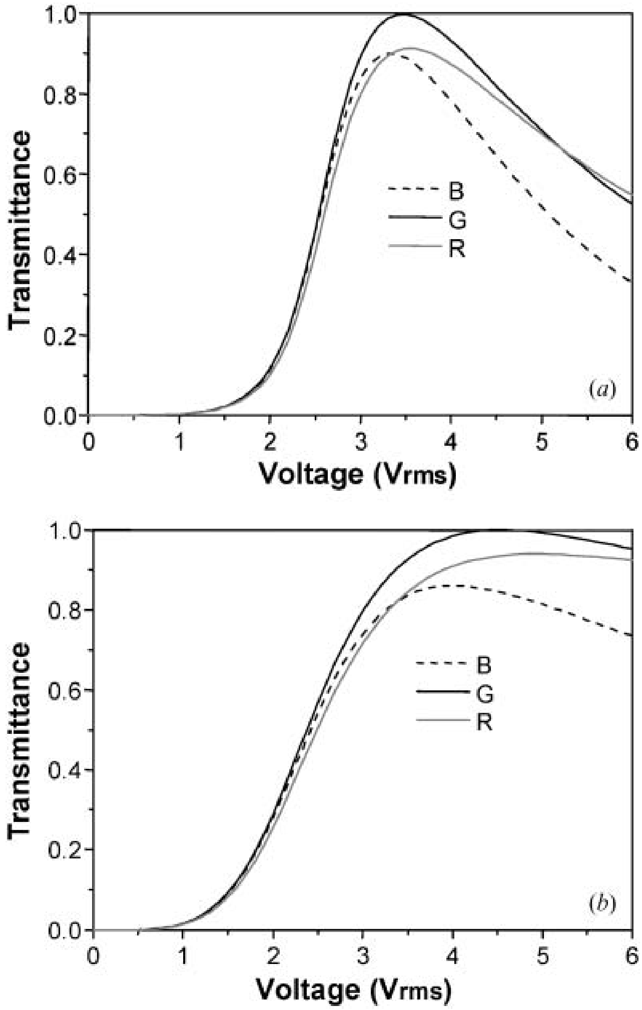

Figure 5. The wavelength effect on IPS LC cells at (*a*) $\Phi=10°$, (*b*) $\Phi=30°$; R=650, G=550 and B=450 nm.

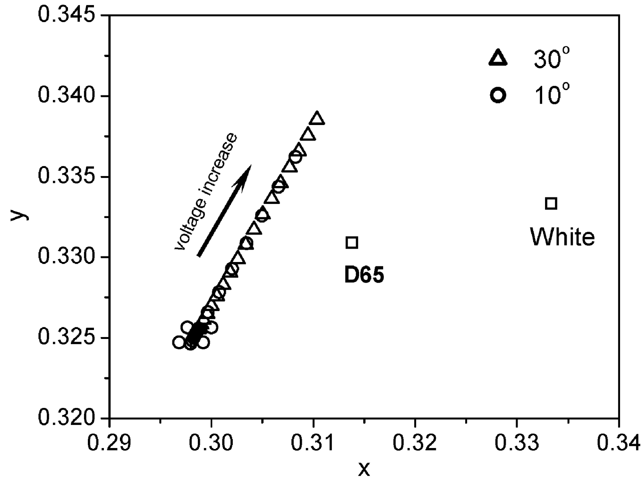

Figure 6. The CIE 1931 chromaticity diagram of different IPS cells with rubbing angle 10° and 30° to the normal incident light, scanned along the whole voltage range under light source CIE-D65.

3. Summary

In conclusion, we observe that rubbing angle makes an important contribution to rise time, brightness and grey scale of transmissive IPS LCDs. The optimum rubbing angle is around 30°–40°; the optimum product of cell thickness and birefringence is about 0.33 μm, which is independent of LC material. Increasing the rubbing angle from 10° to 30° enlarges the grey scale voltage interval and shortens the rise time by a factor of three.

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