Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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To cite this Article Jung, Byoung Sun , Baik, In Su , Song, Ii Sub , Lee, Gi-Dong and Lee, Seung Hee(2006) 'Study on colour characteristics depending on orientation of liquid crystal in the in-plane switching mode', Liquid Crystals, 33: 9, 1077 — 1082

To link to this Article: DOI: 10.1080/02678290600930923

URL: http://dx.doi.org/10.1080/02678290600930923

Liquid Crystals, Vol. 33, No. 9, September 2006, 1077–1082

Study on colour characteristics depending on orientation of liquid crystal in the in-plane switching mode

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(*Received 3 November 2005; in final form 20 June 2006; accepted 20 June 2006*)

The degree of colour shift depending on viewing direction in the in-plane switching (IPS) mode has been investigated. The IPS cell with pure twist deformation exhibits a stronger colour shift than that of the IPS cell with tilt as well as twist deformation, although the former has better luminance uniformity in the bright state than the latter. Furthermore, the IPS cell with multi-directional LC orientation, with tilt as well as twist deformation, shows the least colour shift.

1. Introduction

Thin film transistor liquid crystal displays (TFT-LCDs) are being used widely in application fields such as mobile phones, personal digital assistants, notebooks, monitors and LC-televisions (TV). Recently, large sized TFT-LCDs for LC-TV applications have been developed using wide viewing angle LC modes such as the in-plane switching (IPS) mode [1–3], fringe field switching (FFS) mode [4–7] and the multi-domain vertical alignment (MVA) [8] mode including patterned VA (PVA) [9]. Nevertheless, a drawback to TFT-LCD compared with emissive displays is that the colour characteristics depend on viewing direction since the cell retardation value varies according to viewing direction. Although several LC modes are being commercialized, the IPS and the FFS modes, in which the LC has homogenous alignment in the initial state, show relatively little colour shift.

At an early stage of IPS mode development, both signal and counter electrodes used opaque metals preventing light transmission above the electrodes, resulting in low transmittance. Nowadays, to improve the transmittance, transparent materials such as indium tin oxide (ITO) are used for both electrodes. With transparent electrodes, the LC orientation between and above electrodes in a white state is different, such that between electrodes the LC director is rotated by 45° with mainly twist deformation, but above electrodes the degree of average rotation angle is about 22.5° [10]. In this paper, we use computer simulation to investigate in detail how the LC orientation, such as (a) pure twist deformation, (b) twist as well as tilt deformation, and (c) multi-directional LC rotation with twist as well as tilt deformation, affects colour and iso-luminance characteristics in the IPS mode.

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2. Cell structure and simulation conditions

In the IPS cell, where a uniaxial LC medium exists under crossed polarizers, the normalized light transmission (light efficiency) of the cell is expressed as [1]:

$$T/T_o = \sin^2(2\psi)\sin^2(\pi d\Delta n_{\mathrm{eff}}(\theta, \varphi, \lambda)/\lambda)$$

where ψ is the angle between one of the transmission axes of the crossed polarizers and the LC director, Δn_{eff} is the effective birefringence of LC medium, d is the cell gap, λ is the wavelength of incident light, and θ and φ represent polar and azimuthal angles in spherical coordinates, respectively. Using this equation, it can be seen that the wavelength showing maximum transmission can be varied depending on the value of $d\Delta n$, which is a viewing angle dependent value, and thus the transmittance and colour characteristics change as the viewing direction changes.

Three different IPS cell structures are considered as shown in figure 1. In the first (C-1), the signal and counter electrodes are formed in a wall shape, so that with bias voltage, a pure horizontal field (E_y) is generated. In the second (C-2), both electrodes are composed of opaque metals, so that with bias voltage the horizontal electric field E_y between the electrodes is

Liquid Crystals
ISSN 0267-8292 print/ISSN 1366-5855 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/02678290600930923

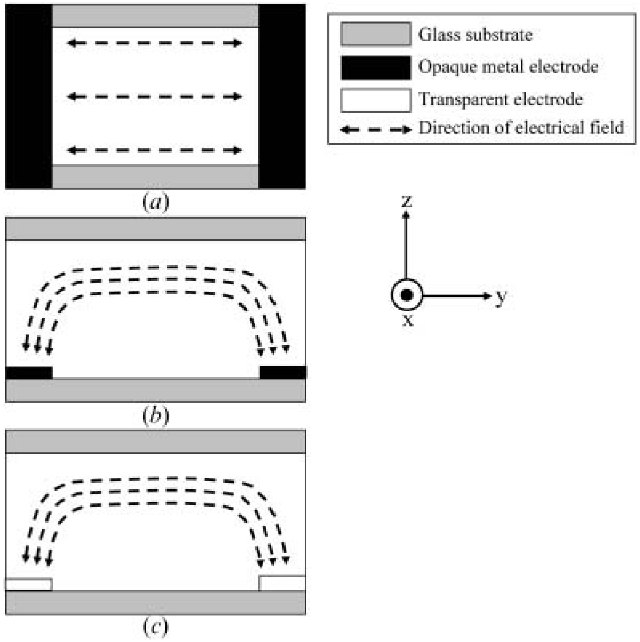


Figure 1. Cross-sectional view of the IPS cell structures with electrical field lines: (*a*) C-1, (*b*) C-2, and (*c*) C-3.

predominantly generated; but close to the electrodes the field E_z is also generated. In this case, we need not consider the field and LC orientation above the electrodes. In the third structure (C-3), both electrodes are transparent so that with bias voltage, E_y and E_z are generated predominantly between the electrodes and above the centre of the electrodes, respectively. In this cell, the LC orientation between and above the electrodes should be considered as an influential factor affecting image quality of the IPS cell.

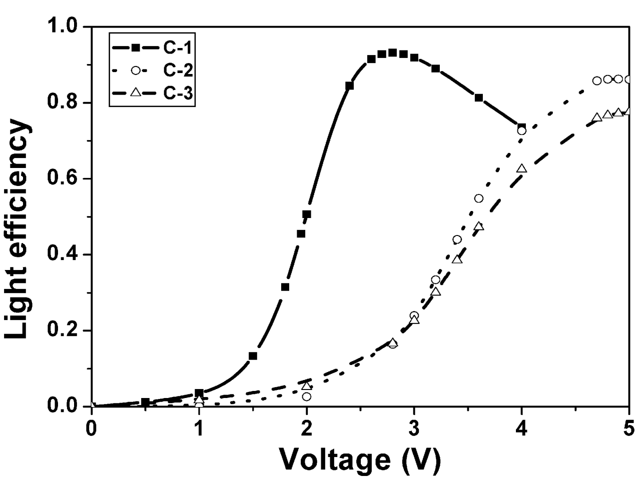


Figure 2. Voltage-dependent transmittance curves for three different IPS cells.

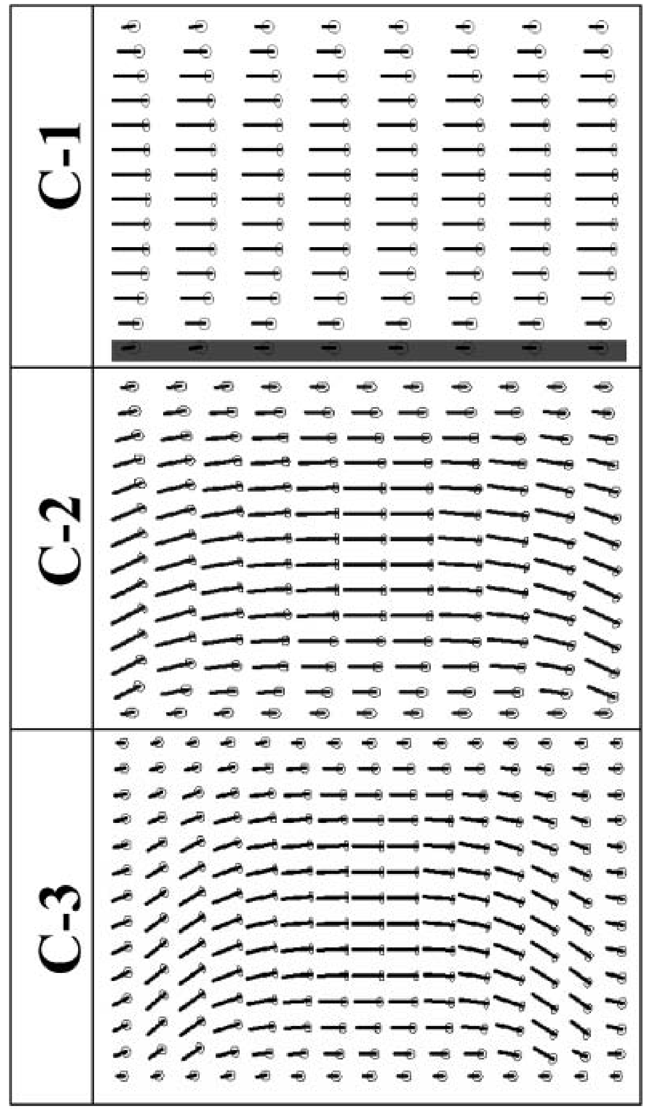


Figure 3. LC orientation in the white state of the IPS cells: (*a*) C-1, (*b*) C-2, and (*c*) C-3.

For calculations of electro-optic characteristics, we used commercially available software, 'LCD Master' (Shintech, Japan), where the motion of the LC director is calculated based on the Ericksen–Leslie theory, and the 2×2 Jones matrix is applied to perform the optical transmittance calculation. Here, the electrode width and distance between electrodes are assumed to be 5 and 10 μm, respectively, and electrode thickness is assumed to be negligible in the cases of C-2 and C-3. The LC MJ951160 from Merck-Japan with a positive dielectric anisotropy ($\Delta\varepsilon$=8.2), elastic constants (K_1=9.7 pN, K_2=5.2 pN, K_3=13.3 pN) and birefringence of 0.08 at 550 nm is used. The cell gap is 4 μm. The LC is aligned to 80° with respect to the *y*-direction, and has a surface tilt angle of 2°. The transmission axis of the bottom polarizer coincides with the optic axis of the LC. Strong anchoring at both substrates is assumed, such that the LCs will not rotate at the interface between alignment and LC layers. The transmittances for the single and parallel polarizers were assumed to be 41%, and 35%, respectively.

3. Results and discussion

Figure 2 presents voltage-dependent light efficiency curves for the three different cells. Since the LC director rotates fully enough between the electrodes in the C-1 cell, this cell exhibits the highest light efficiency among the three cells, while the C-3 cell shows the lowest due to insuffient rotation of the LC director above the electrodes. In addition, the operating voltage was lower in the C-1 cell than in the other two cells, because the intensity of the in-plane field required to rotate the LCs is stronger in the C-1 cell than in the other two cells. Figure 3 shows the LC orientation in a white state. In C-1, the LC experiences only twist information as expected. However, in C-2, mainly twist deformation occurs between the electrodes, while a slight the tilt angle of the LC is generated near the electrodes. Tilt directions near the two electrodes are opposite to each other due to the field distribution. In the C-3 cell, the LC orientation is the same as that in the C-2 cell between electrodes; however, above electrodes the rotation angle of the LC director differs from that between the electrodes.

We have calculated the LC orientation for the C-2 and C-3 geometry along the vertical direction (z) at several electrode positions in a white state, as shown in figure 4. As indicated, the maximum twist angle of 60° occurs in the middle of the vertical layer, that is, $z/d=0.5$ at positions 4 and 5 while at positions 1 and 2, maximum twist angles of 20° and 28°, respectively, occur at $z/d=0.38$. Near the electrodes (position 3) it is 45° at $z/d=0.32$. The tilt angle of the LC, is very low at electrode positions 1, 4 and 5; however, it exceeds 25° at $z/d=0.22$ at electrode positions 2 and 3 since a relatively high intensity of vertical field exists in these regions compared with other regions. This clearly indicates that effective cell retardation value, not only at a normal direction, but also at a certain viewing direction, is dependent on cell structure.

Next, the luminance uniformity was calculated. Figure 5 exhibits iso-luminance uniformity at mid-grey and white states for the three cells. Here, iso-contour lines that represent relative transmittance of 70%, 50% and 30% with respect to the maximum transmittance at the normal direction are compared. Ideally, an iso-contour line with a circle shape is best, because in this case, the luminance is constant along the azimuthal direction. In the mid grey range, the change in luminance as the viewing direction changes at each polar angle is largest in the C-3 cell; that is, the shape of the iso-luminance contour is more similar to two lobes in the C-3 cell than in the C-1 cell with an elliptical shape. Even in the white state, the C-1 cell exhibits an almost perfect iso-luminance curve, such that each contour line has the shape of circle, while in the C-3 cell it has the shape of an ellipse. The difference between the C-1 and C-2 cells is minimal in terms of iso-luminance contours.

The viewing angle dependence of colour characteristics according to 1931 CIE colour chromaticity was now examined for the three cells, as shown in figure 6.

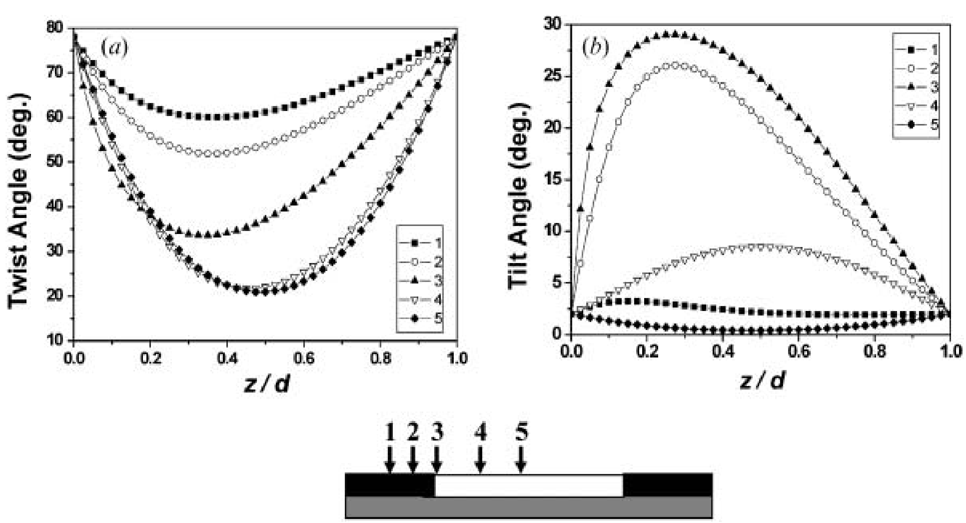


Figure 4. LC orientation (a) twist and (b) tilt angle in the white state along the vertical direction at several electrode positions.

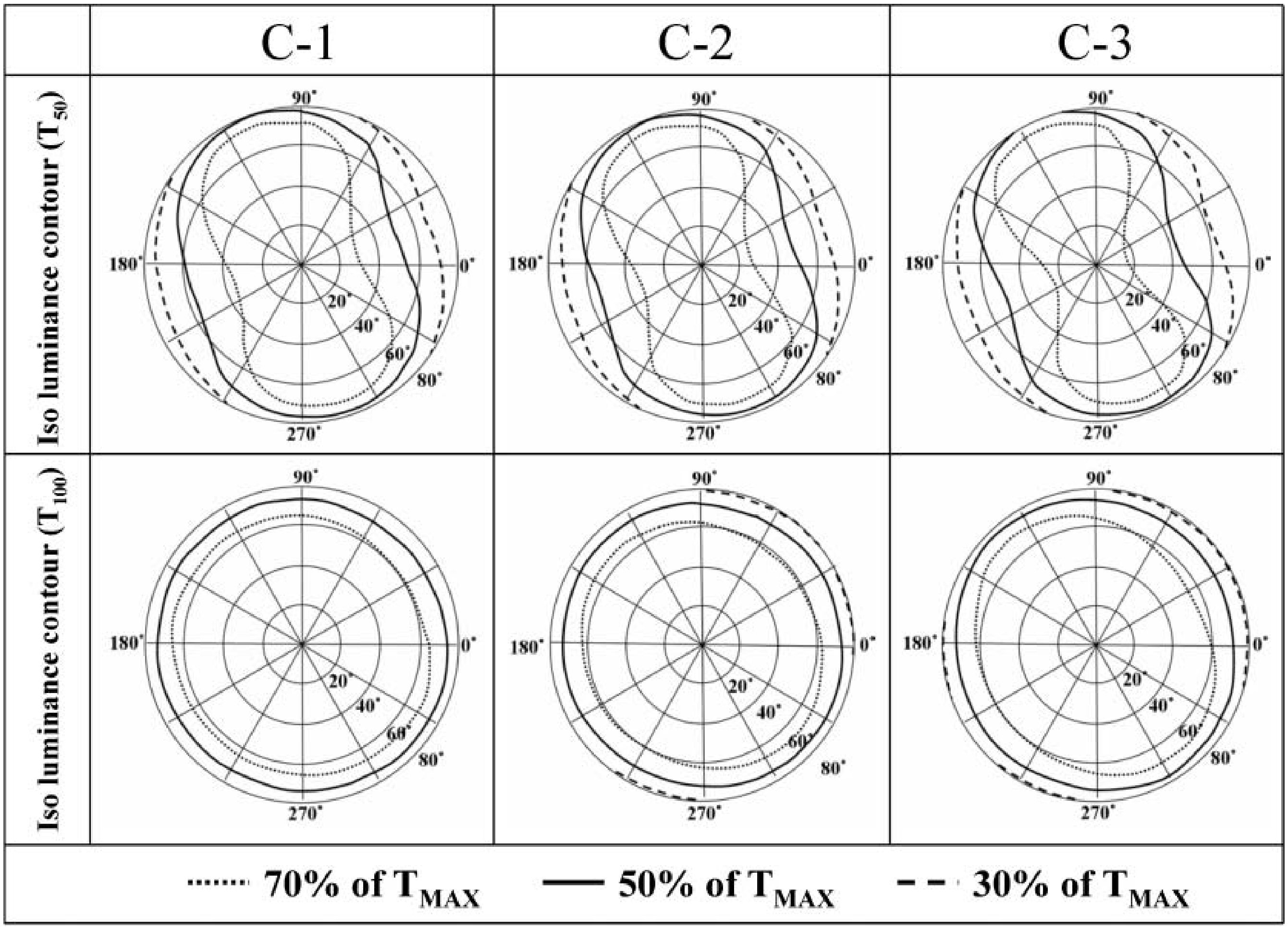
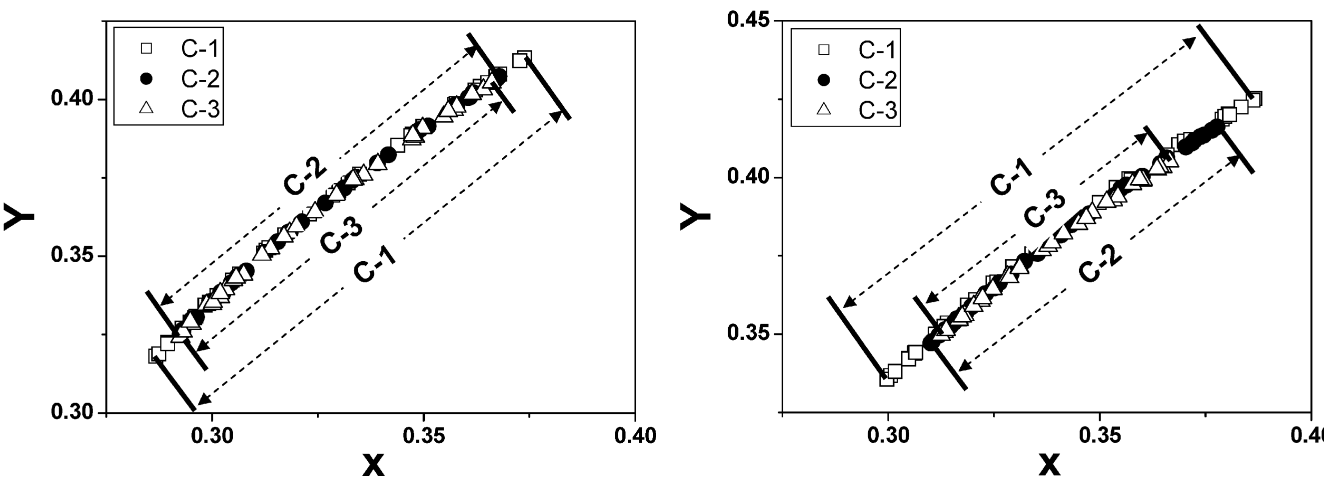
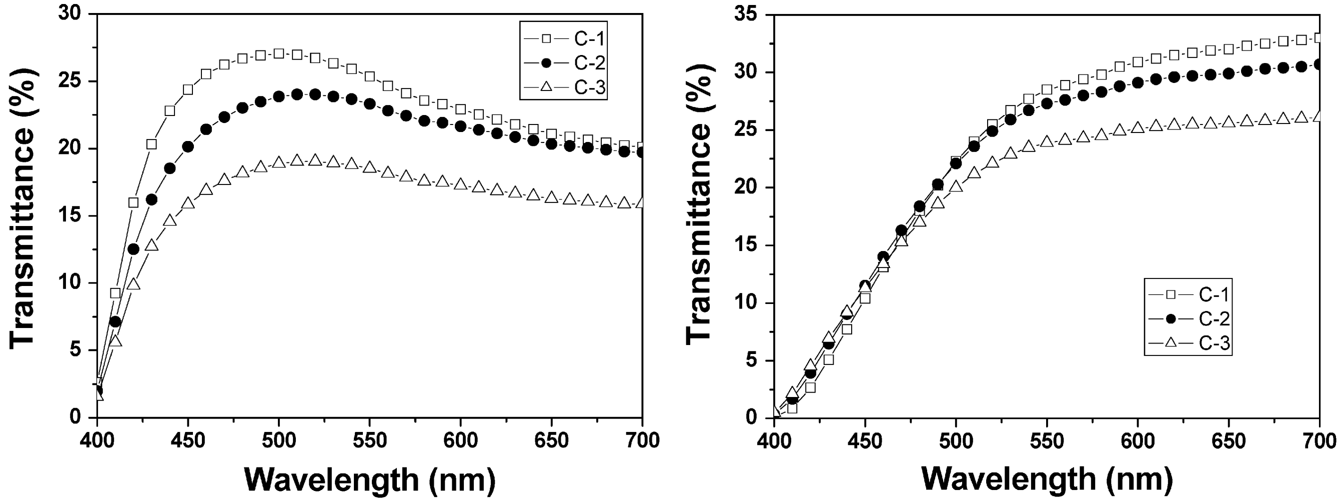


Figure 5. Iso-luminance uniformity of mid-grey and white states for three different IPS cells.



(*a*) (*b*)

Figure 6. Degree of colour shift in the three different IPS cells for a 60° polar angle at all azimuthal directions at mid-grey and white states.



(a) (b)

Figure 7. Wavelength dispersion of the three different IPS cells for a 60° polar angle in two azimuthal directions: (a) 45° and (b) 135° in the white state.

For this study, we used a light source D_{65}[11]. To observe any differences between the cells, data were obtained at a polar angle of 60° in all azimuthal directions. At mid-grey, the C-1 cell shows a slightly larger colour shift than those in the C-2 and C-3 cells, but the difference between the C-2 and C-3 cell is minor. In the white state, the degree of colour shift is smallest in the C-3 cell, as compared with the other two cells. The results demonstrate that excellent luminance uniformity in the cell does not always mean a smaller degree of colour shift with variation in viewing direction. Therefore, when designing high image quality *LCD*s, both luminance uniformity and colour shift, which are inversely related, should be optimized.

Since the effective cell retardation $d\Delta n_{\mathrm{eff}}$ is viewing angle- and wavelength-dependent, the degree of wavelength dispersion in a white state at two azimuthal directions 45° and 135°, where the viewing direction is approximately parallel and perpendicular to the LC director in a white state, respectively, was calculated at a given polar angle of 60°, as shown in figure 7. At an azimuthal angle of 45°, the short wavelength (480 nm) has more transmittance than the red wavelength (630 nm); however, at an azimuthal angle of 135°, the red wavelength has much greater transmittance than the short wavelength (480 nm). These are related to the smaller and larger effective $d\Delta n_{\mathrm{eff}}$, respectively, compared with that at normal direction at an azimuthal angle of 45° and 135°. This wavelength dispersion results in bluish and yellowish white colours at all viewing angles. Nevertheless, the degree of wavelength dispersion in the C-1 cell is greatly reduced in the C-3 cell.

Finally, the colour chromaticity was measured at a specific polar angle of 60° along all the azimuthal directions. Oscillation in colour chromaticity *x*, *y*-coordinates is observed since the in-plane switched LC director is located in one specific azimuthal direction (figure 8). The difference between the trough and peak is reduced to a greater extent in the C-3 cell than in the C-1 cell, indicating that the C-3 cell experiences a smaller degree of colour shift than does the C-1 cell.

4. Summary

Image quality of three in-plain switching cells, depending on the LC orientations such as pure twist and twist

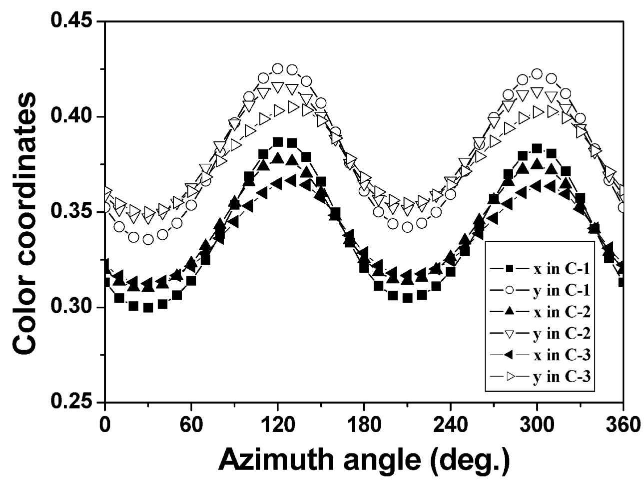


Figure 8. Shift of colour coordinates of the three different IPS cells for a 60° polar angle along all azimuthal directions in the white state.

as well as tilt, was investigated. The cell with only twist deformation of the LC shows the best uniformity in luminance. However, the cell with twist as well as tilt deformation of the LC, with two rotation angles of the LC director, exhibits much less colour shift than that in the cell with pure twist deformation. The results illustrate that to achieve a high image quality in terms of colour characteristics, the IPS cell should use transparent electrodes for both common, and pixel electrodes rather than using opaque metals.

Acknowledgement

This research was supported by a grant (F0004132) from Information Display R&D Center, a 21st Century Frontier R&D Program funded by the Ministry of Commerce, Industry and Energy of the Korean government.

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