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Compensation for phase dispersion in horizontal-switching liquid crystal cell for improved viewing angle

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Abstract
In this paper we propose an optical configuration of a horizontal-switching liquid crystal (LC) cell with two positive C-plates and a single A-plate in order to improve the optical property in the diagonal direction, which is a weakness of horizontal-switching LC cells. The proposed configuration's optical design was performed on a Poincaré sphere with the trigonometric method. From calculations, we show that the proposed structure can increase the contrast ratio in the diagonal direction by about 10 times.

1. Introduction

Horizontal-switching liquid crystal (LC) modes such as the super-in plane switching (S-IPS) mode [1, 2] and the fringe field switching (FFS) mode [3] show wide viewing angle characteristics without compensation film. In spite of their excellent viewing angle performance, the contrast ratio in the diagonal direction is lower than in the horizontal and perpendicular direction because the effective angle between the polarization directions of the crossed O-type polarizers increases in proportion to the observation direction [4–6]. This degradation of the contrast ratio in the diagonal direction increases in larger displays, such as in TV applications. In order to consider the effective angle of the absorption axis of the polarizer in the off-axis direction, several types of optical configurations of the S-IPS cells have been proposed. Chen has shown a combination of an A-plate with a positive C-plate [7]. Saitoh has shown a configuration using one biaxial film [8], and Ishinabe also has shown a configuration using two biaxial films [9]. In general, however, optical configuration with biaxial film has the weakness of showing relatively poor uniformity because uniformity of the biaxial film is hard to control.

In this paper we propose an optical configuration of a horizontal-switching cell for wide viewing angles in all directions and over all visible wavelength regions by using uniaxial films. We have found that the proposed configuration provides an excellent dark state by removing the phase dispersion between the visible wavelengths in all oblique directions. The proposed optical configuration consists of the horizontal-switching cell, two C-plates and an A-plate. Optimization of the optical configuration was performed on a Poincaré sphere with a spherical trigonometric method [10]. To verify the proposed optical configuration, we calculated its optical characteristics by the DiMOS program, which is supplied by autronic-MELCHERS Gmbh in Germany and uses a 4×4 matrix method. As a result, we found that the contrast ratio of the proposed configuration can be increased by about 10 times compared with the conventional S-IPS cell in the diagonal direction.

2. Light leakage of horizontal-switching LC cells due to the O-type polarizer in a diagonal direction in the dark state

There are several reasons for the light leakage of the horizontal-switching LC cell in the diagonal direction with oblique incidence. An important reason for the light leakage is the change in the effective angle of the two crossed O-type polarizers' absorption axes, which increases with the polar angle of the observation angle θ in the off-axes direction.

So the absorption axis of the polarizers deviates from normal incidence by angle $\pm\delta$. In the case of small birefringence (i.e. $|n_e - n_o| \ll n_e, n_o$), deviation angle δ in terms of ϕ_c, θ_c, θ_o and ψ can be described as below [11, 12]:

$$\delta = \psi - \arcsin\left\{\frac{\sin\phi_c\cos\phi_c\cos\theta_o - \cos\theta_c\sin\theta_o}{[1-(\sin\phi_c\cos\phi_c\cos\theta_o + \cos\theta_c\cos\theta_o)^2]^{1/2}}\right\}, \quad (1)$$

where ϕ_c and θ_c are the azimuth angle and the polar angle of the optical axis of the polarizer, θ_o is the polar angle of the incident light in the LC cell layer and ψ is the polarizer's angle in a normal direction. n_e and n_o represent the extraordinary and ordinary refractive index of the polarizer, respectively. Generally, θ_c is $\pi/2$. From equation (1), the deviation angle δ is maximized in the diagonal direction ($\phi_c = 45°$). We can also calculate the effective slow and fast axis of uniaxial films through equation (1). In general, the effective angle of the optical axis of the A-plate, including the LC cell, moves to δ from the angle of a normal incidence, as mentioned above. In the case of the positive C-plate, the effective fast axis moves to 90° with respect to the projected angle of the incident k vector.

The second factor is the change of retardation in each optical film. The effective retardation of the A-plate, two C-plates and the homogeneous LC cell in the oblique incident angle can be described as below [11]:

$$\Gamma_A = \frac{2\pi}{\lambda} d\left[n_e\left(1 - \frac{\sin^2\theta\sin^2\phi}{n_e^2} - \frac{\sin^2\theta\cos^2\phi}{n_o^2}\right)^{1/2} - n_o\left(1 - \frac{\sin^2\theta}{n_o^2}\right)^{1/2}\right], \quad (2)$$

$$\Gamma_C = \frac{2\pi}{\lambda}\frac{d}{\cos\theta_o}\left[\left(\frac{n_o^2 n_e^2}{n_o^2\sin^2\theta_o + n_e^2\cos^2\theta_o}\right)^{1/2} - n_o\right], \quad (3)$$

where Γ_A and Γ_C represent the retardation of the A-plate and the C-plate at the oblique incidence, respectively. d represents the thickness.

The last factor is caused by wavelength dispersion and material properties. In this paper we considered every factor which can induce phase dispersion between all wavelengths in the proposed configuration, in order to minimize light leakage in the dark state and to achieve an achromatic black state.

In general, the effective angle of the optical axis of the retarder in oblique incidence is also changed as the observation angle θ is changed. The effective angle of the optical axis of the A-plate including the LC cell will move to δ from the angle of a normal incident, as mentioned above. In the case of the positive C-plate, the effective fast axis moves to 90° with respect to the projected angle of the incident k vector.

3. Geometric design on Poincaré sphere

3.1. Polarizations of the conventional horizontal-switching LC cell

The conventional horizontal-switching cell consists of a homogeneous LC cell and two tri-acetyl-cellulose (TAC) films on crossed-polarizers as shown in figure 1(*a*). In principle, the optical axis of the LC cell is aligned parallel to the absorption axis of the input polarizer for the dark state and that of the

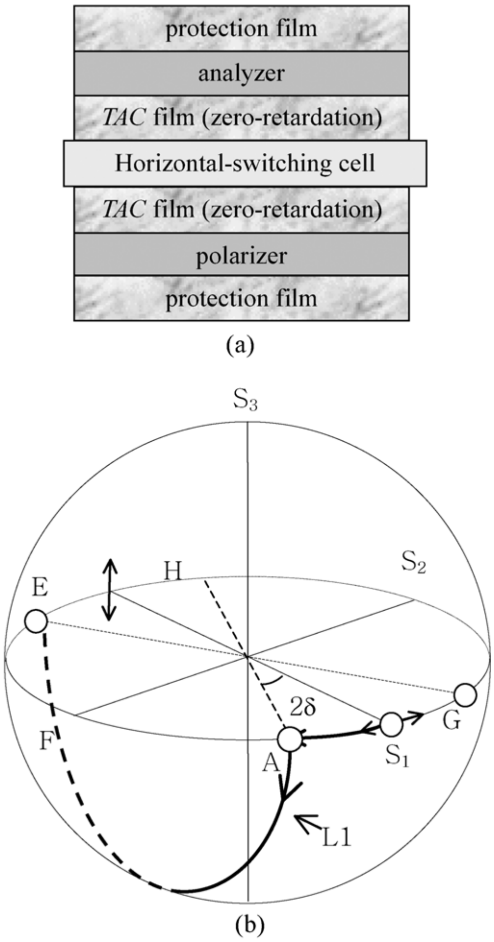


Figure 1. Optical configuration of the conventional horizontal-switching LC cell and polarization state of the oblique incident light in the LC cell; (*a*) optical structure (*b*) polarization path on the Poincaré sphere. L_1 represents the transfer path of the polarization by the cell in the bright state.

LC cell should move to 45° from the initial angle for the bright state. Generally, the recent TAC film does not have retardation.

Figure 1(*b*) shows the polarization state of the light obliquely passing through the cell in the diagonal direction on the Poincaré sphere. In the dark state, oblique incident light in the diagonal direction will has a deviated polarization angle δ compared with normal incident light, so that the polarization position of the polarizer will deviate by 2δ from S_1, which is the polarization state of the polarizer in a normal direction. Therefore, the start position of the oblique incident light is position A. The polarization of the light passing through the LC cell never changes because the optical axis of the LC cell is coincident with input polarizer. From the figure, the polarization state in front of the output polarizer A is quite different from the opposite position G of the output polarizer. Therefore, we can assume that the deviation between A and G will cause serious light leakage in the dark state. In the bright state, the optical axis of the LC cell will move to 45° from the initial state, so the polarization of the light passing through the LC cell will rotate to position H from the position E along the circle L_1 which is centred at point S_2. The optical axis of the cell in the bright state is never changed because the observation angle in azimuth angle is the same as the optical axis of the cell ($\phi_c = 45°$). Therefore, the polarization of the bright state H in front of the output polarizer is almost matched with the output polarizer E so that the light transmittance in the bright state of the conventional configuration can exhibit the relatively high transmittance. However, contrast ratio property of the cell is almost dependent on the dark state, so preventing the light leakage in the dark state will be the most important process for the optical design.

3.2. Polarizations of the proposed horizontal-switching LC cell

Compensation for phase dispersion with the oblique incident light can be achieved by adding several retarders to the conventional LC cell. The optical configuration of the proposed LC cell consists of a horizontal-switching LC cell with half-wave retardation, two C-plates, an A-plate and crossed polarizers coated with TAC film that has no retardation, as shown in figure 2. The A-plate is aligned perpendicular to the absorption axis of the input polarizer between the LC cell and the upper C-plate. An improved optical polarization path of the proposed LC cell for the dark state can be described on the Poincaré sphere as shown in figure 3(*a*). With oblique incidence, the polarization position of the input polarizer will

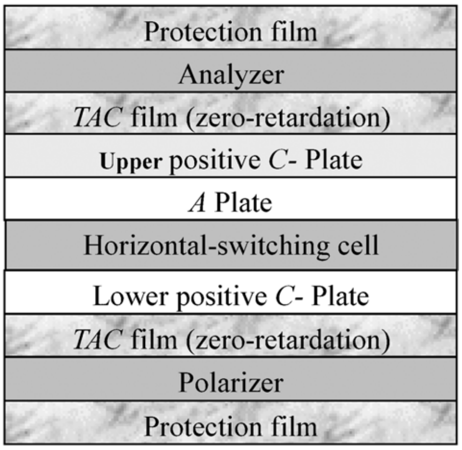
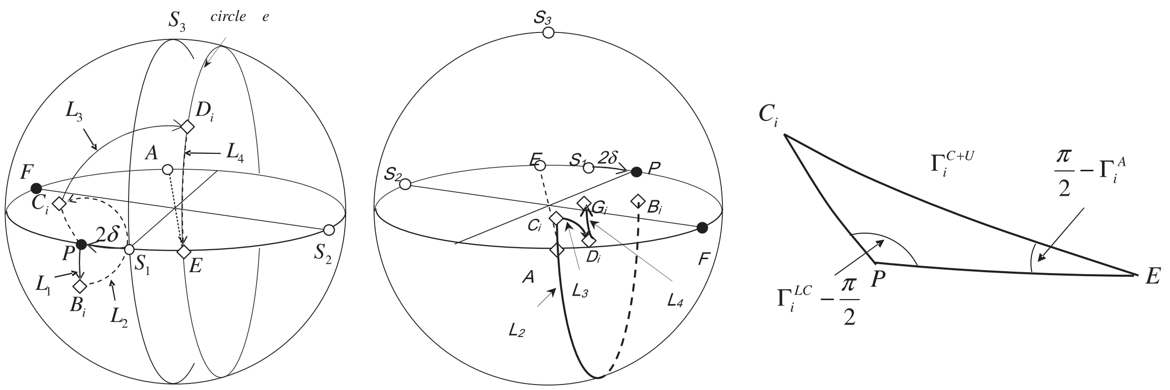


Figure 2. Optical configuration of the proposed horizontal-switching LC cell.

move to P with 2δ from S_1, which is its polarization position in a normal direction. Position A represents the position of the output polarizer. The polarization of the light passing through the lower C-plate moves to position B_i along the circle path L_1, which is centred at position F. Then, the polarization of the light approaches the position C_i along the circle path L_2 by the LC cell, which is centred at position P. Next, the polarization state rotates to D_i on circle e along the path L_3 by passing through the upper A-plate, which is centred at position A. Finally, the polarization state will rotate to position E along the path L_4 on circle $e$by passing through the upper C-plate. Position E is adjusted to exactly the opposite position of the polarization position A, which is the position of the output polarizer. Therefore, it clearly blocks light leakage in the dark state. In the bright state, the optical axis of the LC cell moves to 45° from the initial position. Polarization state of the light passing through the cell will move to position C_i along the path L_2. The circle path L_2 is centred at S_2 because the azimuth angle of the observation angle is parallel to the optical axis of the cell as shown in figure 3(*b*). Polarization position of the light moves to D_i along the circle path L_3 by passing through the A-plate, which is centred at position A. Finally, polarization of the light at point D_i rotates to G_i along the circle path L_4 by the C-plate. In the figure, polarization of the light in front of the output polarizer in the bright state is not adjusted to the position of the output polarizer, so that we can assume that light transmittance of the proposed configuration may be not superior to that of the conventional configuration. In contrast, the proposed configuration can provide an excellent dark state. As mentioned above, optical performance is strongly dependent on the optical property in the dark state. Therefore, it will induce the improvement in the optical viewing angle.

3.3. Optimization of the proposed horizontal-switching LC cell

In order to get an excellent dark state, polarizations of the entire wavelength should gather at point E the same way as shown in figure 3(*a*). Especially, gathering the polarization positions along all wavelengths to position E can be performed by optimizing the phase dispersion of the lower C-plate and the



(a) (b) (c)

Figure 3. Polarization states of the oblique incident light in the proposed cell on the Poincare sphere; (*a*) in the dark state, (*b*) in the bright state and (*c*) Trigonometric representation to remove the phase dispersion of the LC cell. L_1, L_2, L_3, L_4 represent the transfer path of the polarization by the lower C-plate, the LC cell, A-plate and the upper C-plate, respectively. Subscript i represent the wavelengths R, G and B.

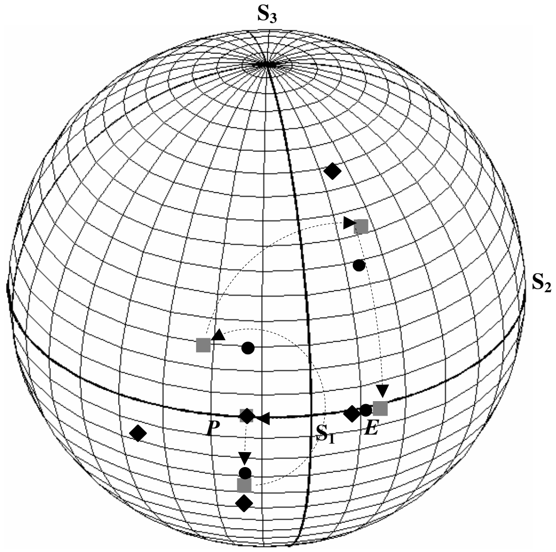


Figure 4. Calculated polarization states of the light passing through each retarder in the proposed LC cell on a Poincaré sphere ●, ■ and ◆ represent the polarization positions of red, green and blue wavelengths, respectively.

A-plate so that the polarization state of all wavelengths is on circle e, as shown in figure 3(a). Finally, gathering the light's polarization states at position E is done by optimizing the upper C-plate's phase dispersion. The process for optimizing the phase dispersion of the retarders to get an excellent dark state can be calculated by the trigonometric method on a Poincaré sphere, as shown in figure 4. Optimization of the optical configuration has been performed in the diagonal direction, $\phi = 45°$, because light leakage in the dark state is maximized at $\phi = 45°$.

The first step towards optimizing the retarders starts with the relationship, $\text{arc}(PB_i) = \text{arc}(PC_i)$. $\text{arc}(PB_i)$ is related only by the lower C-plate such as $\text{arc}(PB_i) = \sin^{-1}[\sin(\Gamma_i^{\text{L+C}})\cos 2\delta]$. Moreover, $\text{arc}(PC_i)$ can be described by the function of the phase dispersion of the LC cell, the upper A-plate and the upper C-plate by using the trigonometric method as below:

$$\sin[\text{arc}(PC_i)] = \sin\Gamma_i^{\text{C+U}} \frac{\sin[\pm(\pi/2 - \Gamma_i^{\text{A}})]}{\sin(\Gamma^{\text{LC}} - \pi/2)}, \qquad (4)$$

where $\Gamma_i^{\text{C+L}}$, Γ_i^{LC}, $\Gamma_i^{\text{C+U}}$ and Γ_i^{A} represent phase retardation of the lower C-plate, LC cell, upper C-plate and A-plate in each R, G and B wavelength, respectively. The Γ_i^{A} term's sign in equation (4) is decided by position C_i which depends on the phase retardation at each wavelength i. So the upper part of equator on the Poincaré sphere induces a positive sign and the lower part induces a negative sign. From equation (4), the relationship of phase retardation between the A-plate and the two C-plates for optimization can be calculated as below,

$$\Gamma_i^{\text{A}} = \pi/2 \pm \sin^{-1}[\sin(\pi/2 - \Gamma_i^{\text{LC}})\alpha_i \cos 2\delta], \qquad (5)$$

where $\alpha_i = \sin(\Gamma_i^{\text{C+L}})/\sin(\Gamma_i^{\text{C+U}})$. The A-plate obviously decides the path length of L_3. For the normal phase dispersion of the A-plate, therefore, a positive sign in equation (5) should be used for the B wavelength and a negative sign should be used for the G and R wavelengths. In addition, we can decide the dispersed retardation of the A-plate in each wavelength by using the dispersion ratio

Table 1. Calculated material dispersions and retardations of the upper A-plate and two C-plates.

	$\Delta n/\Delta n_(546\,nm)$		Δnd (nm)
	436 nm	633 nm	(546 nm)
Upper C-plate	1.04	0.91	138.66
Upper A-plate	1.13	0.97	106.73
Liquid crystal cell	1.09	0.98	318.72
Lower C-plate	1.13	0.98	61.94

$$\text{ratio}(i, j) = \frac{(\Delta nd)_i^{\text{A}}}{(\Delta nd)_j^{\text{A}}} = \frac{\lambda_i}{\lambda_j}\frac{\Gamma_i^{\text{A}}}{\Gamma_j^{\text{A}}}. \qquad (6)$$

Substituting Γ_i^{A} from equation (5) into equation (6) can make equation (6) a function of the parameter α_i. Therefore, once we decide the dispersion ratio ratio(i, j), we can calculate the optimized value of α_i from equation (6). Then we can decide the phase dispersion of the upper C-plate from the optimized parameter αi if we design the appropriate phase dispersion of the lower C-plate. The optimized phase dispersion of the A-plate Γ_i^{A} can be obtained from equation (5) with the optimized α_i. For example, we set the dispersion ratio between the wavelengths as ratio(B,G) = 1.134 and ratio(R,G) = 0.972 for the appropriate normal dispersion of the A-plate in this paper. From this we obtained the optimized parameters α_i; $\alpha_{\text{R}} = 0.49$, $\alpha_{\text{G}} = 0.45$ and $\alpha_{\text{B}} = 0.49$ from equation (6). In order to optimize the C-plate, we set the phase dispersion of the lower C-plate at normal dispersion as shown in table 1. From the optimized α_i and the phase dispersion of the lower C-plate, we can calculate the optimized phase dispersion of the upper C-plate as shown in table 1. Γ_i^{A} was obtained from equation (5).

3.4. Calculation and discussions

Figure 4 shows the calculated polarization state at the three wavelengths in the proposed configuration with optimized parameters of table 1 with the oblique incident light ($\phi = 45°$, $\theta = 70°$). From these figures we can observe that the polarization states of the R, G and B wavelengths successfully encounter the opposite position E of the output polarizer in the dark state, so an excellent contrast ratio can be expected. Figure 5 shows the calculated transmittance of the cell with the oblique incident light ($\phi = 45°$, $\theta = 70°$) in the dark and bright state. As shown in figure 5(a), transmittance of the proposed configuration in the bright state decreases 3–4% compared with conventional configuration. However, the proposed configuration can decrease the transmittance in the dark state significantly as shown in figure 5(b), so that it can show excellent viewing angle property even if the small decrease in the transmittance of the bright state takes place compared with the conventional cell. We verified the improved viewing angle of the proposed horizontal LC-cell using the helpful commercial LC software DiMOS instead of experiment because the experiment using optical films as shown in table 1

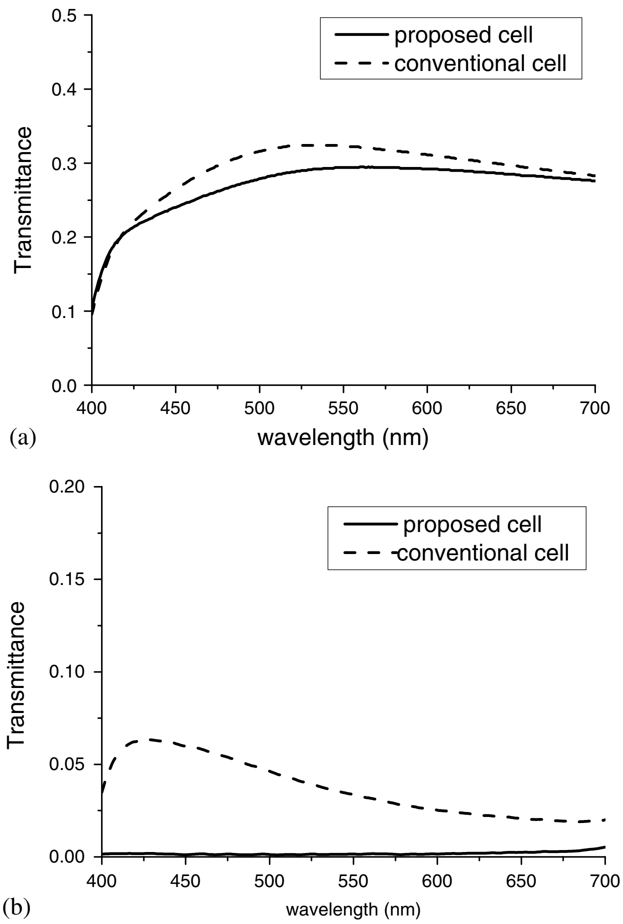


Figure 5. Comparison of optical transmittance of the proposed cell with that of the conventional cell; (*a*) in the bright state (*b*) in the dark state.

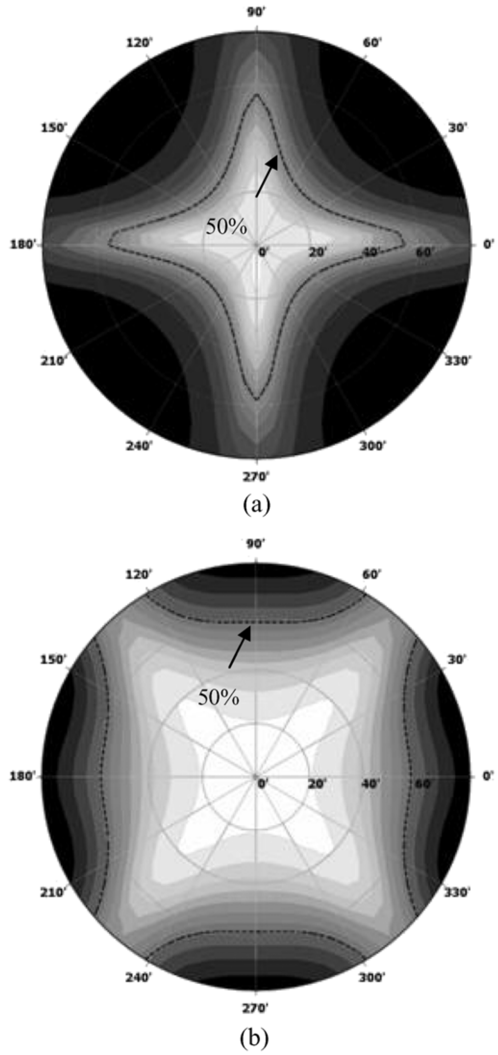


Figure 6. Normalized iso-contrast contour of the horizontal-switching cell. The dashed line represents the position of the half contrast ratio compared with the normal direction. (*a*) Conventional LC cell and (*b*) proposed LC cell.

needs a very long time to achieve the effective optical films. Figure 6 shows a comparison of the calculated iso-contrast graphs of the conventional configuration and the proposed configuration by the DiMOS software. We confirm that the minimum contrast ratio in the diagonal direction increased by about 10 times (3.9 [au] → 37.84 [au]) compared with the conventional LC cell in oblique incidence.

4. Conclusion

In conclusion, we propose a novel optical configuration of a horizontal-switching LC cell with an A-plate and two C-plates, which can improve the viewing angle in the diagonal direction. In order to compensate phase dispersion of the entire wavelength to achieve an excellent dark state, we optimized phase dispersion of the retarders by using spherical trigonometry on a Poincaré sphere. The calculation shows that the proposed configuration of the cell can provide excellent dark state even if it induces small decrease in the transmittance of the bright state. As a result, we found that the contrast ratio in the diagonal direction can be increased by 9.7 times by applying the proposed horizontal-switching LC cell.

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