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Grey behaviour analysis of in-plane switching mode liquid crystal displays with weak-anchoring effects

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In this paper we calculate the relative transmittance variation at grey level voltage with cell gap variation, and the different surface anchoring strengths at both interface. The threshold voltage of an IPS mode LCD with weak anchoring strength was investigated by linear stability analysis; it was strongly dependent on the variation of cell gap. We analyse the transmittance variation at grey level voltage from the threshold behaviour of an IPS mode LCD with symmetric and asymmetric weak anchoring surface conditions. The ratio of relative transmittance variation of cells with weak anchoring and strong anchoring surfaces at the grey level voltage, $\Delta T_{\mathrm{grey}}^{\mathrm{weak}}/\Delta T_{\mathrm{grey}}^{\mathrm{str}}$, depends linearly on $V_{\mathrm{c}}^{\mathrm{weak}}/V_{\mathrm{c}}^{\mathrm{str}}$.

1. Introduction

Excellent viewing angle characteristics are obtained systematically with in-plane switching (IPS) mode liquid crystal displays (LCDs). The electro-optical effects, threshold behaviour and dynamical response mechanism of this mode have been calculated by Oh-e and co-workers [1–5]. The angular range of the grey scale non-reversal region and high contrast ratio is extremely wide, even along a quite oblique direction in the IPS mode LCD; it is the electric field and not the voltage that drives the liquid crystals. This relationship is due to the independence of the electric field regarding the liquid crystal layer normal direction. The threshold voltage of the IPS mode LCD is thus strongly dependent on the cell gap.

The cell gap margin of the IPS mode LCD is important; we propose to enlarge the effective cell gap by using weak-anchoring effects [6]. It has been reported that the IPS mode LCD has a far narrower cell gap margin than the TN-LCD; in fact, it is comparable to that of the super-twist mode LCD [2]. In this case, it was observed that the narrower the cell gap, the smaller the cell gap margin. In practice, there are always some variations in the cell gap, so the study of the threshold voltage of the IPS mode LCD in the weak anchoring strength limit is important.

In this paper, we discuss enlarging the cell gap margin of IPS mode LCDs by using weak anchoring. This will be studied using the threshold voltage equation assuming weak anchoring at the LCD surfaces. The second section discusses this situation with identical weak anchoring at both interfaces. This is called the symmetrical weak-anchoring case. The third section generalizes this result to the situation where the anchoring is weak, but different on the two surfaces; this is called asymmetrical weak anchoring. The final section summarizes our findings.

2. Cell gap margin enlargement with symmetrical weak-anchoring

The basic switching behaviour of the IPS mode is well understood with a simple one-dimensional LC continuum model (along the LC layer thickness direction coordinate x) with the assumption of a uniform in-plane electric field [2, 4]. This simplified 1D IPS model is described by the following equation for positive dielectric anisotropy ($\Delta\varepsilon$) LC materials:

$$k_{22}\frac{\mathrm{d}^2\phi}{\mathrm{d}x^2}+\varepsilon_0\Delta\varepsilon E^2\sin\phi\cos\phi=0. \qquad (1)$$

Here, ϕ stands for the in-plane twist angle of the LC director, ε_0 is the vacuum dielectric constant, E is the in-plane electric field strength and k_{22} the twist elastic constant of the LC material. When the field strength is lower than the threshold field, the boundary condition is:

$$\phi(0)=\phi(d)=0 \qquad (2)$$

where d is the cell gap. In these displays, the extrapolation length b is related to the twist elastic coefficient k_{22} and the in-plane twist anchoring coefficient A, and is given by the equation $b=k_{22}/A$ [7]. The threshold (Fréedericksz) electric field E_{c} for the weak anchoring boundary condition is given by the following [2, 8]:

$$E_{\mathrm{c}}\cong\frac{V_{\mathrm{c}}}{l}\quad\text{and}\quad u=\frac{V_{\mathrm{c}}^{\mathrm{weak}}}{V_0}=\frac{1}{\lambda}\cot\left(\frac{\pi}{2}\frac{V_{\mathrm{c}}^{\mathrm{weak}}}{V_0}\right). \qquad (3)$$

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Here V_c^{weak} is the threshold voltage for the cell with weak-anchoring effects, $V_0 = \pi l (k_{22}/(\varepsilon_0 \Delta\varepsilon))^{1/2}/d$ is the threshold voltage for the cell with strong anchoring, l is the electrode spacing and $\lambda = \pi k_{22}/(Ad)$ is the azimuthal anchoring coefficient; evidently $b/d \equiv \lambda/\pi$.

We now discuss the situation when there are variations in the cell gap d of $\pm\Delta d$. Furthermore, our analysis compares the results with weak anchoring to those obtained assuming strong. Therefore, the relative variation of the threshold voltage for the strong anchoring limit is given by [6]:

$$\frac{V_c^{strong}(d-\Delta d) - V_c^{strong}(d+\Delta d)}{V_0(d)} \equiv \frac{\Delta V_c^{str}}{V_0} - \frac{2d\Delta d}{d^2 - \Delta d^2} \tag{4}$$

where V_0 is for the threshold voltage of the cell with cell gap d. We use u^- and u^+ standing for u, corresponding to the cell gap variation of $\mp\Delta d$, respectively. From equation (3), we can rewrite them as follows:

$$u^- = \frac{V_c^{weak-}}{V_0(d-\Delta d)} = \frac{V_c^{weak-}}{V_0}\left(1 - \frac{\Delta d}{d}\right)$$

and

$$u^+ = \frac{V_c^{weak+}}{V_0(d+\Delta d)} = \frac{V_c^{weak+}}{V_0}\left(1 + \frac{\Delta d}{d}\right).$$

Here, $V_0(d-\Delta d)$ and $V_0(d+\Delta d)$ are the threshold voltages for cells with gap $d \pm \Delta d$. The relative variation of the threshold voltage for the weak anchoring limit is

$$\frac{\Delta V_c^{weak}}{V_0} = \frac{V_c^{weak-} - V_c^{weak+}}{V_0} = \frac{d\Delta d(u^- + u^+) + d^2(u^- - u^+)}{d^2 - \Delta d^2}. \tag{5}$$

Then, the ratio between ΔV_c^{weak} and ΔV_c^{str} can be expressed as follows:

$$\frac{\Delta V_c^{weak}}{\Delta V_c^{str}} = \frac{u^+ + u^-}{2} + \frac{d}{2\Delta d}(u^- - u^+). \tag{6}$$

We can obtain the ratio of the relative transmittance variation at the grey level voltage when we consider that the variation ΔT_{grey} is proportional to ΔV_c as reported by Yoneya *et al.* [6].

$$G_1 = \frac{\Delta T_{grey}^{weak}}{\Delta T_{grey}^{str}} \propto \frac{\Delta V_c^{weak}}{\Delta V_c^{str}} \propto u_1 = \frac{V_c^{weak}}{V_0}. \tag{7}$$

From equation (12) in ref. [6], the ratio of the relative transmittance variation with weak-anchoring and strong-anchoring conditions at the grey level voltage can be rewritten as follows, with the form of the threshold voltage as given by equation (5) in ref. [6]:

$$G_2 = \frac{\Delta T_{grey}^{weak}}{\Delta T_{grey}^{str}} \propto \left(\frac{V_c^{weak}}{V_0}\right)^2 = u_2^2. \tag{8}$$

Figure 1 shows the computed data from equations (7) and (8). u_1 and u_2 are the ratios between V_c^{weak} and V_0 reported by us and Yoneya *et al.* [6]. G_1 and G_2 are the ratios between ΔT_{grey}^{weak} and ΔT_{grey}^{str} reported by us and Yoneya with the cell gap variation of $\pm\Delta d/d = \pm 0.1$. The experimental and theoretical data in [6] are also shown in figure 1. The circle and diamond dots are the experiment data and theoretical result in [6], respectively. Only when $b/d \ll 1$, i.e. $\lambda \ll 1$, can equation (5) in [6] be obtained approximately from equation (3) [8]. Using the experiment data in [6] we have $b/d \approx 0.23$ and $\lambda = 0.72$, so equation (12) [6] does not agree with the experiment; and above equation (7) is thus the correct analysis for the ratio of the relative transmittance variation of the cell with weak and strong anchoring surface conditions at the grey level voltage with variation of cell gap. For an asymmetrical surface anchoring cell, the evaluation of the ratio $\Delta T_{grey}^{weak}/\Delta T_{grey}^{str}$ is the same manner from equation (7).

3. Threshold voltage with asymmetrical surface effects

The work of Yoneya [9] leads to an equation for the threshold electric field in IPS mode LCDs with asymmetrical surface effects. This field is found by self-consistently solving the following equation:

$$-\beta + \frac{r\alpha_2^2}{\beta} + (1+r)\alpha_2 \cos\beta = 0. \tag{9}$$

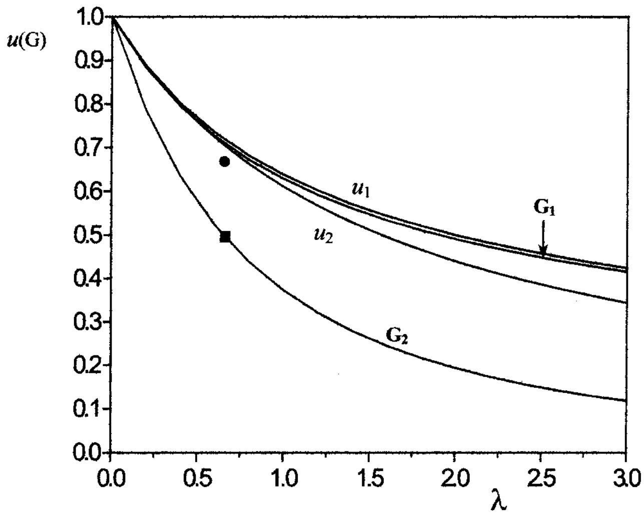

Figure 1. The grey effect with cell gap variation of ±10%. The circle and diamond dots are the experimental data and theoretical result in ref. [6], respectively.

Here, $\beta^2 = \Delta\varepsilon d^2 E^2/k_{22} = \pi^2 E^2_{\mathrm{weak}}/E^2_{\mathrm{c}} = \pi^2 u^2$; $\alpha_2 = \pi/\lambda$, with $\lambda = \pi k_{22}/A_2 d$, is the anchoring coefficient corresponding to one surface and r is an asymmetric factor ($\alpha^1_2 = r\alpha_2$ with α^1_2 corresponding to the other surface anchoring coefficient; $r = 1$ corresponds to the symmetric case and $r < 0$ corresponds to the 90° twisted rubbing condition). By substituting equation (3) into (9), we obtain the relation between threshold voltage and the anchoring coefficient:

$$-\lambda^2 u^2 + r + (1 + r)\lambda u \cot(\pi u) = 0. \tag{10}$$

Usually, we discuss the threshold voltage in relation to symmetric surface effects. In fact, two surfaces are asymmetric because of different rubbing conditions, so we may calculate the threshold voltage by considering this. Assuming an anchoring energy variation of 10% then figure 2 shows the relationship of threshold voltage to anchoring coefficient λ for two asymmetric factors $r = 0.9$, 1.1. The relationship between the threshold voltage and the asymmetric factor with various anchoring coefficients λ are shown in figure 3. When $r = 0$, one of the LCD surfaces is free relative to the other; there is a threshold field in the cell with a free boundary (see figure 4).

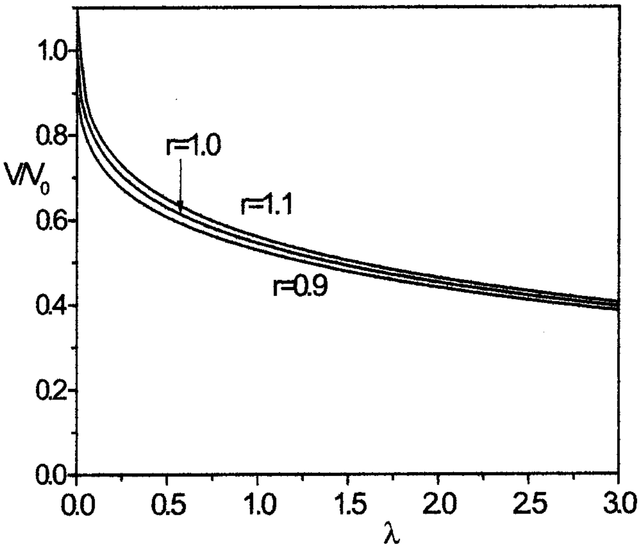

Figure 2. Relative threshold voltage versus anchoring coefficient for three asymmetric factors $r = 0.9$, 1.0, 1.1.

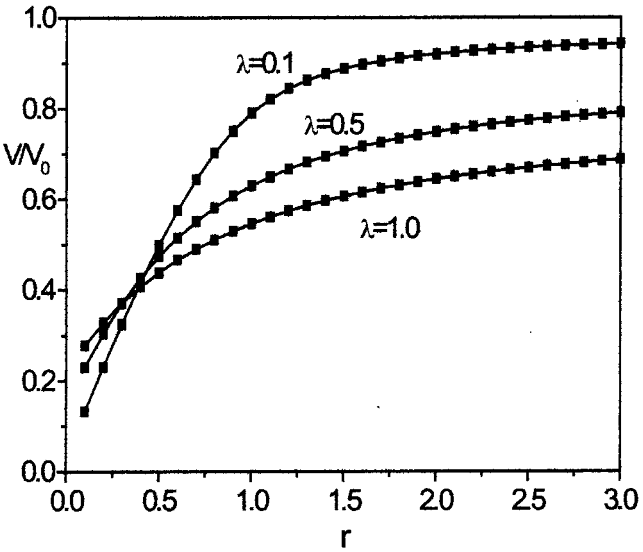

Figure 3. Relative threshold voltage versus asymmetric factor r for various anchoring coefficients $\lambda = 0.1$, 0.5, 1.0.

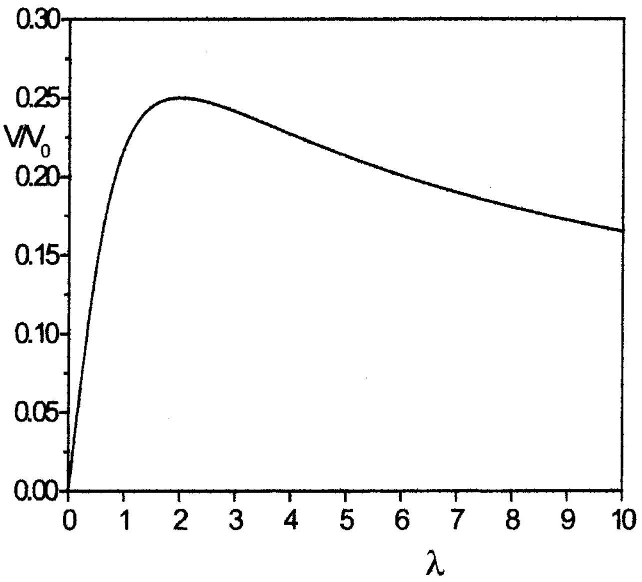

Figure 4. Relative threshold voltage versus anchoring coefficient λ for asymmetrical factor $r = 0.0$.

4. Conclusion

We performed a numerical analysis concerning the ratio of the relative transmittance variation of an IPS mode LCD with margin enlargement and asymmetric weak-anchoring surface at the grey level voltage. In practice, there are always some variations in the cell gap and anchoring energy at LCD interfaces; the qualitative calculation for a cell with 10% variation in the cell gap and anchoring energy, agrees well with experiment. Moreover, the ratio of the relative transmittance variation is less than one, i.e. the transmittance variation is smaller for the weak-anchoring condition than for the strong one (see figures 1 and 2).

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