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Comparison of optical compensations based on discotic liquid crystals with linear and non-linear orientation for wide viewing angle twisted nematic liquid crystal displays

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Abstract

Optical compensation film using discotic liquid crystals has been commercialized to suppress light leakage of twisted nematic (TN) liquid crystal (LC) cells in the dark state when the viewing directions are off-axes. In the conventional film, the tilt angle variation of the discotic LC layers is linear, whereas that of the rod-like LC layers in the TN cell is non-linear with twist alignment. We investigated the optical compensation effects in terms of iso-contrast ratio, gray scale inversion and color shift with linear and non-linear orientation in a tilt angle or twist and non-twist orientation on TN-LC cells. The results showed that the optical compensation with non-linear orientation exhibited an improved performance in suppressing light leakage in the dark state.

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Keywords: Optical compensation; Twisted nematic; Liquid crystal; Discotic

1. Introduction

Twisted nematic-liquid crystal displays (TN-LCDs) [1] have been widely commercialized for portable displays such as cell phones, notebook computers, cameras and navigations because of their lower power consumption, high light efficiency and low cost due to higher processing margin. However, their narrow viewing angle characteristics represent an obstacle to the application to large size displays such as monitors and TVs. Several liquid crystal (LC) modes which intrinsically exhibit a wide viewing angle such as in-plane switching (IPS) [2], multi-domain vertical alignment (MVA) [3,4] and fringe-field switching (FFS) [5–7] have been researched and then commercialized to large size, LC-televisions. Nevertheless, in large size-LCD monitors, the TN-LCDs have become more popular due to low cost and relatively easy fabrication.

Considering the viewing angle characteristics of the normally white TN mode [8], a white state shows good uniformity in brightness according to the viewing direction. However, when a vertical electric field is applied to generate gray scales and a dark state, the mid-director tilts up in one direction, thereby breaking the symmetry of LC orientation. Strong asymmetry in brightness according to the viewing direction exists due to the phase difference in a vertical direction at which the LC tilts upward. Furthermore, strong light leakage at a dark state does occur at off-normal

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directions because of residual birefringence under crossed polarizers, which decreases the contrast ratio (CR) at oblique viewing directions.

In order to remove such light leakage, a polymerized, discotic LC film called wide-view (WV)-film has been developed [9–12]. In this WV-film, the tilt angle of discotic LC layers changes linearly from horizontal to vertical alignment without having twist angle. In this paper, we evaluated the image qualities in terms of iso-CR, gray scale inversion and color shift, depending on the orientation of the discotic LC layers in the film.

2. Switching principle and simulation conditions

LC molecules in TN cells have rod-like shape and are therefore optically positive uniaxial ($n_x = n_y < n_z$). When the compensation films based on discotic LC with disk-like shape and negative birefringence ($n_x = n_y > n_z$) are applied to the TN cell, the optical compensation compresses light leakage in the dark state in all viewing directions more effectively than other methods do, because optical isotropy can be achieved with proper orientation of discotic LC, as shown in Fig. 1. The normalized light transmission (T) of a device under a crossed polarizer is proportional to $\sin^2[\delta(\theta, \Phi, \lambda)/2]$, where δ is the phase difference, θ and Φ are the polar and azimuthal angles in spherical coordinates, respectively, and λ is the wavelength of the incident light. Therefore, to compensate perfectly, the following condition, $\delta_{LC} = \delta_{film}$, should be satisfied in all viewing directions. In other words, the magnitude of the phase difference of the film should be the same as that of the TN cells but the sign should be opposite to each other. Consequently, to compensate for the angular dependent phase difference in LC molecules with non-linear distributions of the dark state TN cells, discotic molecules need to be aligned in hybrid orientations that change from parallel to vertical alignment, as in the case of the dark state TN cells.

Fig. 2 shows the cell structure for optical compensation using discotic LC and the discotic layers were located between the TN cell and polarizer. The TN cell has a left-handed, normally white, O-mode and a cell retardation

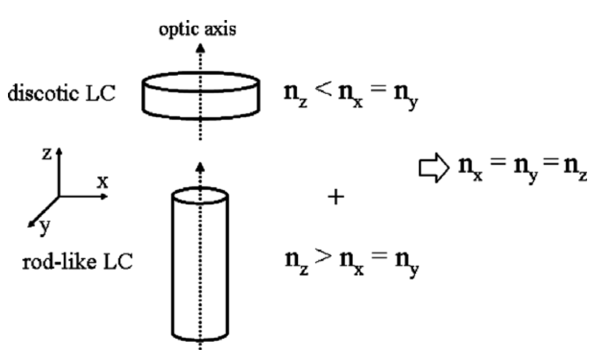

Fig. 1. Optical compensation principle using rod-like LC and discotic LC.

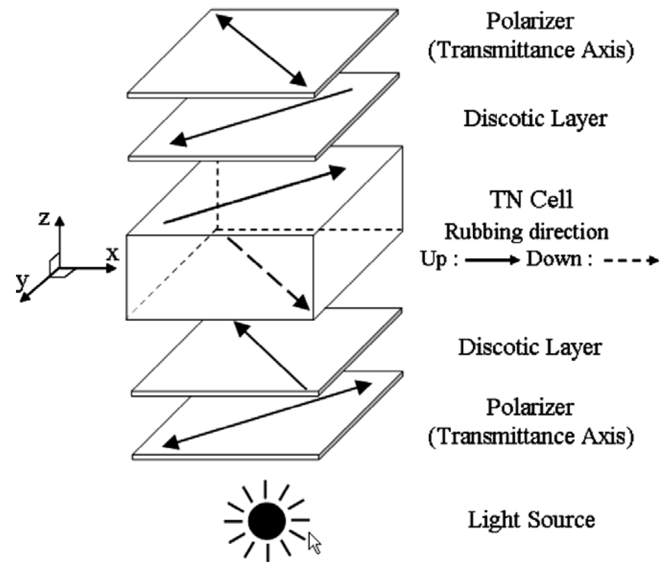

Fig. 2. Cell structure of the compensated TN-LC cells with a discotic LC layer.

value of 0.42 μm which is lower than the optimum value of the normal TN cell, considering the color characteristics when the compensation film was used. The LC with physical properties such as a positive dielectric anisotropy ($\Delta\varepsilon = 7.0$), elastic constants ($K_{11} = 11.7$ pN, $K_{22} = 5.1$ pN, $K_{33} = 16.1$ pN) and birefringence at 550 nm ($\Delta n = 0.0764$) is used. The surface pretilt angle is 3° and the cell gap is 5.5 μm.

The optical design of the discotic layer was applied to an optimized condition. The out-of-plane retardation value $[R_{th} = d\{(n_x + n_y)/2 - n_z\}]$ of the triacetyl cellulose (TAC) film used was 62.8 nm at 550 nm of incident light, where d indicates the film thickness. Refractive indexes in x, y, z coordinate system of discotic film are $n_x = 1.6040$, $n_y = 1.6040$ and $n_z = 1.543$ at 550 nm of incident light and the out-of-plane retardation value of discotic film used was 152.5 nm at 550 nm of incident light. The electro-optic properties, such as the viewing angle dependence of gray scales and iso-CR contours, were calculated under the visible light with a one-dimensional simulator (LCD-Master from Shintech, Japan) in which the transmittance was calculated by 2×2 extended Jones matrix method [13]. The transmittances for the single and parallel polarizers were assumed to be 41% and 35%, respectively.

3. Results and discussion

Fig. 3 shows schematic configurations of the rod-like LC orientation in a half TN cell and of the discotic LC orientation in a hybrid aligned compensation film. Considering the LC orientation in the dark state of the half TN cell, the tilt angle (θ_{LC}) changes from about 3° to 87° from either top or bottom surfaces to mid-director non-linearly with the twist angle (ϕ_{LC}). Nevertheless, conventional WV film has a hybrid alignment with linear change in the

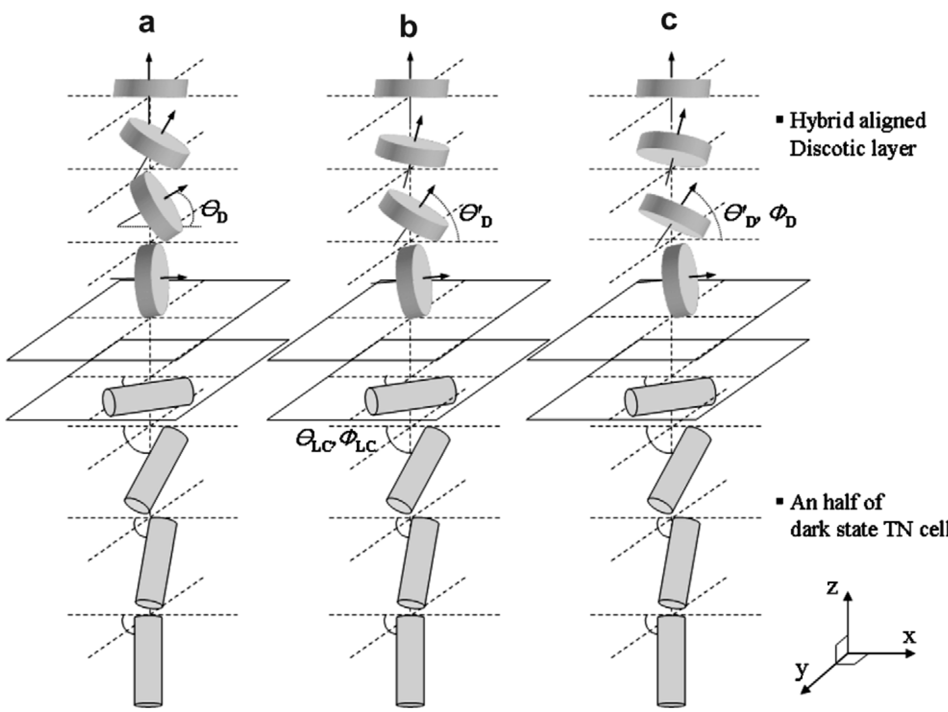

Fig. 3. Schematic configuration of rod-like LC orientation in a half TN cell and discotic LC orientation in a hybrid aligned compensation film with changing its optic axis from vertical to homogenous, layer by layer with: (a) linear tilt change without twist, (b) non-linear tilt change without twist, and (c) non-linear tilt change with twist orientation.

tilt angle (θ_D) of discotic LC layer as shown in Fig. 3a. In this paper, however, the WV film with the tilt angle changing non-linearly from 3° to 87°, i.e. exactly the same variation of the θ_D like in the TN cell, is considered, as shown in Fig. 3b. Therefore, at the same layer in vertical direction of the WV film, the tilt angle, θ_D, in Fig. 3a is not the same each other as that (θ'_D) in Fig. 3b. Finally, the discotic film with its changing director non-linearly in the θ'_D and 45° twist angle (ϕ_D) as shown in Fig. 3c was evaluated. Here, linear orientation means that the optic axis of the discotic LC layers changes constantly with form of linear function along vertical z direction; whereas non-linear orientation means it does not change constantly with the same variations of tilt angle like those in the TN cell.

Fig. 4 indicates the tilt and twist angles of the TN cell in the dark state according to cell gap and also the distribution of optic axes in discotic LC. In the TN cell, the tilt angle distribution of LCs had a symmetric LC orientation from the middle of the TN cell to either top or bottom surfaces, whereas the tilt angle changed non-linearly along the z-axis of the TN cell, as shown in Fig. 4a. In this paper, three cases which were defined by the orientation of the discotic LC layers with hybrid alignment were considered: linear tilt orientation in discotic layer (C-1 cell) as shown in Fig. 4b, non-linear tilt orientation in discotic layer (C-2 cell) as shown in Fig. 4c and both non-linear tilt and 45° twist orientation in discotic layer (C-3 cell) as shown in Fig. 4c and e and those axes of the discotic LC change from each bottom to top surfaces in upper (from 0 to 0.5 in z/d-axis) and lower (from 1 to 0.5 in z/d-axis) discotic films,

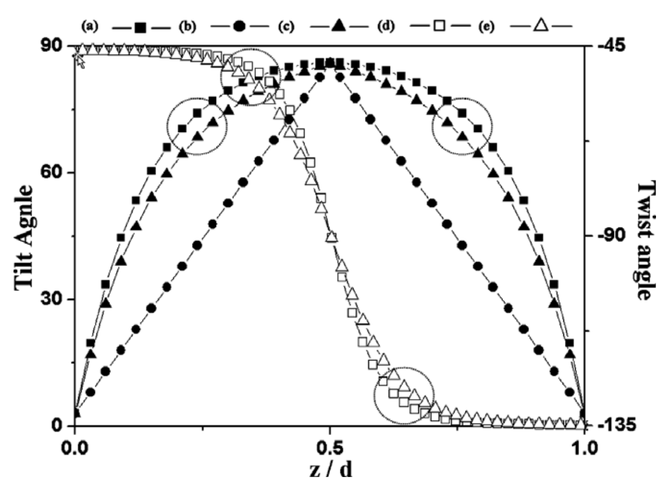

Fig. 4. Director profiles of TN-LC and discotic LC layer: (a) tilt angle in the dark state TN-LC, (b) linear tilt orientation in discotic layer, (c) non-linear tilt orientation in discotic layer, (d) twist angle in the dark state TN-LC and (e) non-linear tilt and 45° twist orientation in discotic LC layer.

respectively. Considering only the rod-like LC profile of the dark state TN cell, discotic LC layers with a non-linear tilt angle and a non-linear twist angle of 45° were the most similar matches to that of the dark state TN cell. Nevertheless, the orientation of the discotic LC layers did not match perfectly to that of the rod-like LC layer in our calculation, as shown in Fig. 4 (see director profiles in circles).

Fig. 5 shows the iso-luminance contours in the bright and dark states and the iso-contrast contours of the com-

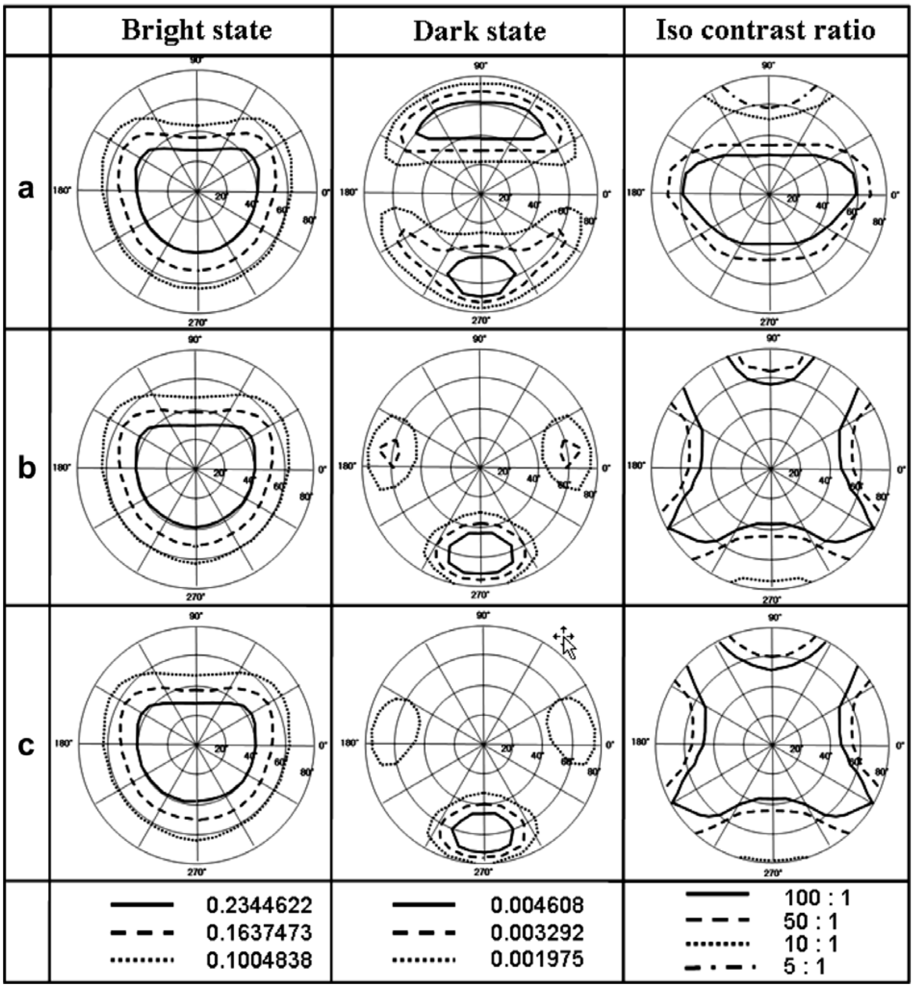

Fig. 5. Iso-luminance contour in the bright and dark states and iso-contrast contour of compensated TN-LC cells: (a) C-1, (b) C-2 and (c) C-3 cells.

pensated TN cells in the optimum retardation value of the discotic layer. Luminance uniformity in the bright state was similar in all three cases but light leakage in the dark state was totally different. Light leakage in the dark state of the C-2 and C-3 cells was much smaller than that in the C-1 cell, especially in the up and down directions. However, light leakage in the dark state of the C-2 and C-3 cells at over polar angle of 40° in the right and left directions was not suppressed perfectly. Nevertheless, light leakage in the dark state of the C-3 cell was slightly smaller than that in the C-2 cell. Considering the light leakage in all viewing directions, the C-3 cell, considering the tilt and twist orientation of the discotic LC layers, produced the smallest light leakage.

Since the C-2 and C-3 cells exhibited the lowest light leakage in the viewing directions, the region in which the CR was larger than 100 in the C-2 and C-3 cells was about 60° and 40° in the upper and lower directions, respectively, while it was only about 30° and 30°, respectively, in the C-1 cell. In addition, CR in the diagonal directions was greatly improved in the C-1 and C-2 cells, whereas that region in the horizontal direction was slightly reduced in the C-2 and C-3 cells compared to that in the C-1 cell. Now considering the region in the C-1 cell in which CR is 10, the region was over 80° of polar angle in the left, right and down directions, as shown in Fig. 5a, whereas in the upper direction, the region was only 50° and, even further, the region in which CR is five existed at less than 60°. On the other hand, in the C-2 and C-3 cells, the region in which CR is 10 existed at over 80° of polar angle in all directions, except that it existed at 75° and 79° of polar angle in the down direction in the C-2 and C-3 cells, respectively.

To evaluate the LCD image quality, the presence of gray scale inversion needs to be checked. The angular dependence of the eight gray levels along the vertical directions in the compensated TN cells was evaluated as shown in Fig. 6. There was a small difference of gray scale inversion among the three cases. Gray scale inversion was much improved in all three cases compared to that in the normal TN cell, although even the compensated TN cells still showed gray scale inversion and the regions free of gray scale inversion were only under 20° (L_7) and 30° (L_0) in the up and down directions, respectively. One noticeable finding was that the luminance in the bright state decreased

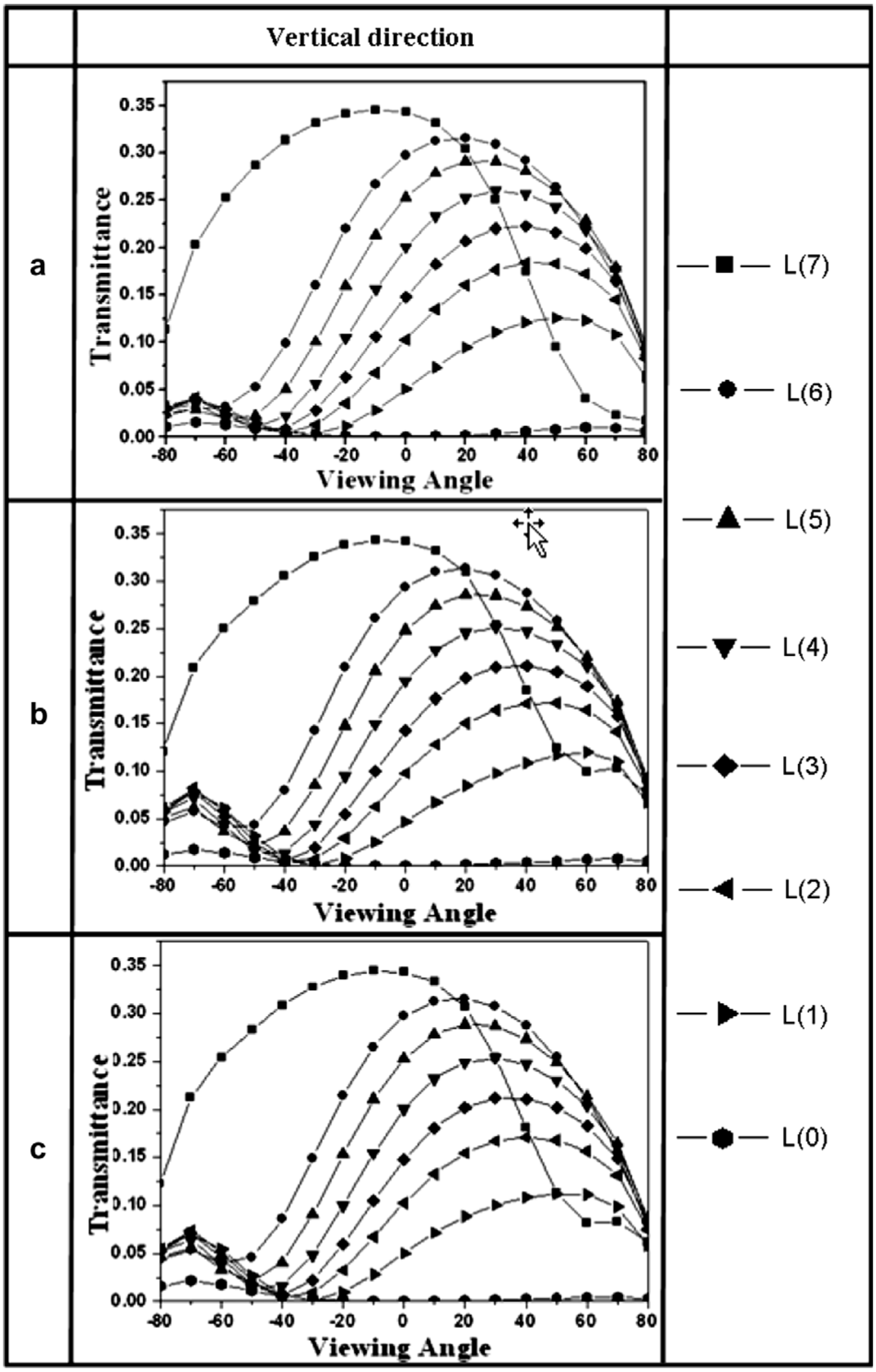

Fig. 6. Viewing angle dependence at the eight gray levels along the vertical direction of compensated TN cells: (a) C-1, (b) C-2 and (c) C-3 cells.

more rapidly in the C-1 cell than that in the other two cells in the upper directions. Consequently, the C-2 and C-3 cells showed slightly better performance in terms of gray scale inversion than the C-1 cell did.

Fig. 7 presents a comparison of the color shift occurring in changing the polar angle from 0° to 70° in all azimuth angles on the CIE 1976 u', v' coordinates [14]. The color shift of TN-LC cell is relatively larger than that of other LC modes such as IPS [15,16] and FFS [17]. Although there was a small difference in luminance uniformity among the three cases in the bright and mid-gray states, the color shift was larger in the C-2 and C-3 cells than in the C-1 cell in the dark state. We calculated $\Delta u'v'$, which is defined as the distance of color shift from maximum to minimum value at a polar angle of 60° along all azimuth angles. In the bright state, there was a small differ-

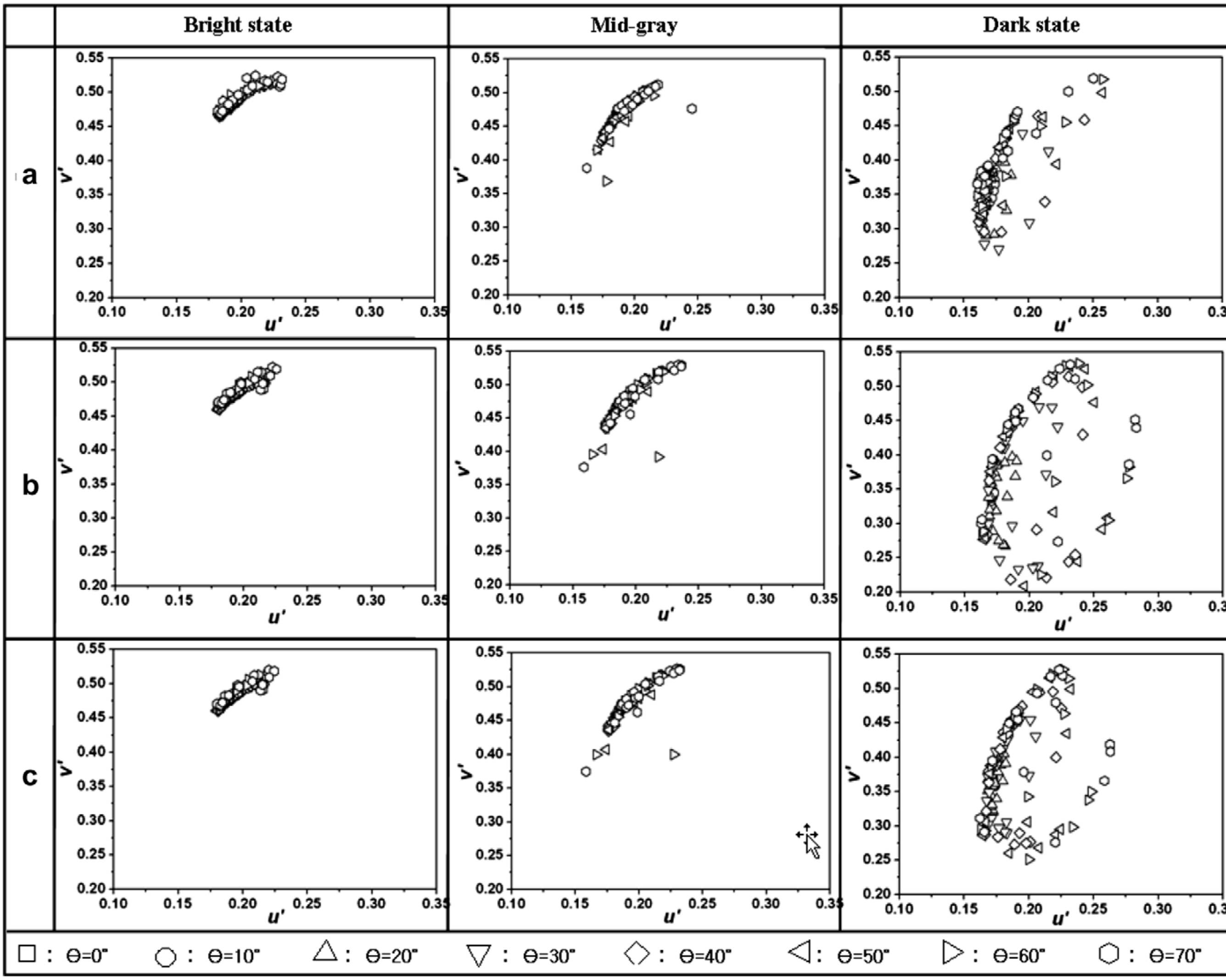

Fig. 7. Comparisons of color shift at all azimuth angles on a CIE 1976 u', v' coordinates system: (a) C-1, (b) C-2 and (c) C-3 cells.

ence in $\Delta u'v'$ among the three cells: 0.06289 in C-1, 0.06371 in C-2, and 0.06182 in C-3. However, in the dark state, $\Delta u'v'$ of the C-2 cell was the largest (0.30951) and of the C-1 cell was the smallest (0.21030), which indicates the trade-off relationship between light leakage and color shift.

Recently, a wide viewing angle in the horizontal direction has been emphasized with the development of wide type LCDs. Fig. 8 shows the off-axis color uniformity along the horizontal direction in the bright, mid-gray and dark states. Here, $\Delta u'v'$ means the distance of color shift from normal to viewing direction on a 1976 CIE coordinates system. Although the color uniformity did not differ greatly among the three cells, the C-1 cell showed the relatively strong color shift in the bright state and showed slightly weak color shift as the luminance decreased to the gray and dark state compared to other two cells. However, the differences between three cells are not so big.

4. Conclusions

We have studied film compensations depending on the orientations of discotic LC to improve the viewing angle for TN-LCDs by considering three different cells: C-1, C-2 and C-3. In terms of CR, the C-2 cell, with a non-linear tilt orientation in the discotic LC layer, showed better performance than the C-1 cell with a linear tilt angle, whereas the C-3 cell with a non-linear tilt and 45° twist orientation was comparable to the C-2 cell. In terms of color shift, the three cells showed similar performance in bright and mid-gray state, although the C-1 cell showed less color shift than the C-2 and C-3 cells in the dark state. Although color uniformity along the horizontal direction did not show a considerable difference, the C-1 cell showed better color uniformity than the other two in gray and dark state. In addition, the degree of gray scale inversion exhibited a similar performance. To summarize, the film compensation in TN-LCDs should be optimized

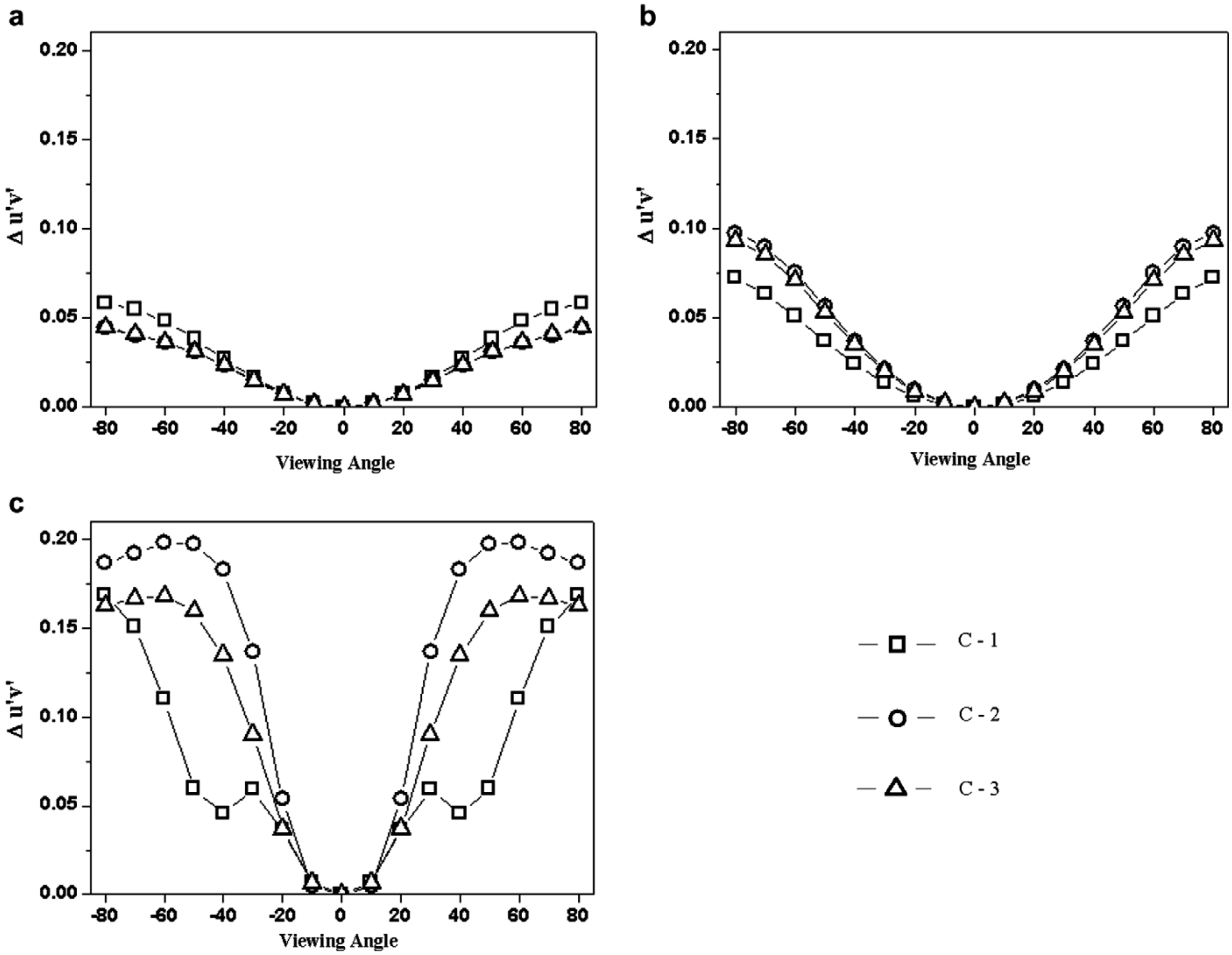

Fig. 8. Off-axis color uniformity along the horizontal direction in the (a) bright, (b) mid-gray and (c) dark states.

according to the application fields which favor improved CR or color performance.

Acknowledgements

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References

[1] M. Schadt, W. Helfrich, Appl. Phys. Lett. 18 (1971) 127.
[2] M. Oh-E, M. Yoneya, M. Ohta, K. Kondo, Liq. Cryst. 22 (1997) 391.
[3] N. Koma, Y. Yaba, K. Matsuoka, SID 95 Digest (1995) 869.
[4] A. Takeda, S. Kataoka, T. Sasaki, H. Tsuda, K. Ohmuro, Y. Koike, T. Sasabayashi, K. Okamoto, SID 98 Digest (1998) 1077.
[5] S.H. Lee, S.L. Lee, H.Y. Kim, Appl. Phys. Lett. 73 (1998) 2881.
[6] S.H. Hong, I.C. Park, H.Y. Kim, S.H. Lee, Jpn. J. Appl. Phys. 39 (2000) L527.
[7] S.H. Lee, S.M. Lee, H.Y. Kim, J.M. Kim, S.H. Hong, Y.H. Jeong, C.H. Park, Y.J. Choi, J.Y. Lee, J.W. Koh, H.S. Park, SID 01 Digest (2001) 484.
[8] H. Takano, S. Suzuki, H. Hatoh, IBM J. Res. Develop. 36 (1992) 23.
[9] H. Mori, Y. Itoh, Y. Nishiura, T. Nakamura, Y. Shinagawa, Jpn. J. Appl. Phys. 36 (1997) 143.
[10] H. Mori, Jpn. J. Appl. Phys. 36 (1997) 1068.
[11] H. Mori, P.J. Bos, SID 98 Digest (1998) 830.
[12] H. Mori, J. Display Technol. 1 (2005) 179.
[13] A. Lien, Appl. Phys. Lett. 57 (1990) 2767.
[14] B. Bahadur, Liquid Crystals – Applications and Uses, vol. 2, World Scientific, Singapore, 1991 (Chapter 8).
[15] S. Aratani, H. Klausmann, M. Oh-E, M. Ohta, K. Ashizawa, K. Yanagawa, K. Kondo, Jpn. J. Appl. Phys. 36 (1996) L27.
[16] B.S. Jung, I.S. Baik, I.S. Song, G.-D. Lee, S.H. Lee, Liq. Cryst. 33 (2006) 1077.
[17] H.Y. Kim, G.R. Jeon, D.S. Seo, M.H. Lee, S.H. Lee, Jpn. J. Appl. Phys. 41 (2002) 2944.