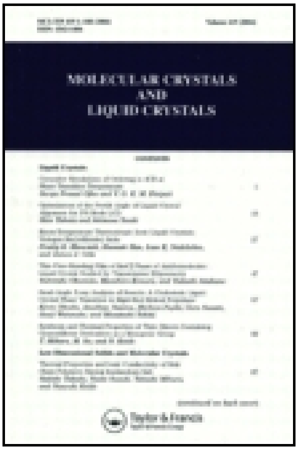

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Analyses of In-Plane Switching Mode LCDs

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The In-Plane Switching (IPS) mode of liquid crystal displays (LCDs) has a wide viewing angle compared with the conventional 90°-TN mode, but requires a higher driving voltage to reach a maximum transmittance. The electro-optical properties of IPS mode LC cells were analyzed by the LC continuum theory to achieve a maximum transmittance with unnoticeable spectra dispersion at low operating voltages.

Keywords: In-Plane Switching; viewing-angle; birefringence

1. INTRODUCTION

It is well known that the normally white twisted nematic liquid crystal displays (NW-TN LCDs) commonly employed in flat panel displays have a narrow and non-uniform viewing-angle weakness [1], which limits the applications, for example, in PC monitors and large screen displays. Several schemes, including film-compensated TN [2], domain-divided TN [3], amorphous TN [4], bend cells [5], and recently the in-plane switching (IPS) mode [6], have been proposed to improve the viewing-angle characteristics of TN LCDs. The film-compensated method needs to add a retardation film to extend the viewing angle. However, the TN cell intrinsically has asymmetric viewing and gray level inversion characteristics and can not be solved by adding a uniaxial retardation film. The domain-divided method averages two opposite angular dependence cells to obtain a symmetry-viewing property in both vertical and horizontal directions, yet it requires complicated processes

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of rubbing and photolithography. The amorphous method can result in a wide viewing angle because of the averaged effect of amorphous structure. Nevertheless, the scattering of the amorphous structure reduces the contrast ratio. The bend-alignment cell has a symmetric structure and thus has a symmetric optical viewing property, but it requires a very complicated bi-axial film to eliminate the light leakage and high accurate cell gap because it uses the birefringence effect. The IPS mode LC cell requires no extra retardation film as the bend-cell method does, yet can yield wide and symmetric viewing which is attractive for display applications.

The in-plane switching (IPS) mode was investigated as early as two decades ago [7], and recently the wide viewing angle of this display was rediscovered and demonstrated [8,9]. Unlike the well-known 90°-TN cells, the liquid crystal molecules of the IPS mode keep their directors parallel to the plane of substrates and an inter-digital electrode is used to switch the molecule directors to be in-plane oriented to control the transmittance. The optical effect of the IPS mode suggests that it functions as a wave-plate to allow maximum transmittance occurring in the optical system. However, the actual electric field produced by the inter-digital electrode of the IPS mode is very complicated and not well understood. In this paper, we have analyzed the electro-optical properties and the operations of the IPS mode to achieve an optimal performance at low operating voltages.

2. SIMULATION MODEL

The electrode of the IPS cell is quite different from the normal 90°-TN cell, which is parallel to the glass substrate. The schematic configuration of the IPS mode cell is shown in Figure 1. The inter-digital electrodes are parallel to the y-axis, while the direction of the LC molecule and polarizer are set at an angle β to the X-axis. When no voltage is applied to inter-digital electrodes, incident light is blocked by the two crossed polarizers. When a voltage is applied between them, the LC directors are forced to align with the electric field except the LC layers adjacent to the boundary, due to strong anchoring. The deformation of the LC medium results in optical retardation, hence, causing light to leak through two crossed polarizers. The deformation distribution of LC directors are quite complicated and can not be revealed by analytic forms. In order to evaluate the electro-optical properties of IPS, an LC continuum theory of elastic anisotropy and inhomogeneous electric field are used to calculate the LC director profiles [10], then extended Jones matrix methods [11] to compute the optical transmittance of the LC layers.

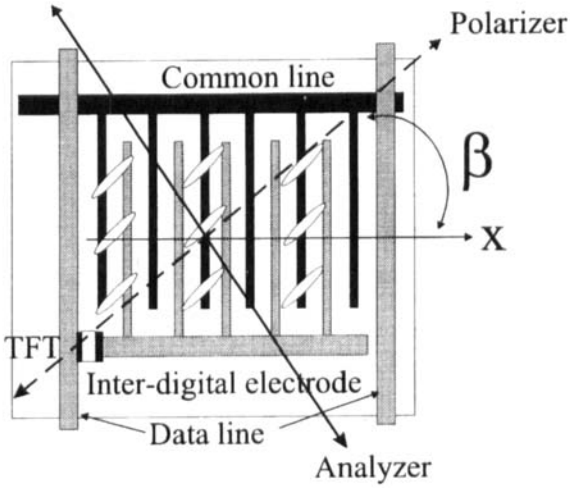

FIGURE 1 Configuration of In-Plane Switching (IPS) LC cells.

3. RESULTS

According to the methods mentioned above, we have calculated the electro-optical properties of the IPS mode by using the parameters listed in Table I. Calculated LC director distribution, electric field, and optical transmittance, are shown in Figures 2(a), (b) and (C), respectively, at a given electrode configuration. The conductive layers of each cell is set to 3.2 um as shown in Figure 2(b). As the driving voltage increases, the transmittance of the area between the Vcom and Vpixel electrode increases, as shown in Figure 2(c). There exists a broad maximum transmittance in the middle area between the Vcom and Vpixel electrode at every driving voltage. Since the electrode width is 5 μm and the cell thickness is 6 μm, the LC directors and electric fields are not quite uniformly distributed, as shown in Figures 2(a) and (b), respectively, at driving voltage of 6 V. To clarify the influence of the electric field on LC directors, the director profiles are shown in Figure 3 as functions of electrode position and LC cell thickness. The directors are strongly anchored on the two boundaries. By applying a voltage of 6 V, the twisted angles of the LC directors increase rapidly near the electrode side. When the twisted angles reach the maximum, they then slowly decrease. When a voltage is applied, the distribution of LC directors is not uniformly varied, thus, the optical performance of the IPS mode is not able to derive analytically. Hence, how to optimize the performance of the IPS mode of LC displays by the numerical method is an important issue.

TABLE I Parameters of LC cell used for calculations

LC Parameters			
$K_{11} = 1.0 \times 10^{-6}$ dyne,	$K_{22} = 9.4 \times 10^{-7}$dyne,	$K_{33} = 1.79 \times 10^{-6}$dyne	
$\varepsilon_{\perp} = 3.6$,	$\varepsilon_{\Pi} = 8.6$,	$n_e = 1.547$,	$n_0 = 1.492$
Device parameters			
LC thickness = 6 μm			
pixel electrode thickness = 0.15 μm			
pixel electrode width = 5 μm			
pixel to pixel width = 10 μm			
glass width = 1 mm			
pretilt angle = 2°			
twist angle = 0°			
rubbing (ground panel to the X axis) = 70°			

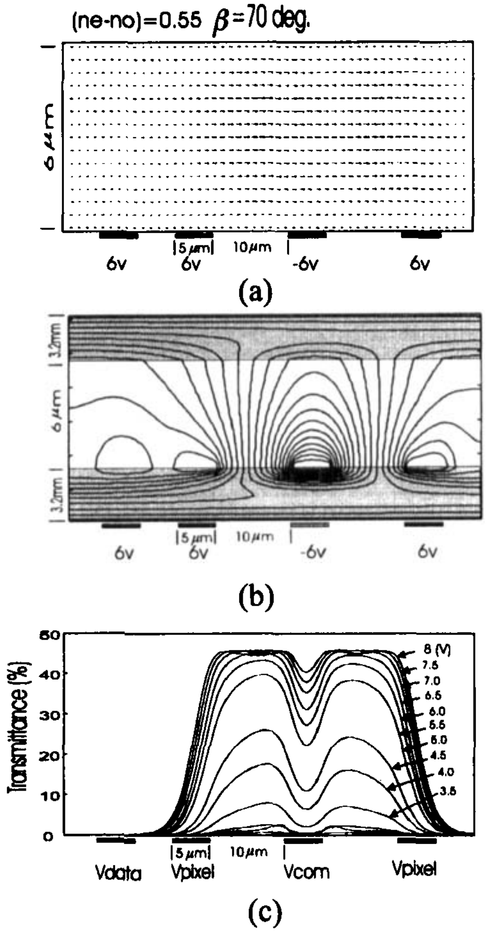

FIGURE 2 The direction distribution, electric field, and optical transmittance of LC cells.

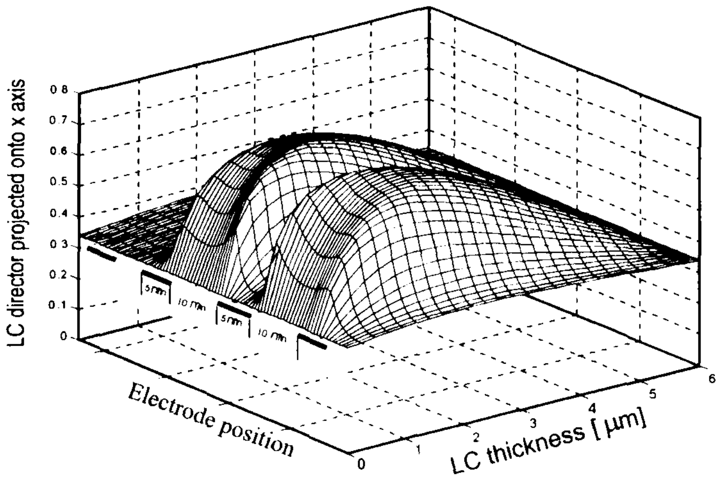

FIGURE 3 LC director profiles of IPS LC cells.

The viewing-angle independence of the electro-optical properties is one of the most promising characteristics of the IPS mode. Transmittance as functions of the viewing angle and gray levels of the IPS mode and the 90°-TN cell are shown in Figures 4(a) and (b), respectively. Apparently, no gray scale reversal occurs in an IPS mode with horizontal and vertical directions up to $\pm 80^\circ$, whereas in the 90°-TN cell with only a horizontal direction of $\pm 30^\circ$ and a vertical direction of -20° to $+15^\circ$. A high contrast ratio is maintained even along a large oblique viewing in the IPS mode. On the contrary, the contrast degrades severely in the 90°-TN cell.

We have explored several critical parameters (such as the cell thickness d, LC birefringence Δn, and angle β) of an IPS mode LC cell by two dimensional simulation to reveal the operation of the IPS mode of the LC cell. For a cell thickness of 6 μm, we calculated v-t curves as a function of birefringence at β angles of 45°, 60°, and 70°, as shown in Figures 5(a), (b), and (c). The v-t curves strongly depend on angle β. When $\beta = 45^\circ$, the driving voltage must be higher than 14 V to achieve a maximum transmittance, as shown in Figure 5(a). When $\beta = 60^\circ$, the driving voltage can be as low as 8 V and the slope of the v-t curve becomes sharper, as shown in Figure 5(b). When $\beta = 70^\circ$, the driving voltage can be only 6.5 V, as shown in Figure 5(c). Thus, as angle β increases, the driving voltage to achieve the maximum transmittance decreases, and the v-t curve becomes sharper. When the birefringence Δn of an LC increases, the transmittance gradually increases to reach a maximum, then decreases. The value of $d\Delta n$ at the maximum transmittance is calculated to be 0.33 for all three cases.

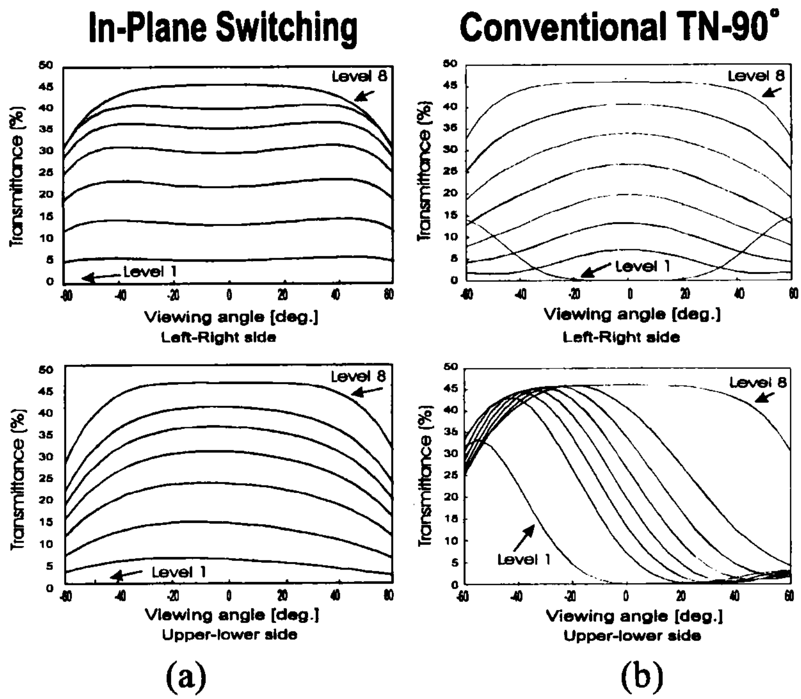

FIGURE 4 The transmittance vs. viewing angle and gray levels of (a) IPS-mode LC cell, and (b) TN-mode LC cell, respectively.

The driving voltage and optimized performance are strongly affected by the cell thickness. The *v-t* curve, as functions of birefringence at a cell thickness of 5, 6, 7, and 9 μm at $\beta = 70°$ are shown in Figures 6(a), (b), (c), and (d), respectively. There exists a maximum transmittance for an LC cell of birefringence Δn shown in each diagram in Figure 6. As the birefringence increases, the transmittance gradually increases until reaching the maximum transmittance. Then, the transmittance decreases as the birefringence decreases. Thus, for a given configuration of an IPS LC cell, there exists an optimized retardation $d\Delta n$ value to maximize the transmittance. Compared the four diagrams, despite the difference in LC cell thickness (5, 6, 7, and 9 μm), the maximum transmittance is of the same value of $T = 45\%$, at retardation of 0.325, 0.33, 0.35, and 0.36 μm, respectively. The same maximum transmittance is due to the fact that the IPS cell can be treated approximately as a half-wave plate to convert all the *s*-polarization to the *p*-polarization state. At the same time, the threshold voltage decreases as the cell thickness increases. It implies that for a thicker cell, the LC molecules can be more easily switched to function as a

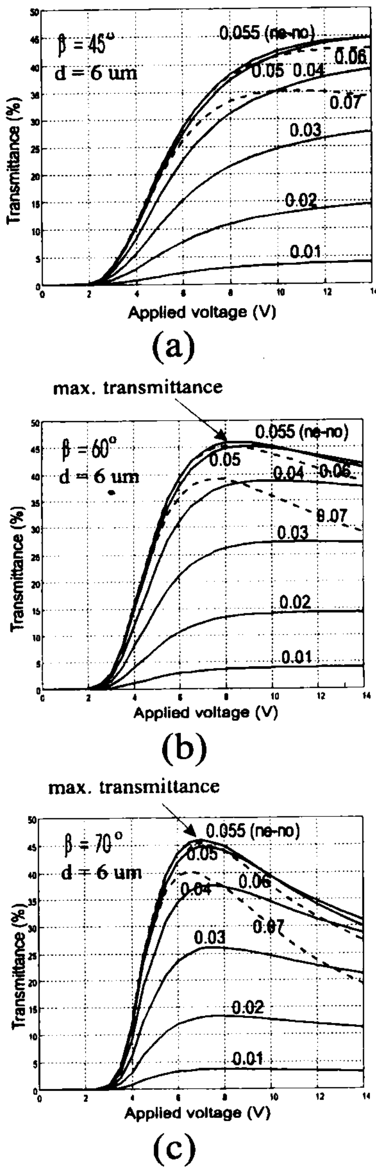

FIGURE 5 The v-t curve as functions of β angles at cell thickness $d = 6\,\mu m$ with respect to different birefringence.

half-wave plate optically. The influence of angle β (45°, 60°, and 70°) and cell thickness (5, 6, 7, and 9 um) on the transmittance of the LC cells are summarized in Figures 7 and 8, respectively, at a fixed birefringence

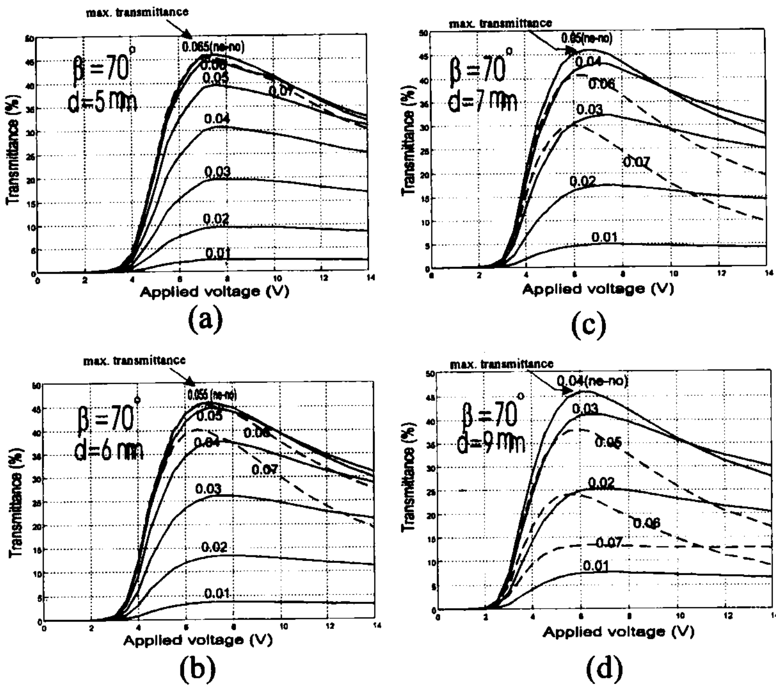

FIGURE 6 The v-t curve as functions of cell thickness at $\beta = 70°$ with respect to different birefringences.

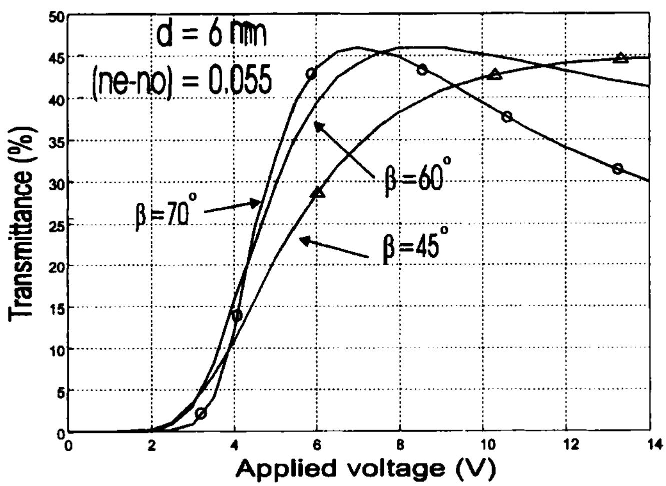

FIGURE 7 The v-t curve as functions of β angle at d = 6 μm and $\Delta n = 0.055$.

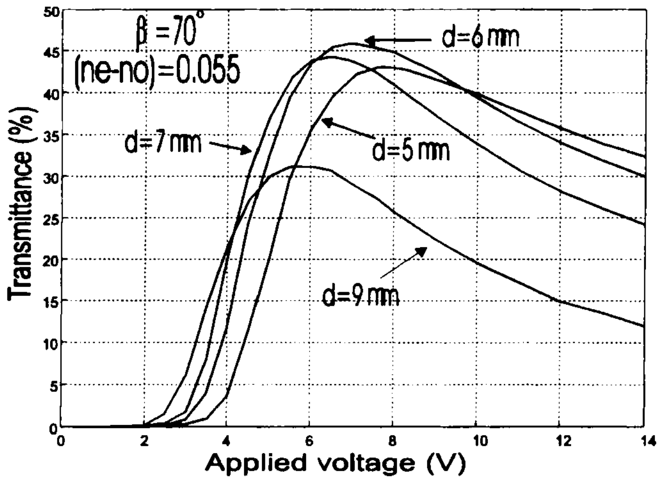

FIGURE 8 The v-t curve as functions of cell thickness at $\beta = 70°$ and $\Delta n = 0.055$.

$\Delta n = 0.055$ for the LC medium. At a cell thickness of 6 um and angle $\beta = 70°$, the driving voltage to achieve a maximum transmittance is the lowest.

The color shift of the IPS mode LC display was observed to be less noticeable compared to that of a 90°-TN cell [12]. The v-t curves at wavelengths of 450, 550, and 650 nm in four different birefringence of LC molecules are shown in Figures 9(a)–(d) to reveal color dispersion. In the dark state, dispersion of the transmittance spectrum is virtually invisible. When the driving voltage increases, the transmittance spectra start to disperse. When the driving voltage is higher, the dispersion becomes more serious. At lower driving voltages, the IPS mode can be treated to function as a polarization-rotator, which is wavelength-independent. At high voltages, the IPS mode still functions as a polarization-rotator, but birefringence of the LC gradually becomes the dominant optical effect. The birefrin gence of LC material can affect the transmittance of different wavelengths at high driving voltages. Hence, the color shift shall be further reduced by optimizing the birefringence of an LC material.

4. CONCLUSIONS

Although the IPS mode has a significantly wider viewing angle than the conventional 90°-TN mode LC display, the IPS mode has a lower aperture ratio because of its inter-digital electrode structure and needs a higher

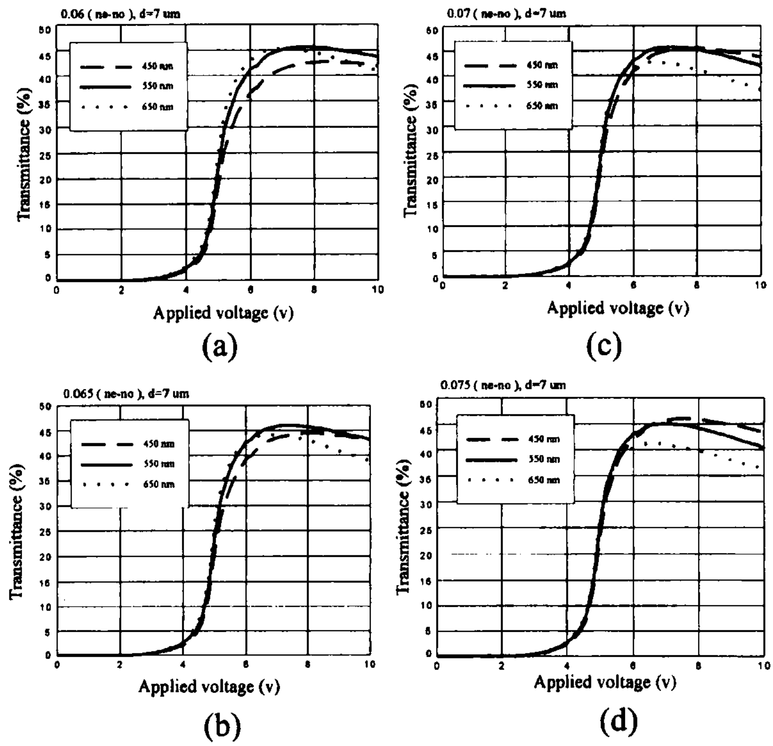

FIGURE 9 The v-t curves at wavelengths of 450, 550, and 650 nm in four different birefringences of LC cells.

driving voltage to switch the LC directors to reach a maximum transmittance. Moreover, the electro-optical properties of an IPS mode can not be fully analyzed by an analytic form. We have analyzed the operation of the IPS mode by the LC continuum theory to achieve an optimal transmittance at a low operating voltage. Color dispersion of the IPS mode LC cell has also been addressed. By adjusting the cell thickness, LC birefringence Δn, and angle β, the IPS mode LC cells can be optimized for high transmittance at a low operating voltage with unnoticeable spectra dispersion.

Acknowledgements

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