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, Jun Ho , Ha, Kyung Su , Chae, Mina , Kang, Wan Seok , Lee, Gi-Dong and Lee, Seung Hee(2010) 'Abnormal behaviour in colour tracking characteristics of the fringe-field switching liquid crystal display', Liquid Crystals, 37: 3, 303 — 309

To link to this Article: DOI: 10.1080/02678290903560104

URL: http://dx.doi.org/10.1080/02678290903560104

Liquid Crystals,
Vol. 37, No. 3, March 2010, 303–309

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Abnormal behaviour in colour tracking characteristics of the fringe-field switching liquid crystal display

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(Received 9 November 2009; final version received 15 December 2009)

Colour tracking behaviour is observed in most liquid crystal displays. In in-plane switching and vertical alignment devices, the colour chromaticity in the normal direction changes linearly from bluish- to yellowish-white as the grey level is increased from the dark to white state. Interestingly, abnormal behaviour in colour tracking is observed in fringe-field switching devices using a liquid crystal with positive dielectric anisotropy, such that the colour chromaticity changes from bluish to yellowish up to a certain grey level, then turns around and becomes bluish-white as the grey level is further increased to the fully white state. According to our theoretical and experimental results, this 'turn around' effect in the colour tracking of the fringe-field switching mode is associated with the generation of a tilt angle of the liquid crystal molecules with increasing voltage in the electrode position where the light modulation is associated with the polarisation rotation.

Keywords: liquid crystal display; colour tracking; fringe-field switching; dielectric anisotropy

1. Introduction

Nowadays, liquid crystal displays (LCDs) are widely used for all kinds of displays, replacing cathode-ray tube (CRT) displays. However, the still image qualities of LCDs need to be improved compared with CRTs. LCDs use a viscous liquid crystal (LC) with birefringence, so that the response time of the device is rather slow and its image quality changes according to the viewing direction. In addition, it has been pointed out that the colour chromaticity in the normal direction changes according to the grey level because of the variation of the effective cell retardation. In order to improve the dependency of the image quality on the viewing angle, many LC devices have been developed and commercialised, such as those using the multi-domain vertical alignment (MVA) or patterned vertical alignment [1, 2], in-plane switching (IPS) [3–5] and fringe-field switching (FFS) [6–9] modes. Among them, the vertical alignment (VA) modes have a fatal defect of severe colour tracking, due to the variation of retardation with the grey level, because the effective birefringence increases with increasing voltage and this problem is solved by means of a driving scheme, which increases the product cost [10]. Unlike VA devices, IPS devices, whose light modulation occurs purely by phase retardation, utilises the concept of the in-plane rotation of the LC directors. Therefore, the change in the effective cell retardation is not as much as that in the MVA mode [11]. Hence, the colour tracking is reduced greatly compared with that in VA devices, but still large enough compared with that of CRTs. In order to achieve colour tracking of $\Delta u'v'$ <0.011, the cell retardation of the LC layer should be greatly reduced, which results in reduced transmittance in the normal direction [12]. In contrast to devices operating in the IPS mode, in FFS devices the light modulation is associated with phase retardation and polarisation rotation, which depend on the position of the electrode, and their electro-optic characteristics also depend on the sign of the dielectric anisotropy [13]. In a previous work, the colour tracking of FFS devices having LCs with negative dielectric anisotropy (–LCs) was investigated in an attempt to achieve authentic colours with only a slight decrease in transmittance, while keeping the colour greenish-white [14]. However, the colour tracking of FFS devices having LCs with positive dielectric anisotropy (+LCs) has not been studied.

In this study, we analysed the colour tracking behaviour of an FFS with a +LC compared with that using a –LC. The research results show that abnormal colour tracking behaviour is observed for the FFS with the +LC and the origin of this abnormal behaviour is explained by simulation and experiment. In addition, the colour chromaticity is investigated in an attempt to achieve authentic colour if the change in $\Delta u'v'$ is less than 0.011 or not.

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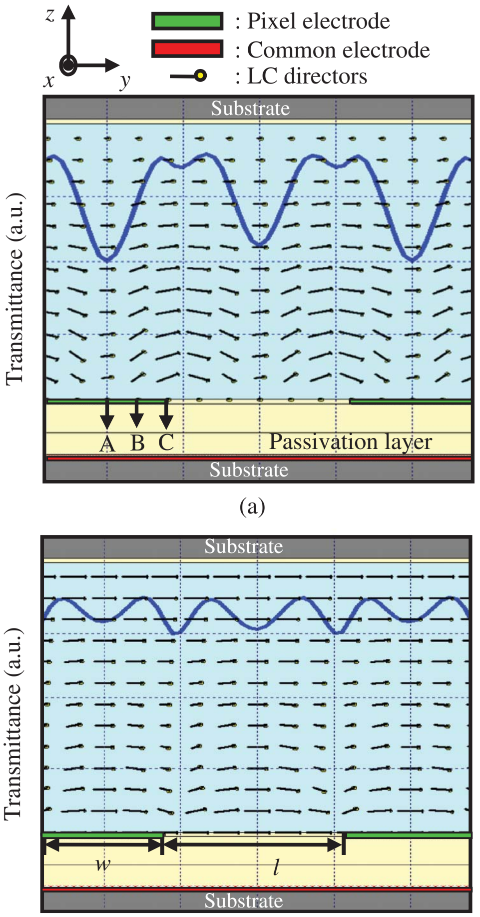
ISSN 0267-8292 print/ISSN 1366-5855 online

DOI: 10.1080/02678290903560104
http://www.informaworld.com

2. Switching principle of the FFS mode and simulation conditions

In FFS devices, regardless of whether a +LC or –LC is used, the plane shape of the common electrode lies above the substrate and the passivation layer exists above the common electrode. Above the passivation layer is a pixel electrode patterned in the form of a slit with a proper gap (l) between them. Hence, both electrodes are made of transparent materials in order to generate a high transmittance. In FFS devices, the LCs are homogeneously aligned in the initial state and the optic axis of the LC is coincident with one of the axes of the crossed polariser. As a result, the device appears to be dark in the off-state. When an electric field is generated between the pixel and common electrodes, fringe electric fields having horizontal (E_y) and vertical (E_z) field components are generated, as shown in Figure 1. This field rotates the LC directors and thus, the transmittance is generated. In FFS devices, E_y is not constant along the electrodes due to the cell structure [15, 16], that is, it oscillates periodically and thus, the transmittance oscillates along the electrodes because the dielectric torque required to rotate the LCs varies along the electrodes (see the transmittance profile shown in Figure 1). Another interesting point regarding FFS devices is that the transmittance is generated by two different torques, that is, with the application of a bias voltage, the LC directors at electrode positions B and C rotate first due to the dielectric torque and then the LC directors at electrode position A rotate due to the elastic torque between the neighbouring LC molecules, although there is no field component, E_y.



(a)

(b)

Figure 1. Cell structure and profile of liquid crystal (LC) orientation and transmittance in the white state of a fringe-field switching device when using the (a) +LC and (b) –LC.

In addition, the LC molecules are twisted at the position nearest to the bottom substrate due to the strong E_y at electrode position C, whereas at electrode position A they are twisted near the middle layer of the LC. As a result, the light modulation mechanism varies depending on the electrode position. Since the light modulation can vary depending on the electrode position, the transmittance is given by the following equation:

$$T/T_0 = \boldsymbol{a}\sin^2 2\psi \sin^2(\pi d\Delta n_{\mathrm{eff}}/\lambda) + \boldsymbol{b}\left(1 - \frac{\sin^2\left(\pi/2\sqrt{1+(2d\Delta n/\lambda)^2}\right)}{1+(2d\Delta n/\lambda)^2}\right) \qquad (1)$$

where $\boldsymbol{a}$ and $\boldsymbol{b}$ are weighting factors, Ψ is the voltage-dependent angle between the transmission axis of the crossed polariser and the LC director, d is the thickness of the LC layer, Δn_{eff} is the voltage-dependent effective birefringence and λ is the wavelength of the incident light. The first term in Equation (1) comes from the transmittance equation associated with the light modulation of the phase retardation, as in the case of an IPS device, and the second term is incorporated from Gooch and Terry's transmittance equation [17, 18] associated with the light modulation of the polarisation rotation, as in the case of a twisted nematic device.

As mentioned above, the twist angle at position A is determined by the elastic torque between the LCs at positions A and B and, thus, the angle of twist at position A depends on that of the surrounding molecules at position B. Hence, when a –LC is used, the tilt angle of the LC at position B is much lower than that when a +LC is used, so that the twist angle of a –LC at position A is much higher than that of a +LC and is close to $\Psi=45°$. As a result, the transmittance at position A is higher with a –LC than that with a +LC, as shown in Figure 1(b).

In order to analyse the colour tracking in the normal direction of an FFS device using a +LC in comparison with that of an FFS device using a –LC, we performed a simulation using an LCD master (Shintech, Houston, TX, USA), where the motion of the LC directors is based on the Eriksen–Leslie theory and the optical transmittance was calculated using a 2×2 extended Jones Matrix [19]. In the calculations, the width (w) of the pixel electrodes and distance (l) between them were 4.0 μm and 6.0 μm, respectively. The thickness of the passivation layer between the electrodes was 7000 Å and d was 3.8 μm. The physical properties of the +LC ($\Delta\varepsilon = 8.2$, $K_1 = 9.7$ pN, $K_2 = 5.2$ pN, $K_3 = 13.3$ pN, $\Delta n = 0.099$) and –LC ($\Delta\varepsilon = -4$, $K_1 = 13.5$ pN, $K_2 = 6.5$ pN, $K_3 = 15.1$ pN, $\Delta n = 0.0842$) were used and the strong anchoring of the LC to the surface was assumed. The surface pretilt angle for both substrates was 2° and the initial alignment of the LC was 83° for the +LC and 7° for the –LC with respect to the horizontal component (E_y) of the fringe electric field. The light source was D_{65}. The transmittances of the single and parallel polarisers were assumed to be 45% and 35%, respectively.

3. Results and discussion

In order to understand the original source of the colour chromaticity, the wavelength dispersion was calculated at six different grey levels from low grey T_1 to the fully white state T_{100} (the numbers in the subscripts indicate the relative transmittance with respect to the maximum transmittance in the normal direction), as shown in Figure 2. As indicated, the transmittance is dependent on the wavelength and, in addition, the peak wavelength, which shows the maximum transmittance, shifts according to the grey level. When using a +LC, the peak wavelength shifts from 550 nm at T_1 to 590 nm at T_{10} and then turns around and is shifted in the reverse direction to 550 nm as the grey level is further increased. However, when using a –LC, the peak wavelength gradually shifts from 470 nm to 520 nm with increasing grey level, as in the case of an IPS device.

The correlation of the colour chromaticity with the colour temperature was investigated in order to determine how it is associated with the wavelength dispersion characteristics, using the CIE 1976 UCS chromaticity diagram, as shown in Figure 3 [20]. As illustrated in Figure 3(a), when using a +LC, the colour chromaticity shifts from relatively bluish-white (5830.1 K) to greenish-white (5287.9 K) up to T_{50} and then reverts to bluish-white (5618.5 K). This abnormal behaviour named 'turning around' has not been reported for any other LC devices. On the other hand, when using a –LC, the colour tracking occurs from bluish-white (7328.0 K) to greenish-white (6159.7 K), as shown in Figure 3(b). Now, the question arises as to why the turning around phenomenon occurs only when using the +LC.

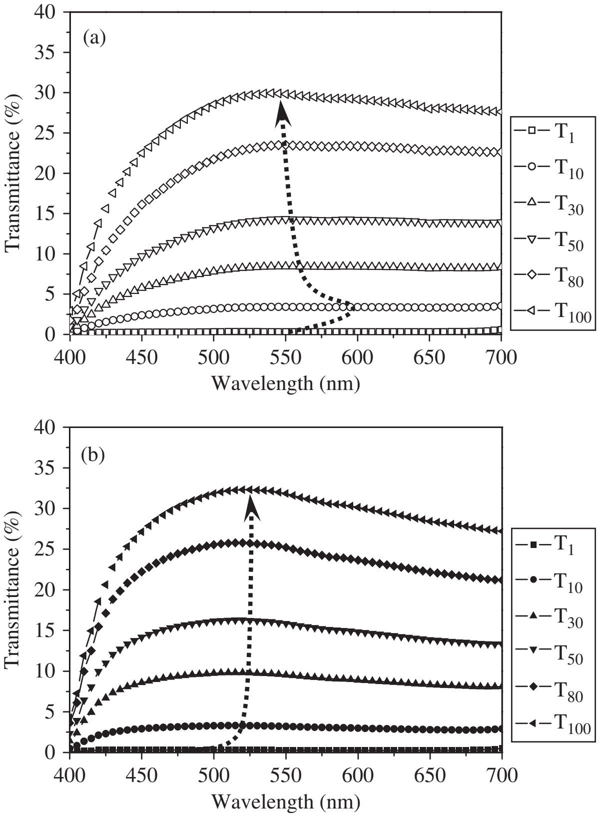


Figure 2. Wavelength dependent-transmittance in a fringe-field switching device using the (a) +LC and (b) –LC with respect to the grey level.

One of the unique characteristics of the FFS device is that the LC orientation in the on state strongly depends on the electrode position, so that different light modulation applies according to the electrode position, as explained in the discussion of the switching principle. Therefore, the colour chromaticity was investigated according to the electrode position, as shown in Figure 4. The colour tracking at position A, in which the light modulation is associated with the phase retardation effect, is similar to that of an IPS device [12], that is, the colour temperature decreases continuously from 6361.0 K to 5085.2 K as the grey level increases from T_1 to T_{100} (see Figure 4 (a)), as in the case of an IPS device. However, unlike at electrode position A, the turning around phenomenon is observed at positions B and C, but at different grey levels, namely T_{40} and T_{30}, respectively (see Figures 4(b) and 4(c)). The colour temperature at position B decreases gradually from 6003.6 K to 5325.8 K with increasing grey level from T_1 up to T_{40}, but increases again to 5936.7 K as the grey level is further increased to T_{100}. Similarly, the colour temperature at position C decreases from 5555.2 K at T_1 to 5316.4 K up to T_{30} and then increases again, reaching

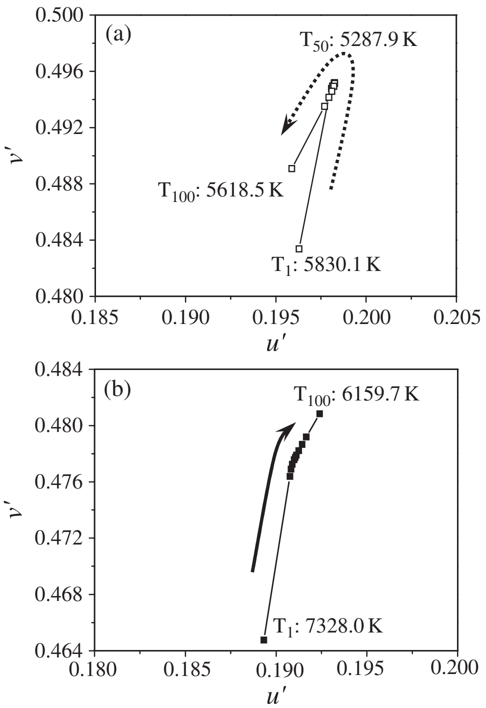


Figure 3. Colour chromaticity in $u'v'$ coordinates of a fringe-field switching device using the (a) +LC and (b) –LC device according to the grey level.

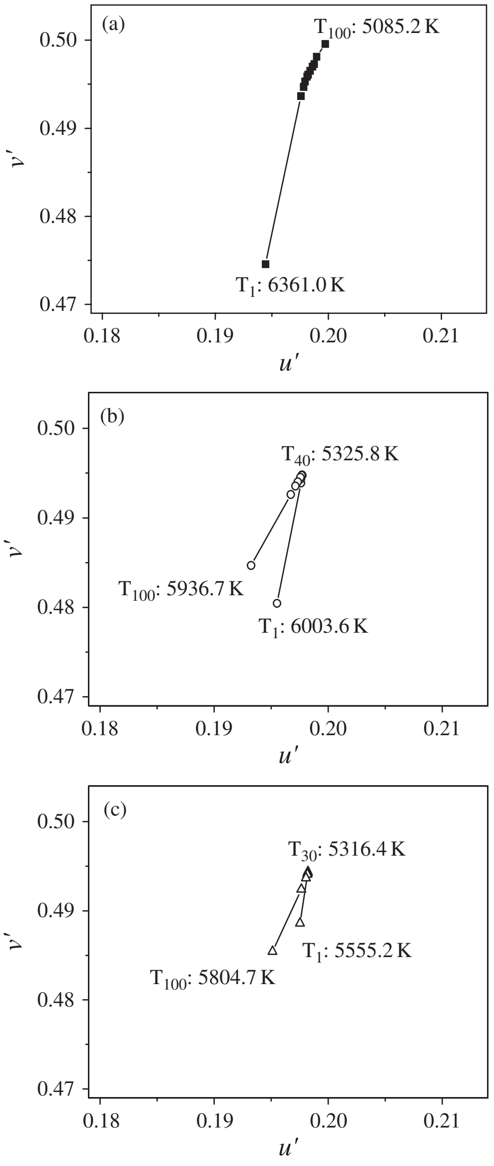


Figure 4. Colour chromaticity in $u'v'$ coordinates of a fringe-field switching device with the +LC according to the electrode position: (a) A; (b) B; (c) C.

5804.7 K at T_{100}. In short, this turning around in which the colour varies from bluish to greenish and then to bluish-white again occurs at positions B and C, but not at position A whose light modulation is a phase retardation effect.

In order to observe the turning around effect in more detail, the colour temperature of the FFS device with the +LC at different electrode positions was calculated for 11 grey levels and then compared with that of the FFS device with the –LC, as shown in Figure 5. The colour temperature decreases continuously without showing any turning around effect at position A when using the +LC, as does the FFS device with the –LC, although the absolute value of the colour temperature is much higher in the device with the –LC. However, as expected, the turning around phenomenon of the colour temperature is observed at electrode positions B, C and the whole area with the +LC. This indicates that the turning around phenomenon does not occur in the FFS device with the –LC or at position A of the FFS device with the +LC when the light modulation is operated mainly by phase retardation and, furthermore, the voltage-dependent effective cell retardation does not show any turning around behaviour with increasing voltage. When considering the whole area in the FFS device with the +LC, the turning around of the colour temperature occurs at T_{50}, whereas at electrodes positions B and C, it occurs at T_{40} and T_{30}, respectively, which is in good agreement with the above results.

Test cells were fabricated in order to confirm the above calculated results. Here, the conditions used for the fabrication of the test cells were almost the same as those considered for the calculated results. Figure 6 shows the wavelength-dependent transmittance for six grey levels in the FFS device using the +LC. The peak wavelength shifts from 500 nm at T_1 to 600 nm at T_{10}. However, it reverts to 530 nm as the grey level is further increased, which corresponds roughly to the calculated result. Figure 7 shows the experimental result for the colour chromaticity diagram in $u'v'$,

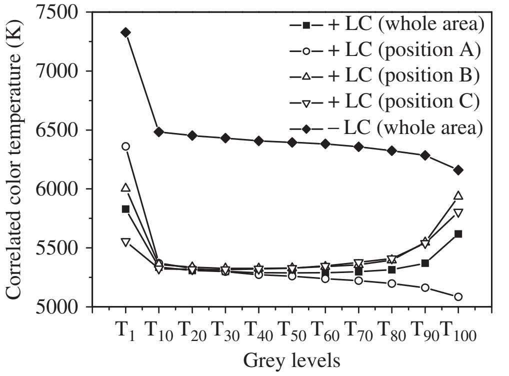


Figure 5. Correlated colour temperature of a fringe-field switching device with +LC and –LC with respect to the grey level.

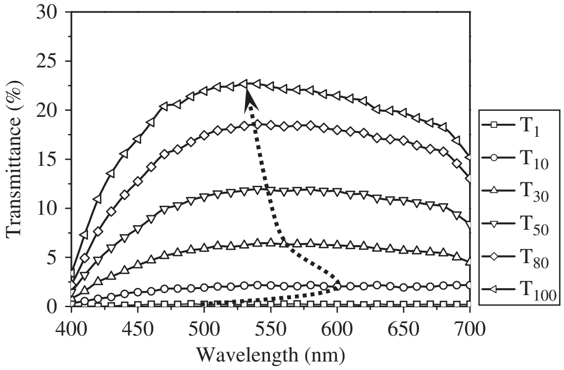


Figure 6. Experimental result obtained for the wavelength dependent-transmittance in a fringe-field switching device using the +LC with respect to the grey level.

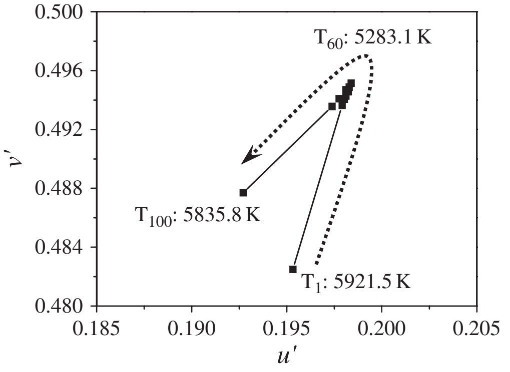


Figure 7. Experimental result obtained for the colour chromaticity in *u′v′* coordinates of a fringe-field switching device using the +LC as a function of the grey level.

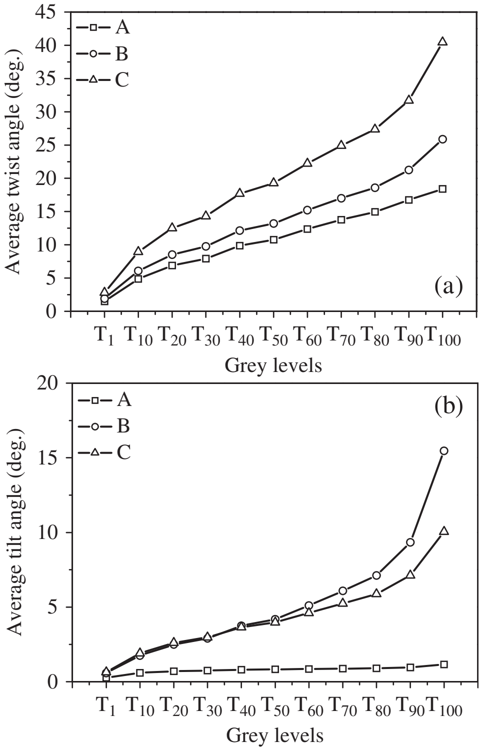


Figure 8. Average (a) twist and (b) tilt angle of liquid crystal directors at three different electrode positions.

which was measured using a spectrophotometer (Minolta, CM 3700-D, Osaka, Japan). As expected, the turning around phenomenon is observed in the fabricated FFS cell at T_{60}.

The average twist and tilt angle orientations of the LC director with increasing grey level were investigated according to the electrode position in order to examine this phenomenon, as illustrated in Figure 8. The average twist angle of the LC directors is largest at position C and then decreases sequentially from position B to position A because the E_y required to rotate the LC is strongest at position C and decreases continuously in the direction of position A, as shown in Figure 8(a). On the other hand, the tilt angle at position A remains almost constant as the grey level increases. Since the effective retardation varies with the applied voltage, irrespective of the electrode position, as in the case of IPS devices, as reported in previous work [21], colour tracking from bluish-white to greenish-white is observed at all of the positions. However, the tilt angle that is generated shows quite different behaviour according to the electrode position, as shown in Figure 8(b). At position A, the change in the tilt angle with increasing grey level is almost negligible for all the grey levels, so the colour tracking at this position is similar to that of the IPS device. At positions B and C, a much greater tilt angle is generated, due to the strong E_z compared with that at electrode position A. Such a high tilt angle at both positions associated with the twist angle results in the turning around of the effective retardation of the LC layer with increasing grey level at positions B and C. In further detail, the turning around phenomenon occurs when the average tilt angle of the LC layer becomes about 3°. It is quite evident that the effective retardation of the LC layer for the FFS device will be reduced if its average tilt angle is over 3° with the certain twist angle of the LCs.

Finally, the effects of the magnitude of the dielectric anisotropy of the LC on the turning around behaviour were investigated. The tilt angle decreases with decreasing magnitude of $\Delta\varepsilon$, due to the reduced dielectric torque [22]. Consequently, if the magnitude of $\Delta\varepsilon$ decreases, the tilt angle decreases and thus, the turning around phenomenon in the colour tracking can be reduced by decreasing the magnitude of $\Delta\varepsilon$. In order to study this phenomenon, three different magnitudes of the dielectric anisotropy ($\Delta\varepsilon$=6.2, 4.2, 2.2) were chosen, while keeping the other conditions constant in order to confirm whether or not the abnormal colour tracking in the FFS device with the +LC is correlated with the tilt angle of the LC directors. As shown in Figure 9, the turning around effect is reduced as the magnitude of $\Delta\varepsilon$ decreases. In addition, the abnormal colour tracking almost disappears when $\Delta\varepsilon$=2.2. This result also confirmed that the abnormal colour tracking of the FFS device with the +LC is caused by the tilt of the LC directors, as explained above.

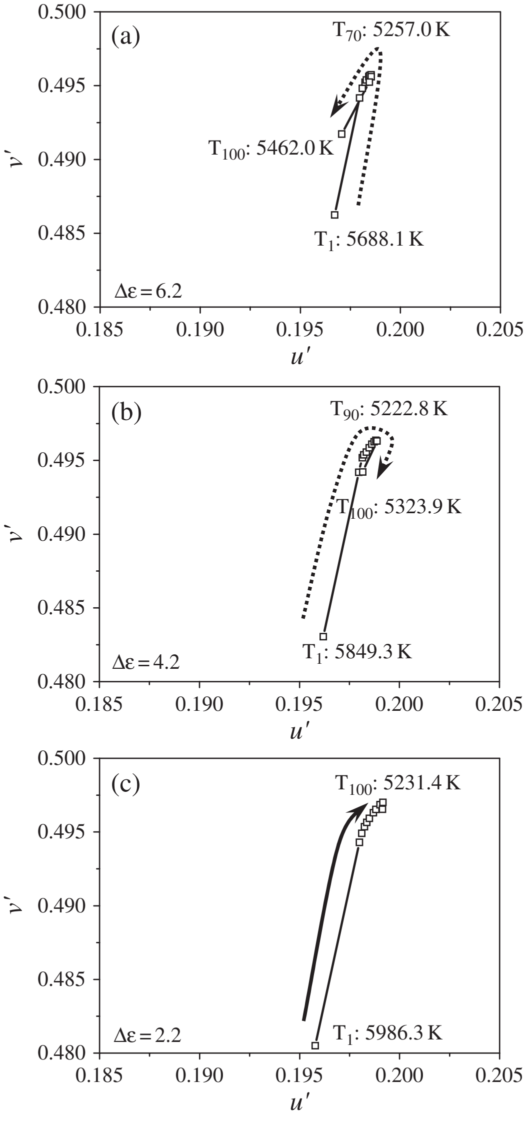


Figure 9. Colour chromaticity in $u'v'$ coordinates of a fringe-field switching device using the +LC according to dielectric anisotropy: (a) $\Delta\varepsilon$=6.2; (b) $\Delta\varepsilon$=4.2; (c) $\Delta\varepsilon$=2.2.

4. Summary

In the FFS device using a +LC, abnormal colour tracking behaviour, which we referred to as turning around, was observed. Based on the calculated results and careful analysis of the experimental results, we found that this peculiar colour tracking behaviour is associated with the change in the effective retardation of the LC layer, due to the tilt angle that is generated with increasing applied voltage. Hence, when using an LC with very low dielectric anisotropy, the tilt angle is increasingly suppressed and ultimately the turning around behaviour disappears. Understanding this unique behaviour would help to achieve FFS LCDs with authentic colour characteristics.

Acknowledgements

This work was supported by the World Class University programme through the Ministry of Education, Science and Technology (R31-2008-000-20029-0).

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