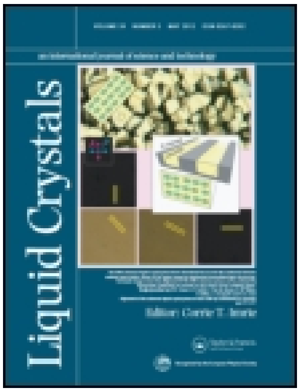

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Film compensation to improve the dark state in the oblique directions of the horizontal-switching mode

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In order to compensate for light leakage in the oblique viewing directions of the dark state of the horizontal-switching mode such as the in-plane switching and fringe field switching modes. The viewing angle performance of the horizontal-switching mode with an compensation film has been evaluated on a case by case basis according to the retardation values of the films. Consequently, we found that a much better dark state can be achieved by using an optimised compensation film.

Keywords: horizontal- switching mode; discotic film; triacetyl cellulose film

1. Introduction

Anisotropic compensation films are used in general to improve the viewing angle characteristics and the contrast ratio (CR) of liquid crystal displays (LCDs). The compensation film can be classified into several types, such as A, C, O and biaxial plates according to the optical axis of the film [1, 2]. Recent developments in compensation film technologies have helped the continuous improvement of the film characteristics in accordance with several LC driving modes such as in-plane switching (IPS) [3–7], fringe field switching (FFS) [8–11], patterned vertical alignment (PVA) [12, 13], polymer stabilised vertical alignment (PS-VA) [14–18] and optically compensated bend (OCB) [19, 20] modes for LCD television applications. The IPS-pro using the concept of FFS has improved dark configuration by applying an optimised biaxial film [21]. Similarly, true wide IPS (TW-IPS) achieved wide viewing characteristics in oblique directions in accordance with the application of a pair of optical configurations [22–24]. However, these biaxial films have difficulties not only in stretching but also in the production process for application in large-sized LC televisions. Hence intense research is necessary for further improvement in the prospective technology. We have demonstrated in our previous papers that the degree of maximum light leakage decreases to 38.7% compared with the value of the non-compensated IPS cell or FFS cell through the 90° tilted optical configuration of a discotic film like negative (-) A plate (refractive index: $n_x < n_y = n_z$) [25, 26]. However, the optical configuration and optimised retardation values of the films individually have not been considered in prior publications.

In this paper, we describe an investigation of the viewing angle characteristics of the horizontal-switching mode by controlling the optical configuration and retardation values of non-stretched discotic and triacetyl cellulose (TAC) films. As a result, a device using an optimised wide view polariser consisting of discotic and TAC films could achieve a wide viewing angle and a high CR.

2. Light leakage of the conventional horizontal-switching mode in the oblique direction

In the horizontal-switching mode, a uniaxial nematic LC medium appears between the crossed polarisers and hence the normalised transmittance is given by

$$T / T_O = \sin^2(2\psi(V)) \sin^2(\pi d \Delta n_{eff}(\theta, \Phi, V, \lambda)/\lambda) \quad (1)$$

where ψ is the voltage-dependent angle between the transmission axes of the crossed polarisers and the LC director, d is a cell gap, Δn_{eff} is the effective birefringence of the LC layer dependent on the polar (θ) and azimuthal (Φ) angles, the voltage (V) and the wavelength of the incident light (λ) in spherical polar coordinates. In a dark state, Δn_{eff} is non-zero at the off-normal axis except for the directions coincident with the polariser axis, resulting in light leakage as well as chromatic. In addition, the color shift shows asymmetry along the rubbing directions since the LC layer has a surface pretilt angle. So, the transmittance through the LC layer depends on the effective retardation as a function of viewing angle in the

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dark state under field-off conditions. Consequently, the horizontal-switching mode shows low CR and colour shift characteristics due to light leakage and, in particular, the varying retardation in the oblique directions.

In addition, for crossed polarisers, the effective angle between the absorption axis of the polariser and the analyser increases as the oblique incident angle in the diagonal direction increases. For oblique incidence, the absorption angle of the polarisers deviates from normal incidence at an azimuth angle of 45°. The light leakage in the dark state is generated due to a change in the effective angle between the two polarisers.

Figure 1(a) shows a conventional horizontal-switching cell consisting of a homogeneously aligned LC cell with a couple of attached TAC films (out-of-plane retardation value (R_{th}) = 48.9 nm), namely the front and rear, and finally polarisers with the transmittance axis mutually perpendicular to each other, similar to the IPS and FFS driving modes. Figure 1(b) shows the polarisation state of the light obliquely passing through the cell in the diagonal direction on the Poincaré sphere. Oblique incident light in the diagonal direction would have a deviated polarisation angle (δ) compared to normal incident light, so that the polarisation direction of the polariser will deviate by 2δ from S_1, which is the polarisation state of the polariser in the normal direction. Therefore, the starting position of the oblique incident light is position A. Then, the light passing through the rear TAC film reaches polarisation position B along the path L_1. Next, the light will move to the C position along the circle path L_2, which is centred at OF by traversing the horizontal cell with fast axis F. Finally, the front TAC film will reach the polarisation state D from C with path L_3 again. From Figure 1(b), we can observe different lengths from the polarisation state D in front of the output polariser to output polariser G. Therefore, we can assume that the deviation between D and G will cause serious light leakage in the dark state. Currently, the light leakage is in an arbitrary unit.

3. Optical configuration of the proposed cell for reducing light leakage

The light leakage in the dark state can be removed by applying an optical compensation film to the conventional horizontal-switching LC cell. Figure 2 shows the proposed first optical configuration and the polarisation state of light passing through the Poincaré sphere in the horizontal-switching LC cell. The optical configuration of the first proposed cell consists sequentially of a discotic film like -A plate and a TAC film like -C plate ($n_x = n_y > n_z$) below the horizontal-switching LC cell, as shown in Figure 2(a). The optic axis of the discotic film and the optical axis of the horizontal-switching cell are aligned perpendicular and parallel with to transmittance axis of the top polariser, respectively. An improved optical polarisation path of the first proposed device is described by the Poincaré sphere, as shown in Figure 2(b). The starting position is position A when the light passes through the polariser from the oblique direction. Then, the polarisation state of the light passing through the rear TAC film like -C plate moves to position B along the path L_1. The polarisation of light passing through the discotic film like -A plate moves to position C along the circular path L_2. The polarisation position does not change after passing through the horizontal-switching cell because the fast axis of the LC cell is at position C. Also, the light passing through the front zero TAC film like isotropic state does not changed. Consequently, the polarisation state of the light is

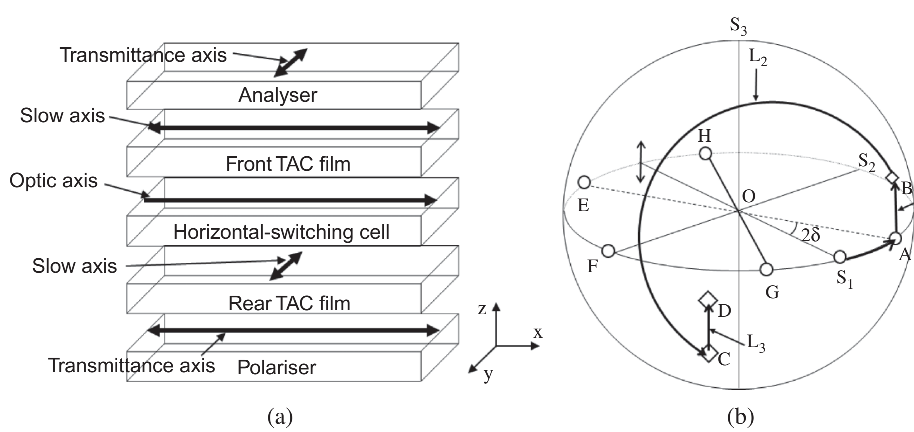
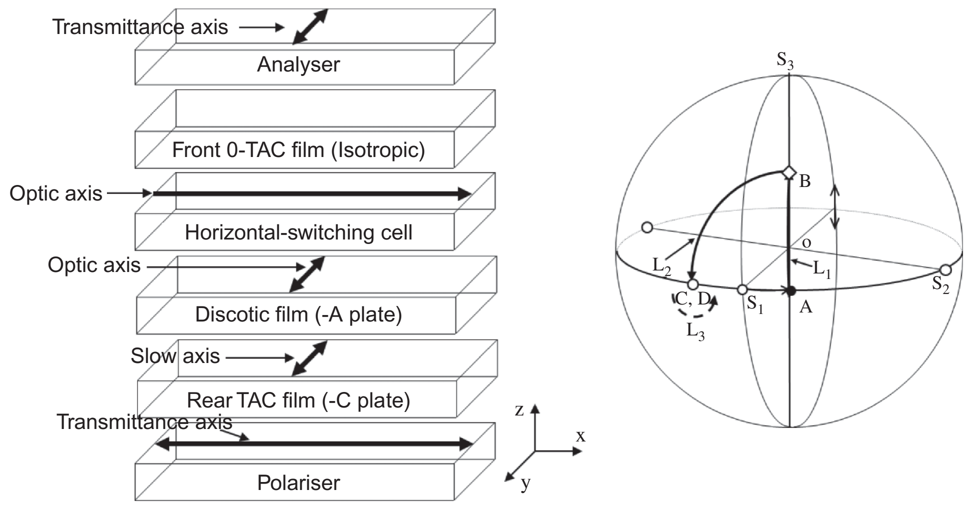


Figure 1. (a) Optical configuration of a conventional horizontal-switching LC cell and (b) the polarisation state of the light passing through a conventional horizontal-switching LC cell at an oblique angle on the Poincaré sphere.

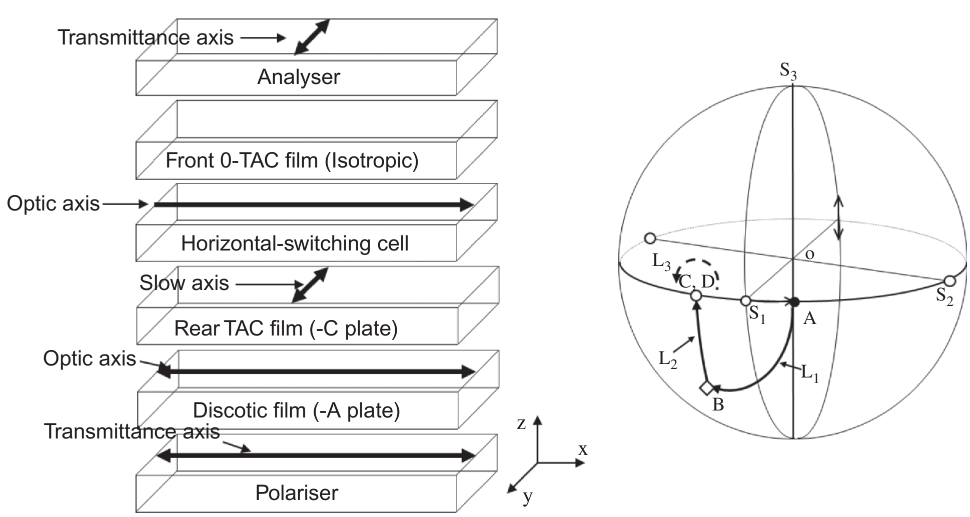


(a) (b)

Figure 2. (a) Optical configuration of the first proposed horizontal-switching LC cell and (b) the polarisation state of the light passing through the first proposed horizontal-switching LC cell at an oblique angle on the Poincaré sphere.

shown by position D along the circular path L_3 and we were able to obtain a perfect dark state in the oblique direction.

Figure 3 shows the proposed second optical configuration and the polarisation state of the light passing the Poincaré sphere in the horizontal-switching LC cell. The optical configuration of the proposed second cell consists sequentially of a TAC film like -C plate and a discotic film like -A plate below the horizontal-switching LC cell, as shown in Figure 3(a). The optical axis of the discotic film and the optical axis of the horizontal-switching cell are aligned parallel and perpendicular to the transmittance axis of the top polariser, respectively, unlike the first proposed structure. An improved optical polarisation path of the second proposed device is described on the Poincaré sphere, as shown in Figure 3(b). The starting position is at position A when the light passes through the polariser from the oblique direction. Then, the polarisation state of the light passing through the discotic film like A plate moves to position B along the circle path L_1. The polarisation of light passing through the rear TAC film like -C plate moves to position C along the path L_2. The polarisation position does not change



(a) (b)

Figure 3. (a) Optical configuration of the second proposed horizontal-switching LC cell and (b) the polarisation state of the light passing through the second proposed horizontal-switching LC cell at an oblique angle on the Poincaré sphere.

after passing through the horizontal-switching cell because the fast axis of the LC cell is in the position C. Also, the light passing through the front zero TAC film like isotropic state does not changed. Consequently, the polarisation state of the light is shown by position D along the circular path L_3. Therefore, the proposed schemes can move the polarisation states efficiently from the starting position A to the ending position D, and hence they clearly remove light leakage in the oblique direction.

Table 1 shows the calculated retardation values and reference of the TAC film and discotic film for R, G and B wavelengths. The dark state optical characteristics have been simulated using commercially available software, 'TechWiz LCD' (Sanayi-system, Korea), where a LC with physical properties of 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 ($\Delta n = 0.1$) was used. The surface pretilt angle was assumed to be 2°. Here, the horizontal-switching LC cell was applied to the FFS mode. The cell gap was 4 μm. The LC was aligned at 0° with respect to the *x*-direction.

Table. 1. The parameters of TAC and discotic films used for the calculations.

■ TAC film (R_{th} = 70–110 nm)			
Wavelength (nm)	n_x	n_y	n_z
436	1.48815	1.48814	1.48751
546	1.47963	1.47962	1.47890
611.5	1.47661	1.47660	1.47585
■ Discotic film (R_o = 120–160 nm)			
Wavelength (nm)	n_x	n_y	n_z
450	1.5001	1.65030	1.65061
550	1.49001	1.63217	1.63224
650	1.48423	1.62171	1.62163

4. Results and discussion

Figure 4 shows the maximum light leakage in a dark state with the R_{th} of the TAC films and the in-plane retardation value (R_0) of the -A plate as given in Figure 2(a) and Figure 3(a). Here, R_0 and R_{th} can be described as follows [27]:

$$R_0 = (n_x - n_y) \times d \tag{2}$$

$$R_{th} = \left\{ \frac{n_x + n_y}{2} - n_z \right\} \times d \tag{3}$$

where n_x, n_y and n_z are the refractive indices in the *x*, *y* and *z* directions.

Figure 4(a) shows that the smallest light leakage in a dark state is 0.000201 at an R_{th} value of 80 nm in the TAC film and an R_o value of 140 nm in the discotic film. Figure 4(b) shows that the smallest light leakage in a dark state is 0.000151 at an R_{th} value of 80 nm in the TAC film and an R_o value of 140 nm in the discotic film. The maximum light leakage of Figure 4(b) is found to be much lower than that in Figure 4(a). Also, the drop ratio of the light leakage is 98.9% in Figure 4(a) and 99.2% in Figure 4(b) compared to normal the horizontal-switching mode.

Figure 5 shows the iso-luminance in a dark state and the iso-CR curves in each case. Here, the iso-luminance curves represent relative transmittances of 70%, 50% and 30% with respect to the maximum transmittances at the off-normal axis in a dark state. As shown in Figures 5(a)–(c), light leakage of

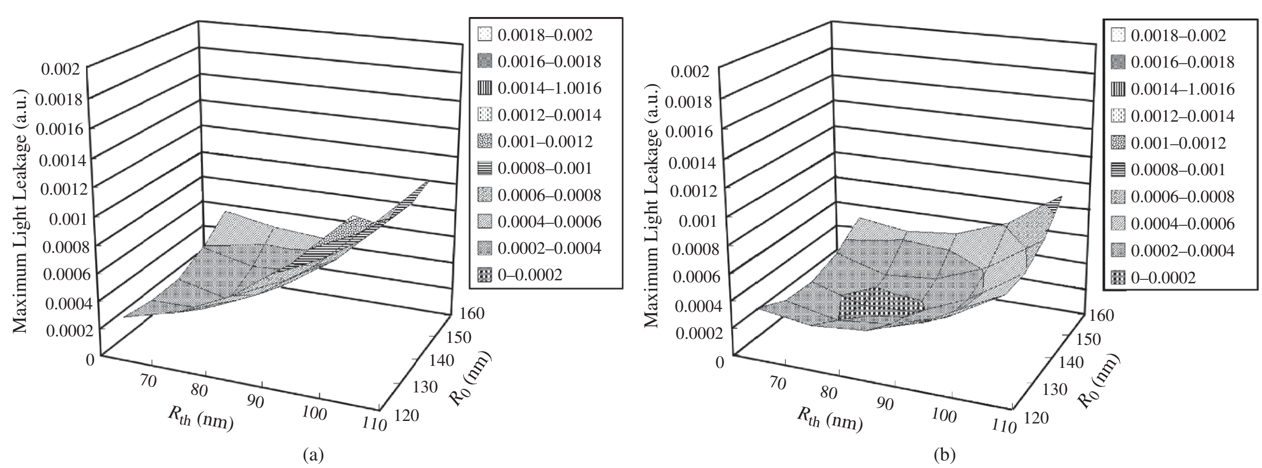


Figure 4. Calculated maximum light leakage in a dark state according to the value of R_{th} of the TAC films and the value of R_o of the discotic film in the first (a) and second (b) proposed horizontal-switching LC cells.

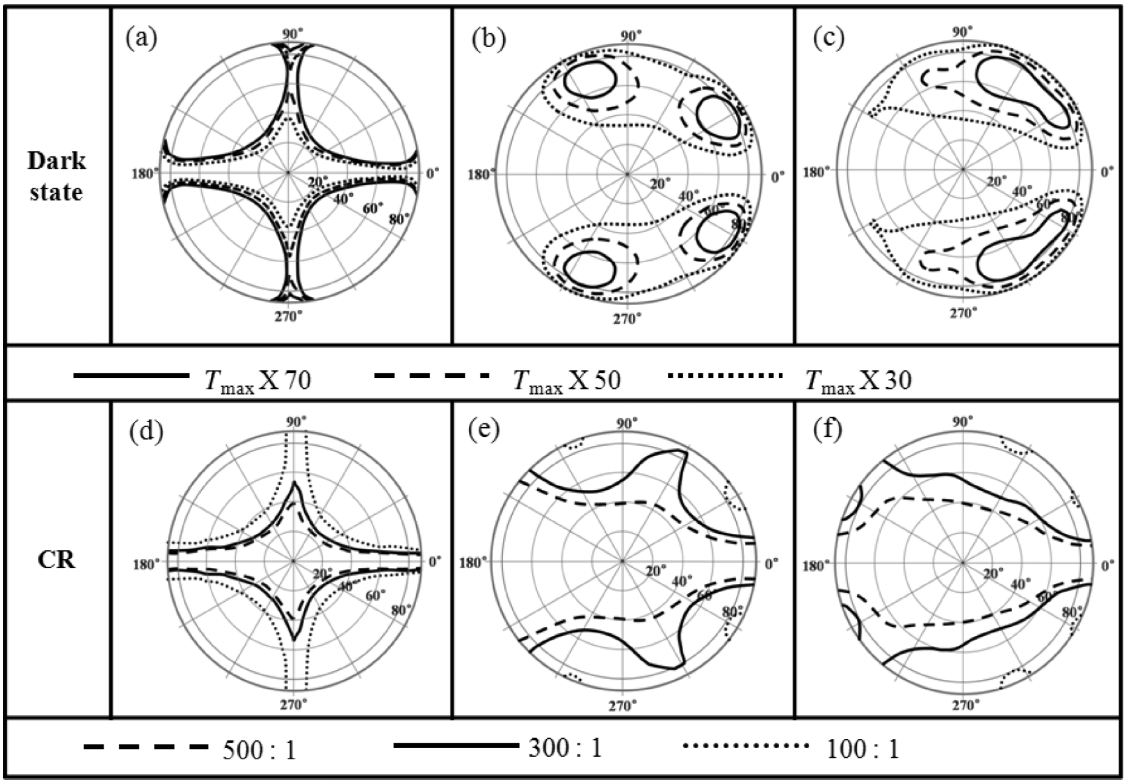


Figure 5. Calculated iso-luminance curves in a dark state of the conventional (a) and the first (b) and second (c) proposed horizontal-switching LC cells and the iso-CR curves in the conventional (d) and the first (e) and second (f) proposed horizontal-switching LC cells.

less than 30% exists within 40° of the polar angle in the vertical directions for both of the proposed structures in the dark state, whereas, for the normal horizontal-switching cell, it exists within 20° of the polar angle in the diagonal directions. This indicates that both of the proposed structures show a much better dark state performance than that of the horizontal-switching cell. Consequently, the region in which the CR is greater than 100 exists within about 80° of the polar angle in all azimuthal directions for both of the proposed structures, as shown in Figures 5(e) and (f). As shown in Figure 5(d), the region with CR larger than 100 in the normal horizontal-switching cell is much narrower than the regions of the proposed cells in the two diagonal azimuthal directions, i.e. it exists within less than 40° of the polar angle. The obtained 100:1 iso-CR when the incident light is of all wavelengths in the proposed optical configuration is almost the same as the reported results by Zhu *et al*. [24] just when the wavelength of the incident light is 550 nm. In the cell configurations of Zhu *et al*. the -A film is replaced by a +A film and also the -C film is replaced by a +C film in the two cell configurations that we propose here. To compare Zhu *et al.*'s results with our results more precisely, the luminance in the dark state and the iso-CR curves have been calculated for incident white light and the results are shown in Figure 6. Here, we employed all the optical retardation values given in Zhu et al.'s paper. As shown in Figures 6(a) and (b), light leakage of less than 30% in the dark state exists within 35° of the polar angle in the vertical directions in the reported results and also the maximum light leakage in then off-normal direction increases by about 30% compared with the results in Figures 5(a) and (b). Consequently, the region in which the CR is greater than 100 decreases to within about 5° of the polar angle in all azimuthal directions compared with both of the proposed structures, as shown in Figures 6(c) and (d). This indicates that the results of our proposed structure show better optical performance.

5. Summary

We have studied film compensations found by changing the out-of-plane retardation value of a triacetyl cellulose film and the in-plane retardation of a discotic film to improve the viewing angle which is dependent on the light leakage in the dark state for high

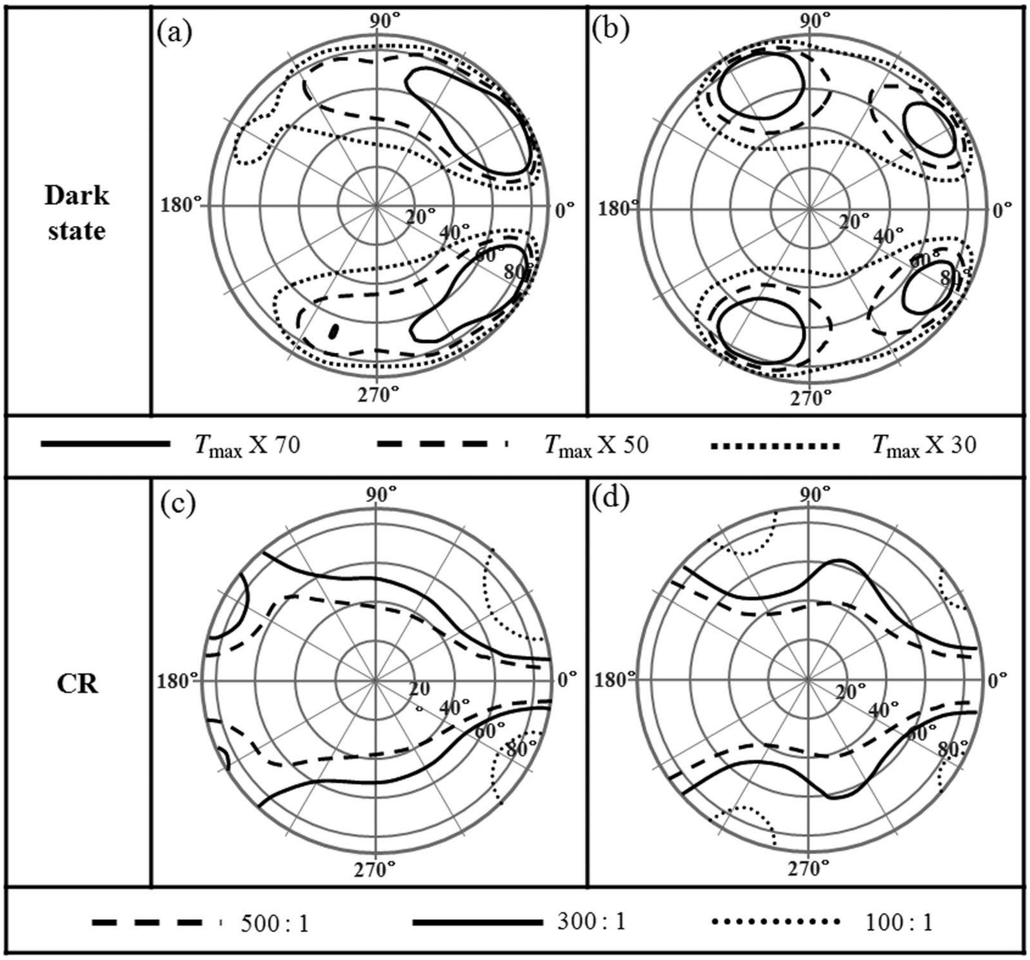


Figure 6. Calculated iso-luminance curves in a dark state of the reported results by Zhu *et al*. [24] using +A- and +C-plates (a) and +C- and +A-plates (b) from the top and the iso-CR curves in the reported results by Zhu *et al*. [24] using +A- and +C-plates (c) and +C- and +A-plates (d) from the top.

resolutions of the horizontal-switching mode by considering two different cases. To obtain a perfect dark state, the calculation results have been investigated in all visible wavelengths and the retardation values of the compensation films have been optimised using the commercially available software 'TechWiz LCD'. As a result, the optimised horizontal-switching cell exhibits much better performance than other methods do in terms of contrast ratio.

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