Study on Color Characteristics of a Dark State in the In-Plane Switching (IPS) Liquid Crystal Cell

B. S. Jung, I-S. Baik, I. S. Song and S. H. Lee

School of Advanced Material Engineering, Chonbuk National University, Chonju, Chonbuk, Korea

D-S. Kim, K-J. Kim and B-C. Ahn

Advanced Technology Development Team, LG-Philips LCD, Kumi, Kyungbuk 730-726, Korea

Abstract

Color characteristics of a dark state in the IPS-mode depending on viewing direction have been studied. IPS-mode is having a little variation of d?n with viewing angle since the LC rotates in plane. However, this mode shows asymmetric light leakage and color characteristics with viewing angle in a dark state. This drawback can be overcome by optimized retardation value of TAC film, pre-tilt angle & d?n of LC.

1. Objective and Background

Nowadays, the liquid crystal displays (LCDs) are in charge of an important role in human to machine interfaces. The application fields of the LCDs are greatly extended ranging from small size PDA to large size LC TV. Therefore, the LCDs should meet customer's high requirements such as wide viewing angle, fast response, high resolution and high color reproducibility.

Recently, the image quality of the liquid crystal displays (LCDs) is greatly improved, owing to the development of the new LC modes such as in-plane switching (IPS) mode [1], fringe-field switching (FFS) mode [2-5], and multi-domain vertical alignment (MVA) mode [6, 7]. Especially, in both IPS and FFS modes, the LCs are aligned homogeneously at initial state, and in-plane and fringe electric field rotate the LC, respectively. Nevertheless, in the FFS mode, the transmittance is dependent on dielectric anisotropy (?e) of the LC since the LC above electrode is tilted upward for the LC with +?e while the tilt angle is not much generated for the LC with –?e. However, In the IPS mode, the transmittance of the cell is not dependent on dielectric anisotropy of the LC [8] since the in-plane field drives the LC to rotate. In both modes, the O-mode is effective to reduce the light leakage than the E-mode [9, 10]. Besides, the O-mode shows better process margin than the E-mode in terms of the contrast ratio (CR) [11].

Especially, in LC-TV applications, high color purity as well as a perfect dark state without color shift in all viewing directions is highly important because a person's spectral luminous efficacy can be felt very sensitively in a dark state. Even with the O-mode, the dark state in the IPS mode is still not satisfactory such that some amount of light leakage and color shift exists simultaneously in oblique viewing directions and also it changes according to the viewing direction.

In the IPS mode where a uniaxial LC medium exists under crossed polarizers, the normalized light transmission is given by:

$$T / To = sin2\ (2?(V))\ sin2(pd?n_{eff}(?,F)/?)$$

where ? is a voltage-dependent angle between the transmission axes of the crossed polarizers and the LC director, d is a cell gap, $?n_{eff}$ is an effective birefringence of the LC layer dependent on polar and azimuthal angle in spherical coordinates, and ? is the wavelength of the incident light.

In the IPS mode, $?n_{eff}$ is not zero at off-normal axis except for directions coincident with polarizer axis, resulting in a light leakage as well as chromatic in a dark state and in addition, it shows asymmetric along rubbing directions since the LC layer has a pretilt angle. In this paper, we have studied how to reduce a light leakage and variation of color coordinate with viewing angle by optimized retardation value of TAC film, pre-tilt angle ($?_p$) & $d?n$ of LC.

2. Results and discussions

To perform the simulation, the LC with physical properties such as ?e=7.0, K_{11}=11.7pN, K_{22}=5.1pN, K_{33}=16.1pN is used. The surface pretilt angle is 2°. Here, the width of pixel electrode and the distance between electrodes is assumed to be 5 and 10μm. The cell gap is 4μm. In this calculation, 2 x 2 extended Johns matrix is applied for optical calculations [12] and the transmittance for a single and parallel polarizer is assumed to be 40% and 35%, respectively.

Here, we also consider a TAC film with retardation value given by:

R_{th} = d · ((Nx+ Ny)/2 -Nz) = 65.2nm (@ 546nm)

δ = (Nx-Ny)· d = 10.4nm (@ 546nm)

Figure 1 describes optical configuration of O-mode in the IPS cell when rubbing direction is in horizontal. Here, ? define an azimuthal angle from the optical axis of LC director counterclockwise. Since the LC layer has a pretilt angle, analysis of asymmetric dark light leakage as well as color characteristics should be performed by comparing right with left azimuthal direction.

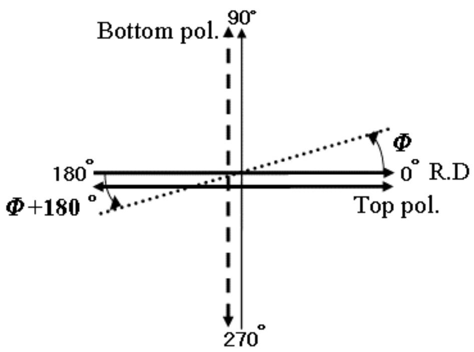


Fig. 1 Optical configuration of O-mode in IPS cell.

Figure 2 shows a degree of light leakage and color characteristics occurred at both sides of rubbing direction, in the dark state. As shown in Fig. 2(a) and (b), the maximum light leakage occurs at ? = ±20° ~30° of R.D. and thus, it strongly depends on R.D.. In terms of symmetry in horizontal direction, a cell with vertical R.D. is favored. However, to achieve a high aperture ratio, rubbing in horizontal direction is favored [13]. Yellowish and bluish color shift exists in a polar angle of 50°~70° at ? = 20° & ? = 160° for the cell with horizontal and vertical R.D., as shown in Fig. 2 (c) & (d). Further, difference in color chromaticity also exists between directions of ? = 20° & ? = 160°. Interestingly, the light leakage at ? = 160° is much smaller than that at ? = 20° but still a yellowish color shift occurs. In terms of human eye's spectral sensitivity, yellowish color shift in a dark state is much more easily observable annoying eyes. Therefore, the light leakage and color suppression for the cell with horizontal rubbing direction need to be controlled to obtain a true black.

Figure 3 shows calculated iso-luminance contour of the dark state (T_0) according to cell retardation value. Three color lines of iso-luminance curve represent the relative transmittance of 70% (I_{70}), 50% (I_{50}) and 30% (I_{30}) with respect to the maximal transmittance at off-normal axis in the dark state. The light leakage was smallest when *d?n* of the cell is 0.36 µm such that the region of I_{70} does not exist while other two have. However, asymmetric light leakage region still exists along horizontal viewing direction.

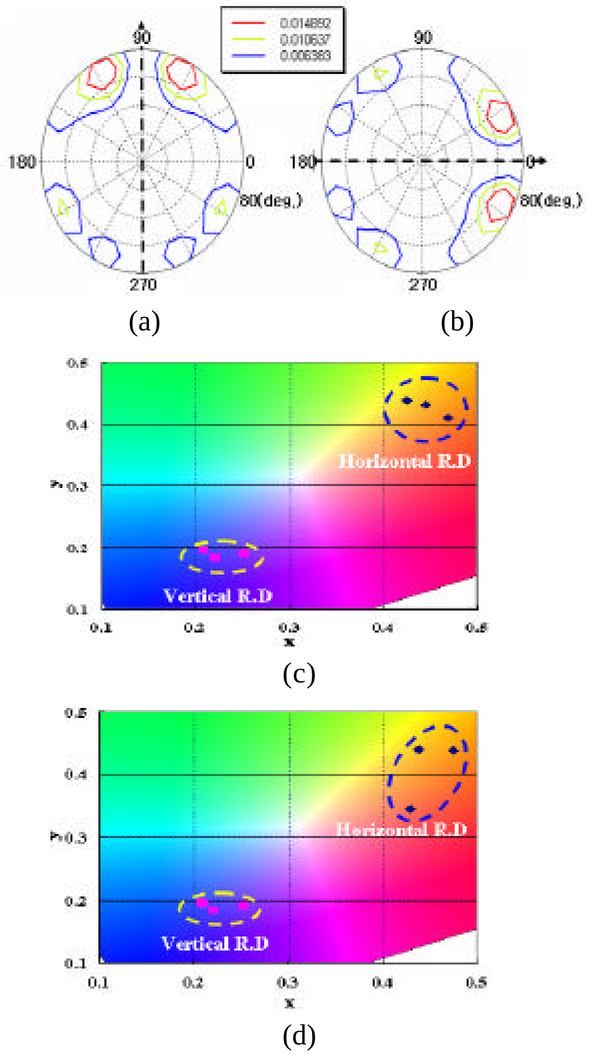


Fig. 2 Calculated iso-luminance contour of dark state (T_0) in (a) vertical R.D & (b) horizontal R.D. Calculated color chromaticity with 50°~70° of polar angle at (C) ? = 20° & (d) ? = 160°.

On the other hand, when *d?n* is 0.40 µm, most light leakage region is shifted to ? = 40 ~ 70°. That is, true dark region in a horizontal viewing direction is slightly wider than some other conditions of d? n, although region of light leakage I_{70} is increased.

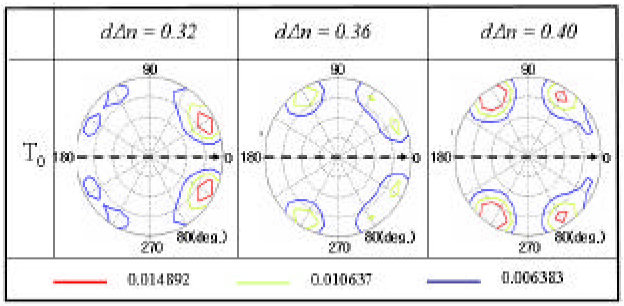
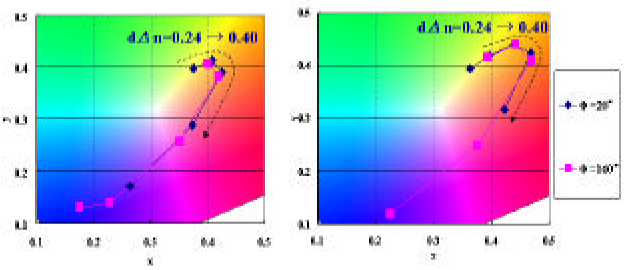


Fig. 3 Calculated iso luminance contour of T_0 with d?n when R_{th} value of TAC film is 65.2nm.

Next, color shift characteristics with *d?n* are calculated at two polar angles 40° and 60°. As shown in Fig. 4 (a), as d? n increases from 0.24㎛ to 0.40㎛, color shift occurred from yellowish to bluish at both horizontal viewing directions. However, when ? = 60°, as *d?n* increases, color shift occurred from yellowish to reddish at ? = 20° while it shifts to bluish color at ? = 20°.



(a) (b)

Fig. 4 Calculated color shift with *d?n* in a horizontal direction at two polar angles: (a) ? = 40 ° and (b) ? = 60 ° .

Therefore, by increasing *d?n* to 0.40㎛, we should be able to reduce yellowish color in a horizontal viewing direction. However, a relatively strong dark light leakage still needs to be suppressed.

In order to reduce it, optimization of the R_{th} values of TAC films while changing d? n from 0.32㎛ to 0.40㎛ has been performed, as shown in Fig 5. In each cell with optimized R_{th} of TAC film, light leakage is greatly reduced in the cell with *d?n* = 0.40㎛. In addition, we calculated color coordinates in a horizontal viewing direction at a polar angle of 60°, as shown in Fig. 6. For the cell with *d?n* = 0.36 ㎛, light leakage is quite reduced but color coordinates change rapidly along azimuthal directions and also show strong asymmetry in a horizontal direction.

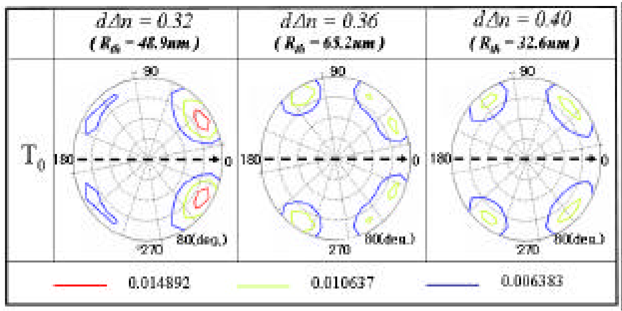


Fig. 5 Calculated iso-luminance contour of T_0 with optimized R_{th} values for each cell.

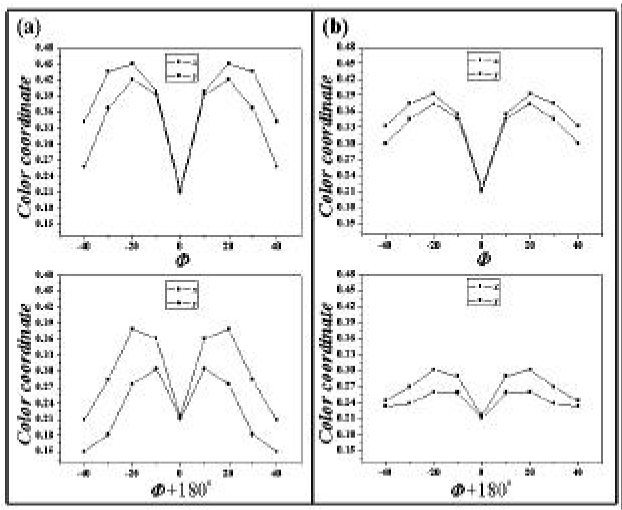


Fig. 6 Calculated color coordinates along azimuthal direction in horizontal viewing direction at ? = 60° for the cells: (a) *d?n* = 0.36㎛, R_{th} = 65.2nm and (b) *d?n* =0.40㎛, R_{th} = 32.6nm.

However, when *d?n* = 0.40㎛ & R_{th} = 32.6nm, not only the light leakage of the dark state decreased but also the region with most light leakage shifted to upper viewing direction horizontal viewing direction.

Besides, color coordinate variation & asymmetric characteristics is also reduced.

Although the IPS cell with *d?n* = 0.40μm shows least color shift and light leakage, the color chromaticity at normal direction is shifted strongly from white to yellowish, which requires an optimization of backlight. However, it is noticeable that the FFS mode matches this cell retardation value.[14]

Finally, we investigate the effect of pretilt angle ($?_p$) in dark state, as shown in Fig 7. As expected, for a cell with *d?n* = 0.32μm & R_{th} = 32.6nm, as $?_p$ decreases, light leakage is reduced greatly with symmetry shape..

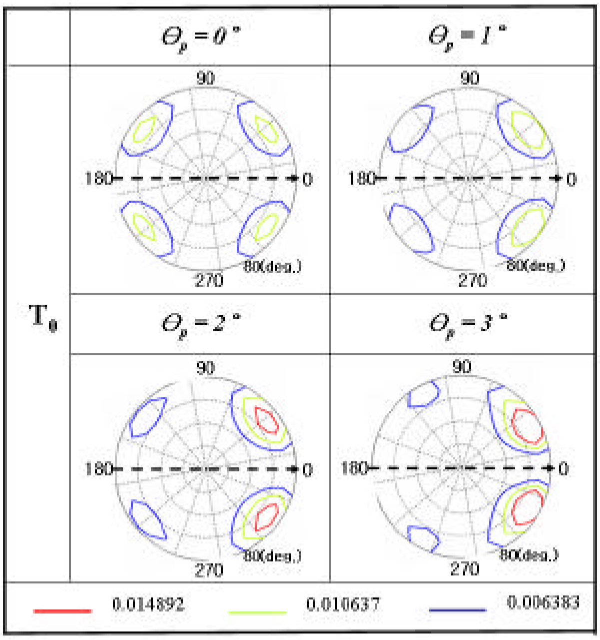


Fig. 7 Calculated iso-luminance contour of T_0 with pretilt angle.

3. Summary

We have studied color characteristics in order to improve asymmetric light leakage and color characteristics with viewing angle in a dark state. Our study shows that asymmetric light leakage and color characteristics can be reduced by increasing *d?n* of LC in horizontal viewing direction. Further, optimizing R_{th} of TAC film matching cell retardation value reduces color shift and also θ_p of LC layer should be as small as possible to suppress asymmetric characteristic in a horizontal viewing direction.

4. Acknowledgements

This work was partly supported by LG-Philips LCD.

5. References

[1] M. Oh-E, and K. Kondo: Jpn. J. Appl. Phys., Vol. 36, p. 6798, 1997.

[2] S. H. Lee, S. L. Lee, and H. Y. Kim, Asia Display '98, p. 371, 1998.

[3] S. H. Hong, I. C. Park, H. Y. Kim, and S. H. Lee: Jpn. J. Appl. Phys., Vol. 39, p. L527, 2000.

[4] H. Y. Kim, G R. Jeon, D-S. Seo, M-H. Lee and S. H. Lee: Jpn. J. Appl. Phys., Vol. 41, p. 2944, 2002.

[5] S. H. Lee, H. Y. Kim, S. M. Lee, S. H. Hong, J. M. Kim, J. W. Koh, J. Y. Lee, and H. S. Park: SID 01 Dig., p. 117, 2001.

[6] N. Koma, Y. Baba, and K. Matsuoka: SID 95 Dig., p. 869, 1995.

[7] Y. TanaKa, Y. Taniguchi, T. Sasaki, A. Takeda, Y. Koibe, K. Okamoto, SID' 99 digest, p. 206, 1999.

[8] Masahito Oh-e, Makoto Yoneya, and Katsumi Kondo, J. Appl. Phys., Vol. 82, p. 528, 1997.

[9] Y. Saitoh, S. Kimura, K. Kusafuka and H. Shimizu: Jpn. J. Appl. Phys. Vol. 37, p. 4822, 1998.

[10] J. E. Anderson and P. J. Bos: Jpn. J. Appl. Phys. Vol. 39, p. 6388, 2000.

[11] I. S. Song, H. K. Won, D. S. Kim, H-S. Soh, W. Y. Kim and S. H. Lee: Jpn. J. Appl. Phys. Vol. 43, p. 4242, 2004.

[12] A. Lien, Appl. Phys. Lett., Vol. 57, p. 2767, 1990.

[13] 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 and H. S. Park, SID ' 01, p. 484, 2001.

[14] S. H. Jung, H. Y. Kim, S. H. Song, J-H. Kim, S-H. Nam and S. H. Lee, Jpn. J. Appl. Phys Vol. 43, p.1028, 2004.