Optimization of an optical configuration in a vertical alignment liquid crystal cell for wide viewing angle

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We propose an optical structure for a vertical alignment (VA) liquid crystal (LC) cell with a wide viewing angle. The proposed LC cell consists of an *A*-plate and two *C*-plates for optical compensation. Optical compensation and optimization to eliminate off-axis light leakage in the entire visible wavelength range are performed on a Poincaré sphere using the Stokes vector and the Muller matrix method. After optimizing the wavelength dispersion of the retardation films that are used, we prove that the proposed VA LC cell can improve the viewing angle and contrast ratio by calculating optical characteristics, particularly in diagonal directions.

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1. Introduction

Generally, an optically wide viewing property for display devices on all azimuth angles is very important for high quality displays such as monitors and TVs. In order to achieve high optical performance, many display modes, such as vertical alignment (VA) [1], in-plane switching [2], and fringe field switching [3], have been developed. In particular, the VA liquid crystal (LC) mode is applied in many advanced display devices because it yields an excellent contrast ratio in the normal direction due to zero phase retardation in that direction. However, the optical performance of the VA LC cell in the oblique direction deteriorates for several reasons, including changes in the polarization axis of the polarizer or changes in the phase retardation of the cell and the films used, particularly in the diagonal direction [4,5]. Light leakage in the oblique incidence can cause a serious decrease in the contrast ratio, especially in the dark state. In order to achieve better off-axis image quality, several LC configurations using compensation films in the VA LC cell have been proposed. For example, Chen *et al.* have also shown an optical configuration using two biaxial films in order to improve optical characteristics [5]. Ohmuro *et al.* showed optical compensation by using a combination of an *A*-plate and two negative *C*-plate films [6]. In addition, Hong *et al.* also proposed an optical configuration VA LCD with a wide viewing angle by using two *A*-plates and two *C*-plates [7]. However, the optical configuration by Ohmuro *et al.* did not show excellent isocontrast contours, and the optical configurations by Chen *et al.* and Hong *et al.* considered the optimization at a single wavelength, so they did not show the optimization in the visible wavelength range.

We introduce another optical configuration for the VA LC cell, which can effectively eliminate light leakage in the oblique direction for a wide viewing angle. The proposed VA LC cell consists of an *A*-plate and two *C*-plates between crossed polarizers to achieve an excellent achromatic black level in diagonal directions. In general, light leakage through the crossed polarizers in the oblique incidence is maximized at the polar angle $\theta = 70°$ and the azimuth angle $\phi = 45°$ [8–10]. Therefore, we optimized the optical configuration of the proposed VA LC cell, particularly in

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the diagonal direction, in order to minimize the light leakage of the cell in the dark state. Optimization of the optical compensation films in the entire visible wavelength range in the dark state was performed on a Poincaré sphere [11–13] in order to achieve the optimized dispersion properties of each used film to get an excellent dark state. We compared the calculated optical properties of the proposed LC cell to the optical characteristics of the conventional LC cell to verify the outstanding optical characteristics of the proposed VA LC cell.

2. Off-Axis Light Leakage in the Dark State

Light leakage in the dark state at oblique incidence could occur for several reasons. One reason is the shift of the polarization axis of the polarizer and the optical axis of the optical film in oblique incidence. This is dependent on the observation angle θ in an off-axis direction. Thus, the effective principal axis of the optical components deviates from the principal axis in the normal incidence by angle δ. In terms of the polarizers, if we apply the very small birefringence approximation ($n_e \approx n_o$), the deviation of the azimuth angle δ from δ_o can be described as below [10]:

$$\sin(\delta - \delta o) = -\frac{\sin 2\phi_c \sin^2(\theta_o/2)}{\sqrt{1-(\sin\phi_c \sin\theta_o)^2}}, \qquad (1)$$

where ϕ_c is the azimuth angle of the polarization axis of the polarizer and θ_o is the polar angle of the incident light in the LC layer. n_e and n_o represent the extraordinary and the ordinary refractive indices of the polarizer and retardation film, respectively. δ_o represents the angle between the polarization axis of the polarizer and the x axis at normal direction. From Eq. (1), the deviation angle $\Delta\delta = (\delta - \delta_o)$ is maximized in the diagonal direction ($\phi = 45°$). Regarding the optical axis of the optical film, the effective angle of the optical axis of the retarder in oblique incidence is changed as a function of observation angle θ. We can also calculate the effective optical axis of the A-plate through Eq. (1). Thus, the optical axis of the A-plate moves as much as the deviation angle $\Delta\delta$ from the optical axis in the normal incidence. In the case of the C-plate and VA LC cell, the effective fast or slow axis moves to 90° with respect to the projected angle of the incident k vector.

The second factor is a change in the retardation value of the compensation film in the oblique incidence. The effective retardation of the A-plate, C-plate, and VA LC cell in the oblique incident angle can be described as [14,15]

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

$$\Gamma_C = \frac{2\pi}{\lambda} n_o d\left(\sqrt{1-\frac{\sin^2\theta}{n_e^2}} - \sqrt{1-\frac{\sin^2\theta}{n_o^2}}\right), \qquad (3)$$

where Γ_A and Γ_C represent the phase retardation of the A-plate and the C-plate at the oblique incidence, respectively. θ represents the polar angle of the incident light in free space, and ϕ is the azimuth angle of the incident angle. d represents the thickness of the film, and λ represents the wavelength of the incident light.

The last issue is the dispersion of the refractive index of the optical components along the wavelength [16]. In general, the dispersion is also dependent on the material property. The polarization states of the three primary colors (R, G, and B) usually differ from one another after passing through the LC cell and the retardation films because of the different material and wavelength dispersion properties. Therefore, to minimize light leakage at the oblique incidence in the dark state, the phase dispersion in the entire visible wavelength should be eliminated.

3. Optical Principle and Optimization of the Proposed VA LC Cell

A. Polarization States in the Conventional VA LC Cell

A conventional VA LC cell comprises a VA LC layer and two crossed polarizers, as shown in Fig. 1(a). The LC director in the VA LC cell is vertically aligned to the substrate in the electric off state. We assume that the optical axis of the VA LC cell in the absence of an electric field is the same as the optical axis of the positive C-plate. Figure 1(b) shows the polarization state of the light on the Poincaré sphere when the light obliquely passes through the cell in the diagonal direction. In the dark state, the oblique incident light experiences the deviated angle δ compared to the normal incidence when it passes the polarizer. Therefore, the position of the polarization axis of the polarizer will deviate by 2δ from S_1, which is the polarization state of the polarizer in a normal direction on the Poincaré sphere. Therefore, the start polarization position in the oblique incidence becomes position A. The polarization state of the light after passing through the VA LC with a position of the fast axis Q is rotated to polarization position B along the circle path P_1. Here, polarization position B is quite different from polarization position H, which is the perfect opponent position of the polarization axis of the analyzer in the oblique incidence. Therefore, we can assume that the large deviation between position B and position H will induce a serious off-axis light leakage in the dark state.

B. Polarization States in the Proposed VA LC cell

Optical compensation for the deviated polarization occurring in the oblique incidence can be achieved by adding several retardation films to the conventional LC cell. Figure 2(a) shows the proposed optical

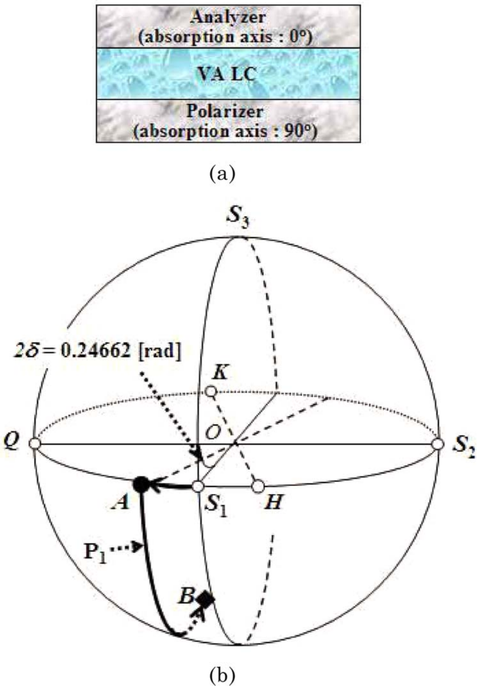


Fig. 1. (Color online) Optical configuration of the conventional VA LC cell and polarization states in the oblique incidence: (a) optical structure and (b) polarization path on the Poincaré sphere in the oblique incidence.

configuration of the VA LC cell that can improve the viewing angle performance. The optical configuration of the proposed LC cell consists of a positive *A*-plate, a positive *C*-plate, and a negative *C*-plate. The optical axis of the *A*-plate is aligned with the absorption axis of the incident polarizer. An improved optical polarization path of the proposed LC cell is described on the Poincaré sphere, as shown in Fig. 2(b).

Like the conventional VA LC cell, the start position in the oblique incidence ($\theta = 70°$ and $\phi = 45°$) on the Poincaré sphere is position A when the light passes through the polarizer. Then, the polarization state of the light passing through the positive *C*-plate moves to position B along the circle path P_1, centered at the point Q. The polarization position of the light moves to position C along the circle path P_2 after passing through the positive *A*-plate, which has a position K for the optical axis. Then, The polarization of the light passing through the VA LC layer moves to position D along circle path P_3 with a centered position Q. Finally, the polarization state of the light passing through the negative *C*-plate rotates in the reverse direction to proceed to position H along path P_4. The position H in front of the analyzer is exactly matched to the opponent position K of the analyzer. Therefore, the process of the proposed optical configuration can effectively move the polarization position of the light passing through the cell to the desired position, which should be the opponent position of the polarization axis of the analyzer in the oblique incidence so that it can clearly eliminate the off-axis light leakage in the dark state.

C. Optimization of Optical Films in the Proposed VA LC Cell

For the optimal dark state, it is necessary to consider phase dispersion of the LC cell because the proposed configuration should satisfy the optical process in the entire visible wavelength range, as mentioned above. This implies that the polarization state of the light in the entire visible wavelength range should move to position H in front of the analyzer, as shown in Fig. 2(b). From this process, we can optimize the retardation value of the compensation films for the perfect achromatic black state. Figure 3 shows the optical principle of the proposed VA LC cell on how to remove the phase dispersion through wavelengths R (630 nm), G (550 nm), and B (450 nm) on the Poincaré sphere. The symbol ○ represents the polarization state of the light with the red wavelength, □ represents the polarization state with the green wavelength, and ◇ represents the polarization state with the blue wavelength. Here, we need to satisfy two conditions to gather the polarization positions of the entire visible wavelength to position H.

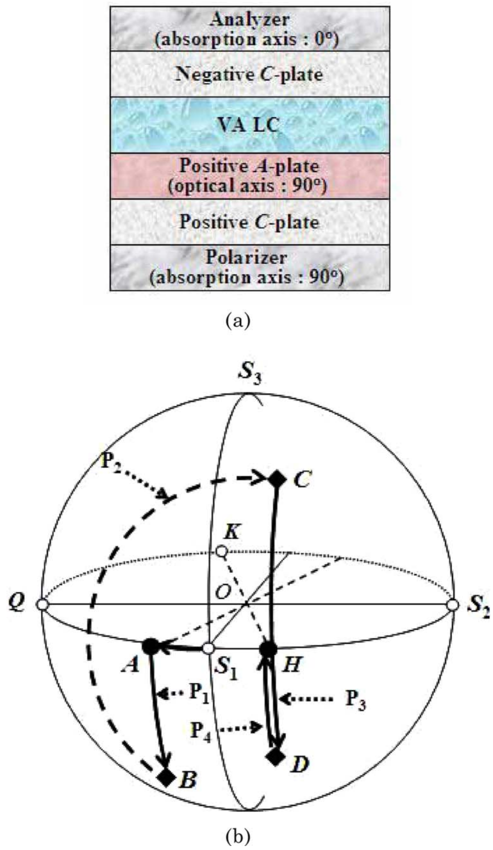


Fig. 2. (Color online) Optical configuration of the proposed VA LC cell and polarization states in the oblique incidence: (a) optical structure and (b) polarization path on the Poincaré sphere in the oblique incidence.

$$S' = R(-2\theta)\cdot M(\Gamma)\cdot R(2\theta)\cdot S(C+)$$
$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta + \cos\Gamma \sin^2 2\theta & (1-\cos\Gamma)\sin 2\theta \times \cos 2\theta & \sin\Gamma \times \sin 2\theta \\ 0 & (1-\cos\Gamma)\sin 2\theta \times \cos 2\theta & \sin^2 2\theta + \cos\Gamma \cos^2 2\theta & -\sin\Gamma \times \cos 2\theta \\ 0 & \sin\Gamma \times \sin 2\theta & \sin\Gamma \times \cos 2\theta & \cos\Gamma \end{pmatrix} \begin{pmatrix} S_{0_{C+}} \\ S_{1_{C+}} \\ S_{2_{C+}} \\ S_{3_{C+}} \end{pmatrix} = \begin{pmatrix} S_0{}' \\ S_1{}' \\ S_2{}' \\ S_3{}' \end{pmatrix}, \quad (5)$$

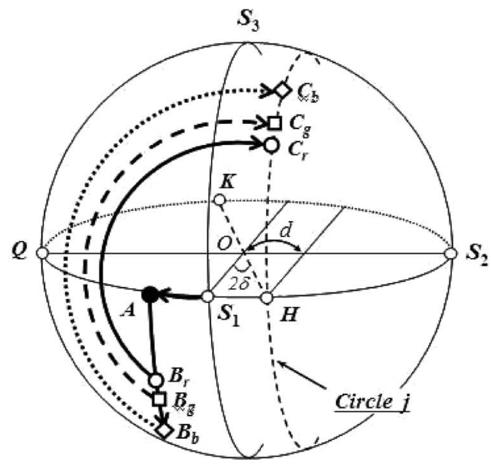
The first condition is that the polarization positions for the R, G, and B wavelengths after passing through the positive C-plate and positive A-plate should be on the circle j, which has polarization positions C_r, C_g, and C_b, respectively, as shown in Fig. 3(a). This condition can permit the polarization positions of the light in the entire visible wavelength range to gather at the opponent position of the polarization axis of the analyzer at the oblique incidence.

For the calculation, we assume that the positive C-plate has normal wavelength dispersion in which retardation decreases in proportion to the increase in wavelengths. A practical example of the dispersion of the refractive index of the positive C-plate is shown in Table 1. Therefore, the polarization positions of the R, G, and B wavelength light passing through the positive C-plate can be described as B_r, B_g, and B_b, as shown in Fig. 3(a). The polarization position of each wavelength light moves to positions C_r, C_g, and C_b by passing through the A-plate. Here, numerical description of the circle j is simply expressed as $S_2 = d$, as shown in Fig. 3(a). Therefore, once we can know the S_2 value d, we can calculate the retardation value of the A-plate in each wavelength to move the polarization state of the light passing through the positive C-plate to the polarization positions B_r, B_g, and B_b on the circle j. Regarding the oblique angle $\theta = 70°$ and $\phi = 45°$, the deviation angle δ is calculated as 0.12331 rad. In this case, the value d of the S_2 axis can be simply described as $d = \sin 2\delta$, so that we can calculate the d value as 0.24413 rad. From this calculated value d, we could find the optimum retardation value of the positive A-plate on a Poincaré sphere using the Muller matrix and the Stokes vector [13,17]. Generally, the four Stokes parameters can be written as

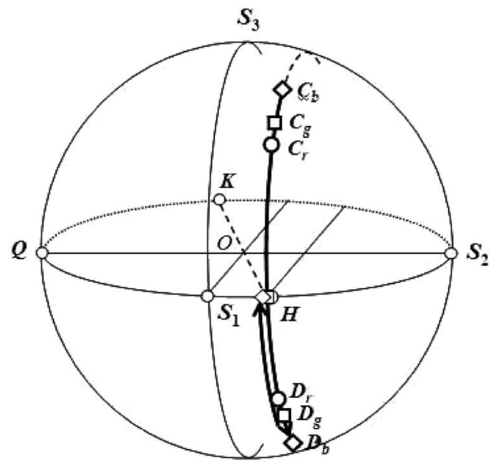
$$S = (S_0, S_1, S_2, S_3)^T. \quad (4)$$

The Stokes parameters of the light for three wavelengths after passing through the A-plate can be described as follows:

where $R(2\theta)$ and $R(-2\theta)$ are the rotating matrix and reverse rotating matrix to the principal axis. $M(\Gamma)$ represents the Muller matrix for rotated polarizing components with phase retardation Γ. $S(C+)$ is



(a)



(b)

Fig. 3. Polarization state of the light for wavelengths R, G, and B on the Poincaré sphere: (a) polarization states of the light passing through the A-plate and positive C-plate and (b) polarization states of the light passing through the VA LC layer and negative C-plate.

Table 1. Calculated Optimized Dispersion Properties of the Optical Anisotropy of the Optical Films

	$\Delta n/\Delta n$ (550 nm)		Δnd (nm)
	450 nm	630 nm	550 nm
Positive C-plate	1.064	0.973	131.40
Positive A-plate	0.866	1.104	226.11
Negative C-plate	1.061	0.946	–155.22

the Stokes vector of the incident light after passing through the positive C-plate, and S' represents the Stokes vector of the output light. S_{0C+}, S_{1C+}, S_{2C+}, and S_{3C+} are the Stokes polarization parameters of the Stokes vector $S(C+)$.

In the proposed configuration, θ for the A-plate is $90° + \delta$ and S_{2C+} values in each R, G, and B wavelength are –0.24413. By using the calculated value, we can calculate the retardation value Γ in each wavelength in order to move the polarization state of the light passing through the A-plate on the circle j on the Poincaré sphere.

The second condition for optimization is to determine the retardation of the negative C-plate. The final positions of the polarization state of the light passing through wavelengths R, G, and B should coincide with the same position H. Therefore, we can put the polarization positions of the light in the entire visible wavelength range by controlling the retardation value of the negative C-plate. The process for the optimization on the Poincaré sphere is illustrated in Fig. 3(b). This shows the polarization states of the light passing through the VA LC and the negative C-plate. To get an achromatic color performance in the dark state, the polarization state of the light after passing through the negative C-plate must move together from D_r, D_g, and D_b to H, which is the desired final destination of the tristimulus light for the perfect dark state. The Stokes vector of point H is $(1, 0.96974, 0.24413, 0)^T$, so we can easily calculate the retardation value of the negative C-plate by using the Muller matrix method.

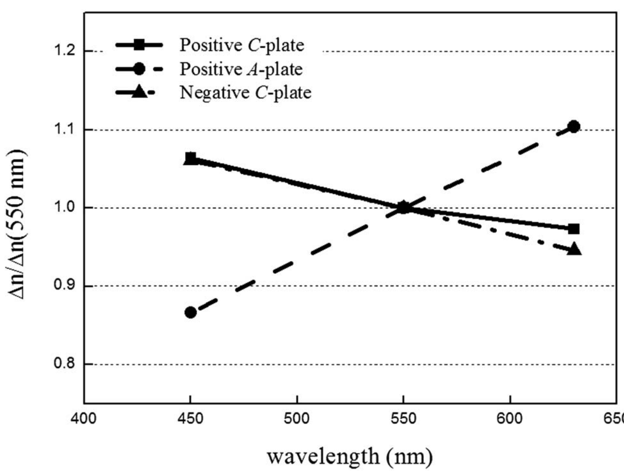


Fig. 4. Calculated optimized optical anisotropy of the optical films.

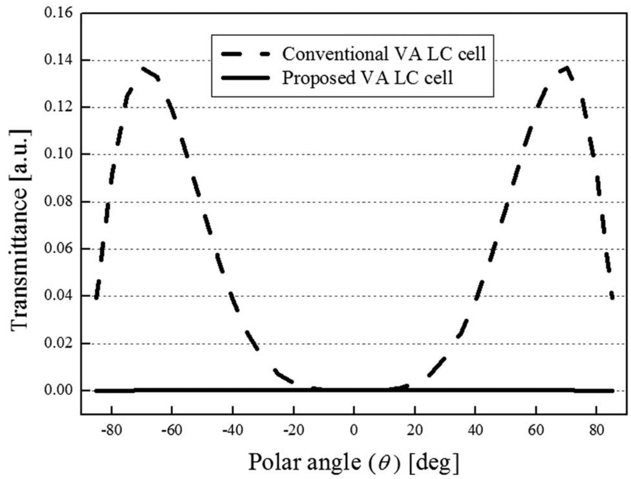


Fig. 5. Comparison of the transmittance between the proposed VA LC cell and the conventional VA LC cell as a function of the polar angle at $\phi = 45°$ in the dark state.

D. Calculated Results of Optical Performance

Table 1 shows the calculated optimized retardation values of three compensation films for the R, G, and B wavelengths. In this calculation, we set the dispersion property of the LC as $\Delta n(\lambda = 450\,\text{nm})/\Delta n(\lambda = 550\,\text{nm}) = 1.04$ and $\Delta n(\lambda = 630\,\text{nm})/\Delta n(\lambda = 550\,\text{nm}) = 0.98$. Cell gap d for the calculation was set to 4.2 μm, and $\Delta nd(\lambda = 550\,\text{nm})$ is 315.4 nm. In terms of the material dispersion, we recognize that the positive A-plate should have a reverse dispersion and the negative C-plate should have a normal dispersion property to achieve an excellent dark state. Figure 4 shows the calculated dispersion property of the optical anisotropy of the used optical films. From Fig. 4, we observed that the calculated result of the used films can show material feasibility for a practical approach to the display device because all the optical films we designed are practically possible to realize [18]. Based on these calculated results, we compared the optical transmittance of the proposed VA LC cell with the conventional VA LC cell for the dark state in the diagonal direction in visible wavelength range, as shown in Fig. 5. From Fig. 5, we observed that the proposed configuration effectively eliminates the off-axis light leakage in the dark state compared to the conventional LC cell. We verified the improved viewing angle of the proposed VA LC cell by using commercial LC software *TechWiz LCD* by Sanayi System Company, Incheon, South Korea instead of performing experiments because each optimized film requires a very long time to be supported. Figure 6 shows the comparison of the luminance of the proposed LC cell to the luminance of the conventional LC cell in the dark state. Figure 7 compares the normalized isocontrast contour of the conventional configuration with the proposed configuration. From the calculated results in Figs. 6 and 7,

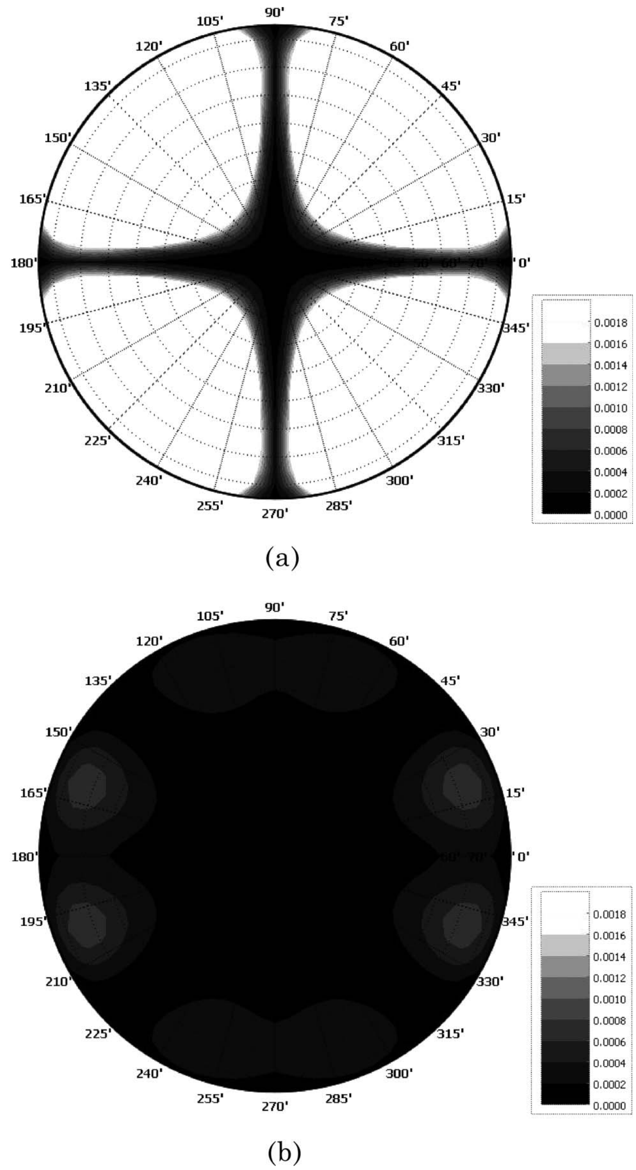


Fig. 6. Calculated luminance in the dark state: (a) conventional and (b) proposed VA LC cell.

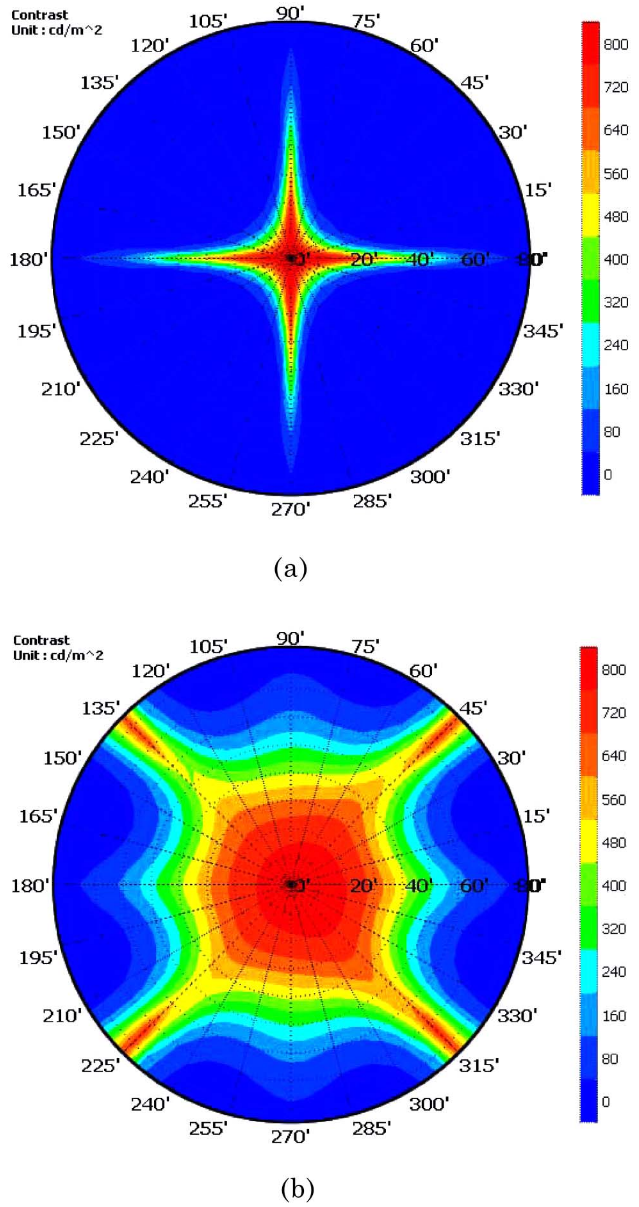


Fig. 7. (Color online) Calculated normalized isocontrast contour: (a) conventional and (b) proposed VA LC cell.

we confirmed that the proposed VA LC cell effectively eliminates light leakage in the dark state so that the off-axis contrast ratio of the proposed LC cell can increase far beyond that of the conventional LC cell in calculations.

4. Conclusions

We propose an optical configuration of a VA LC cell with an *A*-plate and two *C*-plates. In order to compensate for phase dispersion of the entire visible wavelength and to achieve an excellent dark state, we optimized phase dispersion of the compensation films using the Stokes vector and the Muller matrix on the Poincaré sphere. Numerical calculations show that the proposed structure has wide viewing angle characteristics by compensating for light leakage in diagonal directions.

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