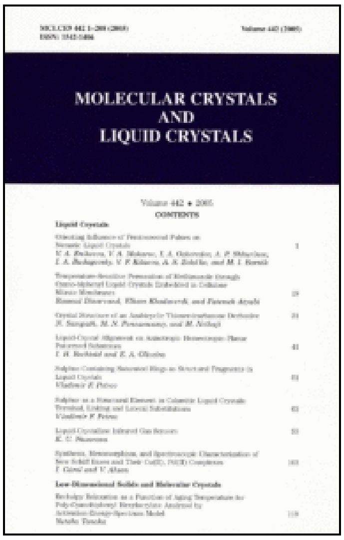

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Optical Compensation of Circular Polarized High-Transmittance Vertically Aligned Liquid Crystal Displays

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Optical Compensation of Circular Polarized High-Transmittance Vertically Aligned Liquid Crystal Displays

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In this paper we propose an optical configuration for the vertical alignment liquid crystal cell with circular polarizer that can realize a wideband and wide viewing angle properties. We expect that the high optical properties will be obtained by using two biaxial films, a quarter-wave plate and a negative C*-plate. The proposed optical configuration was performed on the Poincaré sphere using the Stokes vector and the Muller matrix method. We also compared the improved optical characteristics of the proposed configuration with the conventional configuration in oblique direction.*

Keywords Circular polarizer; color shift; liquid crystal; Poincaré sphere; vertical alignment; wide viewing angle

1. Introduction

Recently, many researches have been conducted to enhancing the optical performance in the liquid crystal display (LCD) industry [1,2]. Especially, optical properties such as high contrast ratio, high transmittance and wide viewing angle are required for various LCD modes. The vertical alignment (VA) LCD using a linear polarizer shows an excellent contrast ratio in normal viewing direction. However, the VA mode using a linear polarizer exhibits a low brightness because the transmittance is relatively lower than that of VA mode using circular polarizer, and the light leakage of dark state is causing problems about contrast ratio in the oblique direction. Presently, the VA LCD mode using circular polarizer can realize a high transmittance [3], but the conventional circular polarizer consisting of two quarter-wave plates significantly debase the viewing angle property at the off-axis direction [4].

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Therefore, there is an important need for circular polarizer for high optical performance that could considerably improve the viewing angle property of LCD using VA mode. In this paper, we introduce an optical configuration consisting of the two biaxial films, a quarter-wave plate and a negative C-plate. This configuration can obtain a wide viewing angle property by eliminating light leakage in the oblique direction. The optimization of the above optical compensation films was performed on the Poincaré sphere [5–7] to obtain the optimized dispersion properties of each used film to get an excellent dark state in the entire visible wavelength. We also compared the optical properties of the proposed configuration with that of the conventional configuration to verify the excellent optical characteristics of the proposed configuration.

2. Light Leakage in the Conventional VA LC Cell with Circular Polarizer in the Oblique Direction

Light leakage in the dark state at the oblique direction results from several reasons. First, it is the shift of the polarization axis of the polarizer and optical axis of the optical film as a function of the observation direction (the polar angle θ and the azimuth angle φ). The effective principle axis of the optical components deviates from the principle axis in the normal direction by angle δ [8]. The change in the retardation value of the compensation film in the oblique direction may also be another factor. The effective retardation value Γ in each optical film as a function of the polar θ and the azimuth angle φ of the incident angles can be easily calculated by using the extended 2×2 Jones matrix method [9–11]. The last factor for light leakage is the dispersion of the refractive index of the optical films along the wavelength [12,13]. The conventional VA liquid crystal (LC) cell with circular polarizer comprises two crossed linear polarizers, VA LC layer and two quarter-wave plates, as shown in Figure 1(a). In this paper, we assume that the optical axis of the vertically aligned LC layer is the same as the optical axis of the positive C-plate when the driving voltage is zero. Figure 1(b) presents the polarization state of the light on the Poincaré sphere when the light passes through the cell in the normal direction. The symbols ◆, ■, and ● respectively represent the polarization state of the light with blue ($B = 450$ nm), green ($G = 550$ nm), and red wavelengths ($R = 630$ nm). The optical components including VA LC layer are not affected by any deviated angle δ and phase retardation Γ in the normal viewing direction. Therefore, the starting point is at position S_1, where the light normally passes through the linear polarizer. Then, the polarization state of the light after passing through the lower quarter-wave plate move to positions Ar, Ag, and Ab which has a circular polarization. The polarization state of the light after passing through the VA LC layer and upper quarter-wave plate moves to position S_1, which is not only the polarization state of the polarizer but also the absorption axis of the analyzer in the normal direction. This means that the conventional VA LC cell with circular polarizer shows a perfect dark property atnormal incidence. However, the conventional VA LC cell with circular polarizer exhibits a light leakage at the oblique direction. Figure 1(c) represents the polarization state of the light when the light obliquely passes through the cell. The polarization state of the obliquely-incident light experiences a deviated angle δ in the dark state when it passes the linear polarizer. Therefore, the position of the polarization axis of the linear polarizer deviates by 2δ from S_1 on the Poincaré sphere. The start polarization position at the oblique incidence

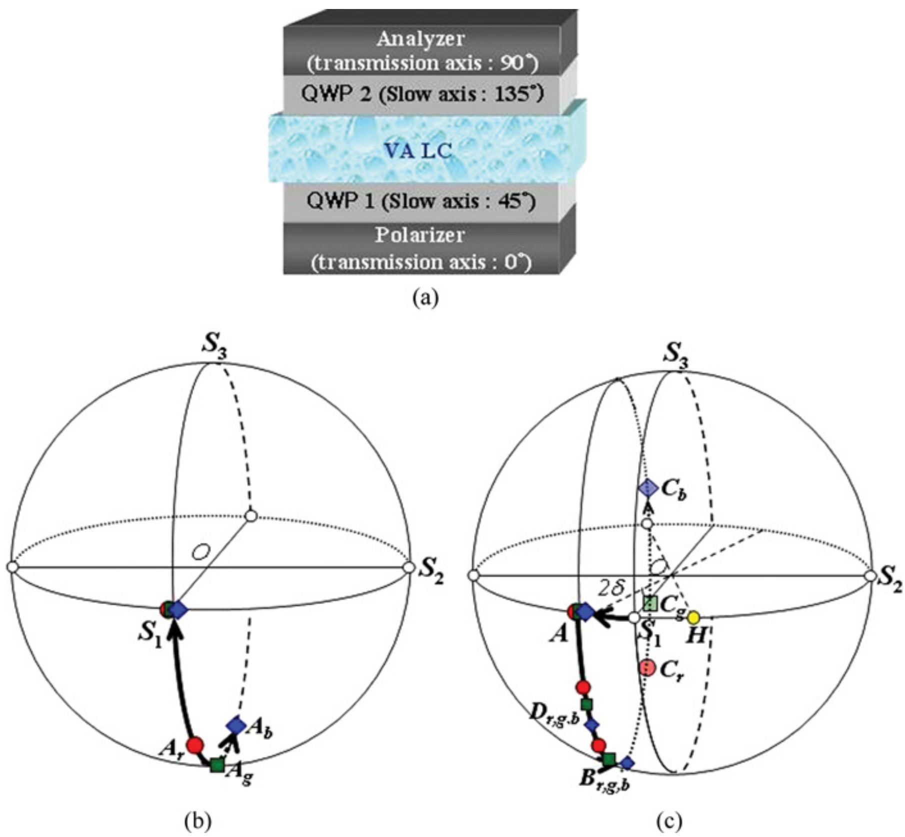


Figure 1. Optical configuration and polarization states of the conventional configuration: (a) optical structure (b) polarization path on the Poincaré sphere in the normal direction and (c) in the diagonal direction. (Figure appears in color online.)

becomes position A. The polarization positions of the light after passing through the two quarter-wave plates and the VA LC layer move to position Dr, Dg, and Db, respectively, because of the phase dispersion of the optical components. The subscript of the letter expresses Red, Green and Blue wavelengths. Here, the polarization positions Dr, Dg, and Db are quite different from the polarization position H, which is the position of the absorption axis of the analyzer in the oblique incidence. Thus, we can see that the large difference between positions Dr, Dg, and Db and position H will cause a serious off-axis light leakage in the dark state.

3. Advanced VA LC Cell with Circular Polarizer for Improving the Optical Properties in the Oblique Incidence

In order to minimize light leakage and color shift at the oblique incidence, we applied several optical compensation films to the conventional VA LC cell. Figure 2(a) shows the proposed optical configuration of the VA LC cell with two biaxial films ($n_x > n_z > n_y$) with $N_z = 0.5$, where $N_z = (n_x - n_z)/(n_x - n_y)$, a negative C-plate ($n_x = n_y > n_z$) and a $\lambda/4$ positive A-plate ($n_x > n_y = n_z$) with its slow axis

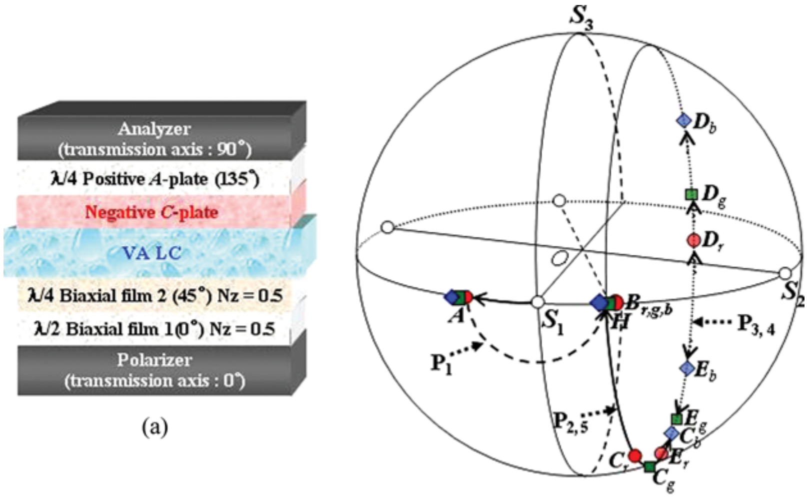


Figure 2. Optical configuration and polarization states of the proposed configuration: (a) optical structure (b) polarization path on the Poincaré sphere in the diagonal direction. (Figure appears in color online.)

parallel to the transmission axis of the incident linear polarizer. The optical polarization path is described on the Poincaré sphere when the light passes through the proposed configuration in the diagonal direction, as shown in Figure 2(b). The start position in the oblique incidence ($\theta = 70^{\circ}$ and $\phi = 45^{\circ}$) is position A when the light passes through the linear polarizer. Then, the polarization state of the light passing through the $\lambda/2$ biaxial film moves to position B along the circle path P_1. The polarization position B moves to position C along the circle path P_2 after passing through the $\lambda/4$ biaxial film. Then, the polarization position moves to positions D and E along the circle path P_3 and P_4 after passing through the VA LC layer and the negative C-plate, respectively. Finally, the polarization position of the light passing through the $\lambda/4$ positive A-plate rotates to position H along circle path P_5. Therefore, a excellent dark state can be obtained in the oblique incidence because the position H in front of the analyzer is precisely corresponded to the opposing position of the polarization axis of the analyzer. In order to achieve the optimal dark state in the oblique incidence, the following two conditions for the polarization states of the light should be satisfied, as shown in Figure 2(b). In this paper, we do not manage the material property of the VA LC, and we optimize the optical configuration in the diagonal direction ($\theta = 70^{\circ}$ and $\phi = 45^{\circ}$) because the off-axis light leakage can be maximized under this condition [8]. The first condition is that the polarization positions for the R, G and B wavelengths after passing through the $\lambda/2$ biaxial film should be at the position H. In order to satisfy the first condition, first, we assume that the $\lambda/2$ biaxial film has a reverse wavelength dispersion, in which rerardation increases in proportion to an increase in wavelength and then we use the $\lambda/2$ biaxial film having Nz factor 0.5 because optical axis orientation has no viewing angle dependence [14]. Here, the arc length is dependent on its in-plane phase retardation value $d(n_x - n_y)$, where d is the thickness and $(n_x - n_y)$ is the in-plane birefringence of the $\lambda/2$ biaxial film. The second condition for optimization is to determine the retardation value of the negative *C*-plate. We can easily calculate the retardation value of the negative *C*-plate by using the Muller matrix and the Stokes vector [5,6]. Generally, the four Stokes parameters can be written as

$$S = (S_0,\ S_1,\ S_2,\ S_3)^T \tag{1}$$

The Stokes parameters of the light for the three primary wavelengths after passing through the negative *C*-plate can be depicted as follows:

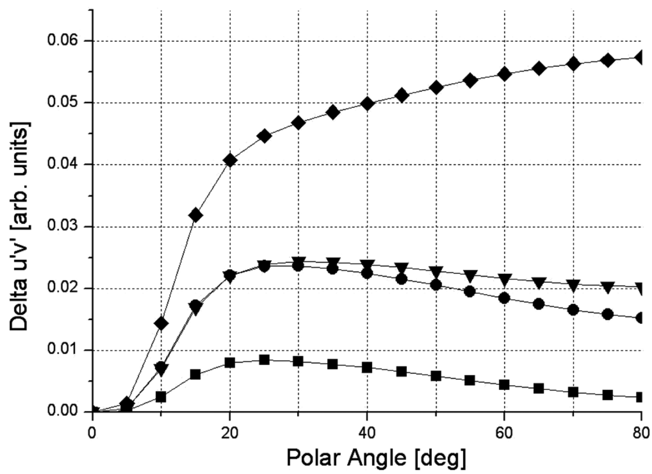
$$\begin{aligned} S' &= R(-2\theta)\cdot M(\Gamma)\cdot R(2\theta)\cdot S(LC) \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta + \cos\Gamma\sin^2 2\theta & (1-\cos\Gamma)\sin 2\theta\cos 2\theta & \sin\Gamma\sin 2\theta \\ 0 & (1-\cos\Gamma)\sin 2\theta\cos 2\theta & \sin^2 2\theta + \cos\Gamma\cos^2 2\theta & -\sin\Gamma\cos 2\theta \\ 0 & \sin\Gamma\sin 2\theta & \sin\Gamma\cos 2\theta & \cos\Gamma \end{pmatrix} \\ &\quad\times \begin{pmatrix} S_{0\,LC} \\ S_{1\,LC} \\ S_{2\,LC} \\ S_{3\,LC} \end{pmatrix} \begin{pmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{pmatrix}, \end{aligned} \tag{2}$$

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. $S(LC)$ is the Stokes vector of the incident light after passing through the VA LC layer, and S' represents the Stokes vector of the output light. S_{0LC}, S_{1LC}, S_{2LC}, and S_{3LC} are the Stokes polarization parameters of the Stokes vector $S(LC)$. In order to eliminate the phase retardation of the VA LC layer, the polarization position of the light after passing through the negative *C*-plate should be located in the position *E* for the three primary wavelengths, as shown in Figure 2(b). Here, the Stokes vector of position *E* is $(1, -0.4133, 0.245, -0.877)^T$, so we can easily obtain the retardation value of the negative *C*-plate by using the Muller matrix method. Table 1 shows the calculated optimized retardation values of the four compensation films for the *R, G*, and *B* wavelengths. In this calculation, we set the dispersion property of the VA LC as $\Delta n(\lambda = 450\,\text{nm})/\Delta n(\lambda = 550\,\text{nm}) = 1.06$ and $\Delta n(\lambda = 630\,\text{nm})/\Delta n(\lambda = 550\,\text{nm}) = 0.97$. The cell gap *d* was set to 3.4 µm for the calculation. In respect to the material dispersion, we can recognize that the $\lambda/4$ biaxial film should have a flat dispersion and the negative *C*-plate and the $\lambda/4$

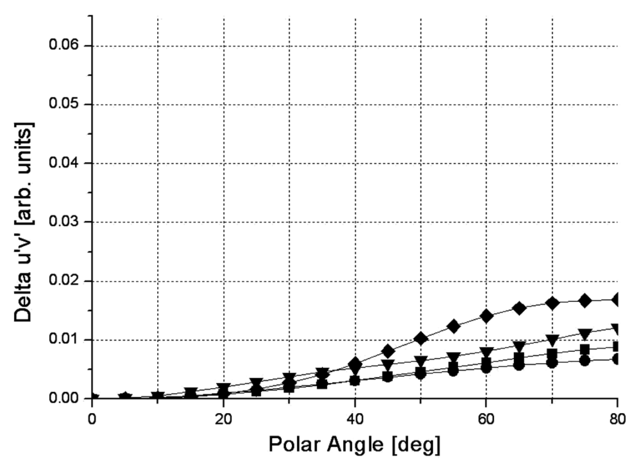
Table 1. Optical constants of thin films of the materials

	$\Delta n/\Delta n(550\,\text{nm})$		Δnd [nm] ($\Delta n = n_x - n_y$)
	450 nm	630 nm	550 nm
$\lambda/2$ biaxial film ($\Delta n = n_x - n_y$, $n_z - n_y$)	0.8166	1.1463	274
$\lambda/4$ biaxial film ($\Delta n = n_x - n_y$, $n_z - n_y$)	1	1	137
negative *C*-plate ($\Delta n = n_x - n_y$)	1.0414	0.9828	−261
$\lambda/4$ positive *A*-plate ($\Delta n = n_x - n_y$)	1.0055	0.9945	137

positive A-plate should have a normal dispersion property to get an achromatic dark state. We verified the improved optical properties of the proposed optical configuration by using the commercial LC software *TechWiz LCD* provided by the SANAYI System Co. in Korea instead of performing experiments, because each optimized film takes a very long time to be supported. Figure 3 represents the calculated $\Delta u'v'$ of the conventional and the proposed VA LCD with circular polarizer as a function of viewing angle in the diagonal ($\phi = 45^\circ$) directions. For the conventional optical configuration, the $\Delta u'v'$ value for a blue wavelength at $\theta = 70^\circ$ is much higher ($\approx$0.05) than the $\Delta u'v'$ value for the green and the red wavelengths ($\approx$0.01). However, we can see that the proposed optical configuration can improve the color difference in the visible wavelengths, compared to the conventional configuration. Figure 4 shows the comparison of the iso-luminance for the proposed configuration to the

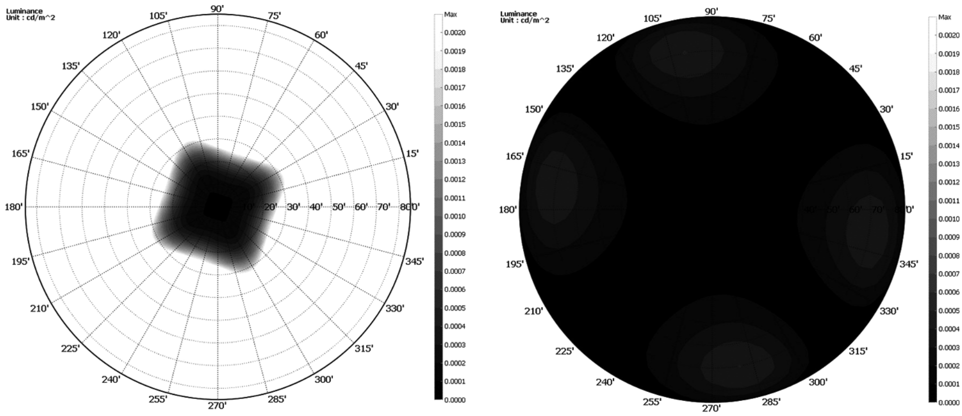


(a)



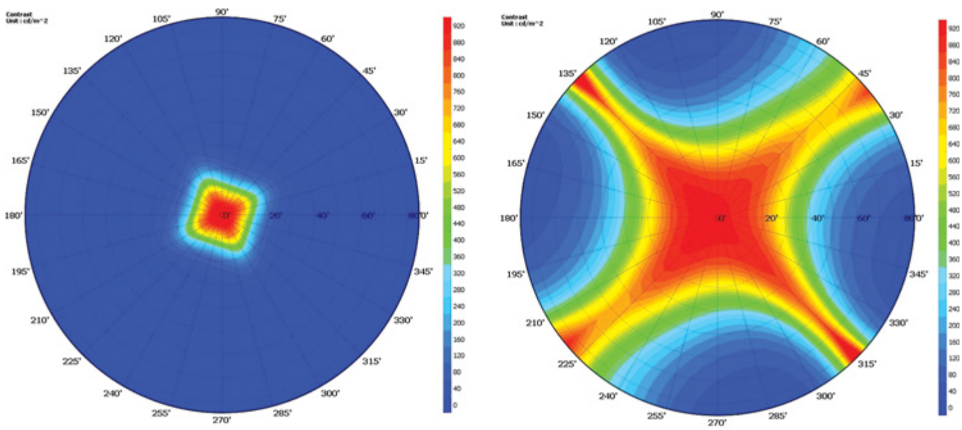
(b)

Figure 3. Color shift for *R, G, B* wavelength in the diagonal directions: (a) for a conventional structure and (b) for the proposed structure. Symbols ●, ■, ◆, and ▼ represent the *R, G, B* wavelength and mixed color in the diagonal direction.



(a) (b)

Figure 4. Calculated luminance in the dark state: (a) the conventional configuration and (b) the proposed configuration.



(a) (b)

Figure 5. Calculated iso-contrast contour: (a) the conventional configuration and (b) the proposed configuration. (Figure appears in color online.)

iso-luminance for the conventional configuration in the dark state. Figure 5 compares the iso-contrast contour of the conventional configuration with that of the proposed configuration in the visible wavelength range. From the results of Figures 4 and 5, we confirm that the proposed configuration has a wide viewing angle and improved color shift properties, as it reduces the off-axis light leakage in the dark state.

4. Conclusions and Perspectives

In conclusion, we propose an optical configuration of a VA LC cell with circular polarizer consisting of the two biaxial films, a quarter-wave plate and a negative

C-plate. Phase retardation, phase dispersion of the compensation films, and the Poincaré sphere for off-axis light are analyzed to eliminate off-axis light leakage factors by using the Stokes vector and the Muller matrix. Therefore, this study demonstrates that the proposed configuration shows not only wide viewing angle characteristics but also a reduced color shift by compensation for the off-axis light leakage in the entire wavelength.

Acknowledgment

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