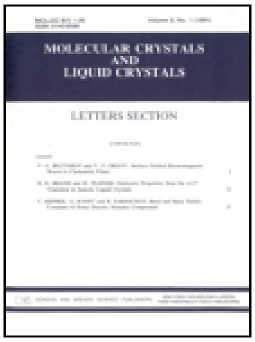

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Optical Compensation for Elimination of Off-Axis Light Leakage in a Homogeneously-Aligned Liquid Crystal Cell

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We propose an achromatic optical compensation method using uniaxial films to eliminate the off-axis light leakage in a homogeneously-aligned liquid crystal cell. In this technique, four uniaxial films with complementary dispersion characteristics are used to compensate for one another, resulting in achromatic effective phase retardation for off-axis angles. The retardation values are optimized with the aid of the Poincaré sphere and through numerical research. The contrast ratio of the proposed configuration for white light is higher than 2400:1 at a polar angle of $\pm 60^\circ$, irrespective of the azimuthal angle.

Keywords polarizers; liquid crystal devices; dark states; light leakage

Introduction

The desired characteristics of a liquid crystal (LC) display include a wide viewing angle, high brightness, and high contrast ratio. The in-plane switching mode exhibits the widest viewing angle because the LCs are initially homogeneously aligned and rotate within a plane parallel to the substrates when an in-plane field is applied [1–4]. However, further improvement is needed for viewing high-quality dark images from the bisector direction of the crossed polarizers. Several compensation schemes have been proposed to eliminate the off-axis light leakage [5–10]. Although a 100:1 iso-contrast contour at an optimized wavelength of 550 nm can cover the entire viewing cone, light leakage at other wavelengths, such as red and blue, remains very severe.

The polarization state of light that passes through retardation films depends on the wavelength because phase retardation is inversely proportional to the wavelength of the incident light. Therefore, a significant reduction in the contrast ratio, gray level inversion, and color shift can be observed in LCD panels. Several approaches have been proposed to reduce the off-axis light leakage, but developing an efficient method is difficult because suitable retardation films are expensive or difficult to manufacture. In choosing the compensation schemes, a trade-off exists between the performance of the compensation films

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and the cost of the films. Moreover, dispersion in uniaxial films worsens the light leakage caused by the compensation films at off-axis viewing angles. To overcome this problem, retardation films with negative or zero dispersion are currently under development; however, they are not widely used because of high manufacturing costs [11]. Recently, compensation methods using normal dispersion of uniaxial films have been proposed [12–14]. The +A/+A/+C configuration can effectively eliminate the off-axis light leakage [12]; still, the positive C film with zero dispersion used in this work may not be easy to fabricate. The +A/+A/+C/+A/+A configuration can eliminate the dark-state light leakage over the entire viewing cone [13], but it contains five uniaxial films, which may increase the manufacturing cost. Thus, there is an urgent need to develop a practical compensation method to widen the viewing angle of LCDs.

In this paper, we propose an achromatic compensation configuration for a homogeneously-aligned LC cell. We used uniaxial films with different dispersion characteristics such that they compensate one another to achieve achromatic optical compensation. The retardation values can be optimized with the aid of the Poincaré sphere [15–18]. To verify the performance of the proposed optical configuration, we calculated its optical characteristics using the simulation program "TechWiz LCD" (Sanayi System, Korea). We found that the off-axis light leakage can be reduced significantly by the proposed configuration.

Off-Axis Light Leakage in a Homogeneously-Aligned LC Cell

Light leakage in an LC cell is caused primarily by the change in the effective angle between the two absorption axes of two crossed polarizers, in particular the bisector of the crossed polarizers, when they are viewed from oblique directions. As the viewing polar angle θ increases, the angle between the two crossed polarizers deviates further from 90°. As a result, the light leakage increases as the polar angle increases. This light leakage lowers the contrast ratio of the LCD panel when it is viewed from an oblique angle, especially along the bisector of the crossed polarizers.

Several compensation schemes using uniaxial films, such as +A/-A, +A/+C, and +A/+C/+A, have been proposed to eliminate the light leakage associated with the crossed polarizers [5, 8, 9]. These uniaxial structures are used to move the polarization state from the transmission axis of the polarizer to the absorption axis of the analyzer, although the rotation routes of the polarization state on the Poincaré sphere are not the same. The primary explanation for the light leakage is that the retardation value of the uniaxial film is a function of the wavelength λ of the incident light. As an example, the calculated Poincaré sphere representation at the polar angle of 70° and azimuthal angle of 45° of the +A/+C/+A compensation structure is shown in Fig. 1. Although we can move the green light from the transmission axis of the polarizer to the absorption axis of the analyzer, the red light and blue light deviate from the absorption axis of the analyzer because of the $1/\lambda$ dependence of the phase retardation. Because the light leakage caused by the wavelength dependence of the phase retardation cannot be removed by additional uniaxial films or by changing the film configuration, it remains the main cause of the dark-state light leakage in an LC cell.

The performance of the compensation method which uses a single biaxial film is better than that which uses uniaxial films because the deviation at each wavelength is reduced by a small radius of rotation of the polarization states on the Poincaré sphere. The use of two biaxial films can effectively eliminate the wavelength dependence through the symmetrical rotation of the polarization state by each biaxial film [9]. However, the compensation using

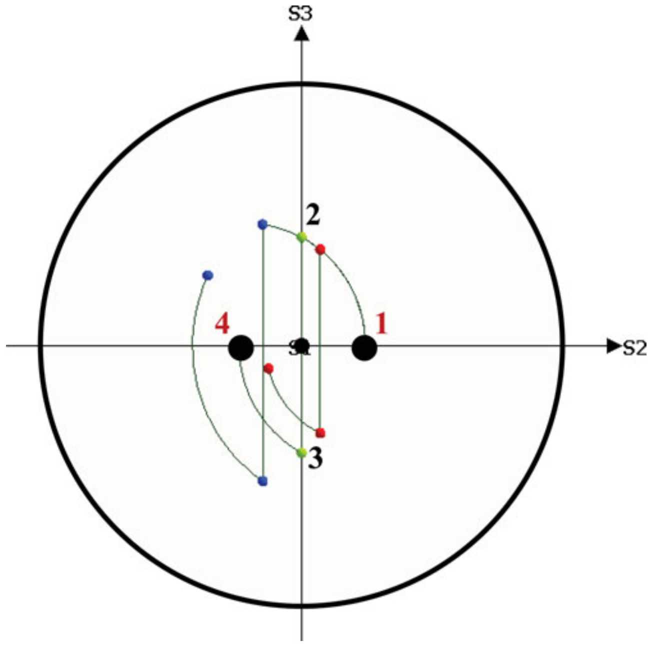

Figure 1. Polarization change in each color on the Poincaré sphere in the +A/+C/+A configuration.

two biaxial films can be cost prohibitive for practical display applications. If films with negative dispersion with refractive indices proportional to the wavelength are used, the light leakage for the blue or red light may be as little as that of the design wavelength of 550 nm [10]. However, the cost of a plate with achromatic or negative dispersion can be much higher than that of a plate with normal dispersion due to complicated fabrication processes. As mentioned previously, a trade-off exists between the performance and the cost of the compensation films among the compensation schemes.

Optical Compensation Scheme

Thus, here we propose an +A/+A/−A/−A optical compensation scheme using a set of orthogonal positive A plates and a set of orthogonal negative A plates for perfect elimination of the dark-state light leakage over the entire viewing cone in a homogeneously-aligned LC cell. Normal dispersion of a uniaxial film commonly increases the dark-state light leakage. However, in our proposed structure, the strong dispersion of the uniaxial films makes the polarization states accumulate at the absorption axis of the analyzer. We therefore use it in an opposite manner to remove the light leakage at off-axis viewing angles. We dissociate the deviation in the retardation value with the wavelength in terms of the inclination angle φ (the azimuthal angle on the Poincaré sphere) and the ellipticity angle θ (the polar angle on the Poincaré sphere) in the polarization ellipse [16]. Then, we individually eliminate the deviations in the inclination and ellipticity angles using the normal dispersion of the films. The orthogonal positive A plates are used to move the polarization states at all visible wavelengths to the S1 axis. The orthogonal negative A plates are used to move the polarization states at all visible wavelengths to the absorption axis of the analyzer. If the two orthogonal negative A plates have the same retardation values and degree of dispersion as

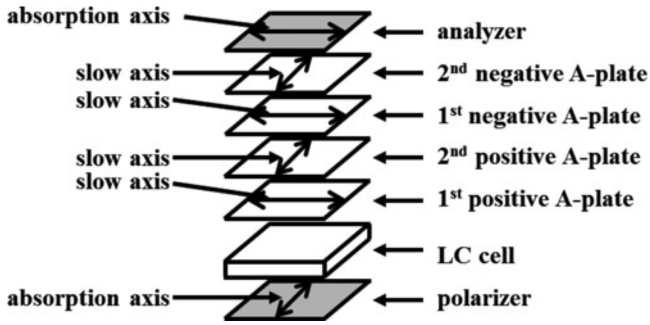

Figure 2. Compensation scheme of the + A/+A/−A/−A configuration.

the two orthogonal positive A plates, the polarization state moves precisely symmetrically to the absorption axis of the analyzer.

Figure 2 shows the proposed +A/+A/−A/−A configuration using a set of orthogonal positive A plates and a set of orthogonal negative A plates. The use of these plates allows for symmetrical rotation of the polarization state on the Poincaré sphere. When unpolarized light from a backlight unit traverses through the polarizer, it becomes linearly polarized, as shown in Fig. 3. The polarization state is located at point 1, which deviates from the absorption axis of the analyzer at point 5. The two positive A plates, whose slow axes are orthogonal to one another, convert the polarization state of the light that passes through them into another elliptical polarization state at point 3(0, θ_0), whose azimuthal angle is the same as that in the S1 axis. Because the slow axes of the two A plates are orthogonal to

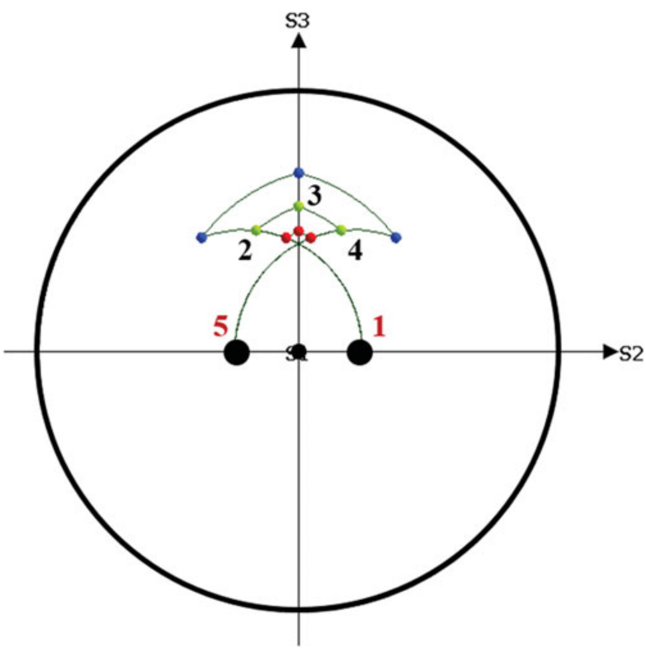

Figure 3. Polarization change in each color on the Poincaré sphere in the +A/+A/−A/−A configuration.

Table 1. Calculated material dispersions and retardations of the uniaxial plates

Uniaxial plates	$\Delta n/\Delta n$(550 nm) 450 nm	Δnd [nm] 650 nm	550 nm
1st + A plate	1.08	0.97	+ 124
2nd + A plate	1.66	0.39	+ 27.5
1st - A plate	1.66	0.39	− 27.5
2nd - A plate	1.08	0.97	− 124

each other, the rotations of the polarization state caused by each A plate are in a direction opposite to each other on the Poincaré sphere. Thus, the wavelength dispersion is cancelled by the two orthogonal A plates. The dispersion can be effectively removed by setting the degree of dispersion of the plates so that the first A plate (which has a high retardation value) has a weak dispersion and the second A plate (which has a low retardation value) has a strong dispersion. If the retardation values and the degree of dispersion of the two negative A plates are the same as those of the two positive A plates, the polarization state moves precisely symmetrically to the absorption axis of the analyzer. The polarization states at all visible wavelengths are effectively accumulated along the absorption axis of the analyzer at point 5.

We set the parameters of the films by computer simulation to confirm the performance of the proposed compensation scheme, as listed in Table 1. The first positive A plate has weak wavelength dispersion, whereas the second positive A plate has strong wavelength dispersion. If the two orthogonal negative A plates have the same retardation values (but with opposite sign) and degree of dispersion as the two orthogonal positive A plates, the polarization state moves symmetrically to the absorption axis of the analyzer. Conventional compensation schemes have poor characteristics when films with normal dispersion are used. In the proposed configuration, however, uniaxial films with normal dispersion are used to remove the deviation in the polarization states over all visible wavelengths. The retardation values and the degree of dispersion of the films can be freely changed and optimized under the above-mentioned condition.

Numerical Results and Discussion

The dark state light leakage was calculated using the simulation program "TechWiz LCD 1D." In this numerical calculation, we assumed that the pre-tilt angle of the LC layer is 0°. We also assumed an ideal polarizer. A cold cathode fluorescence lamp, which is a broadband light source with continuous spectrum, was used as the light source.

To demonstrate the compensation performance, we calculated the light leakage over the entire range of polar angles at $\varphi = 45°$, as shown in Fig. 4(a). The red line represents the dark-state light leakage in the +A/+C/+A configuration. A strong off-axis light leakage can be observed at any polar angle. The green and blue lines represent the light leakages in the +A/+A/+C and +A/+A/−A/−A configurations, respectively, which show little light leakage over the entire range of visible wavelengths. We also calculated the light leakage as functions of φ at $\theta = 70°$, as shown in Fig. 4(b). The red line represents the dark state light leakage in the +A/+C/+A configuration. A maximum off-axis light leakage of 0.2113% can be observed at azimuthal angles of 45°, 135°, 225°, and 315°. The green line represents the light leakage in the +A/+A/+C configuration, which shows

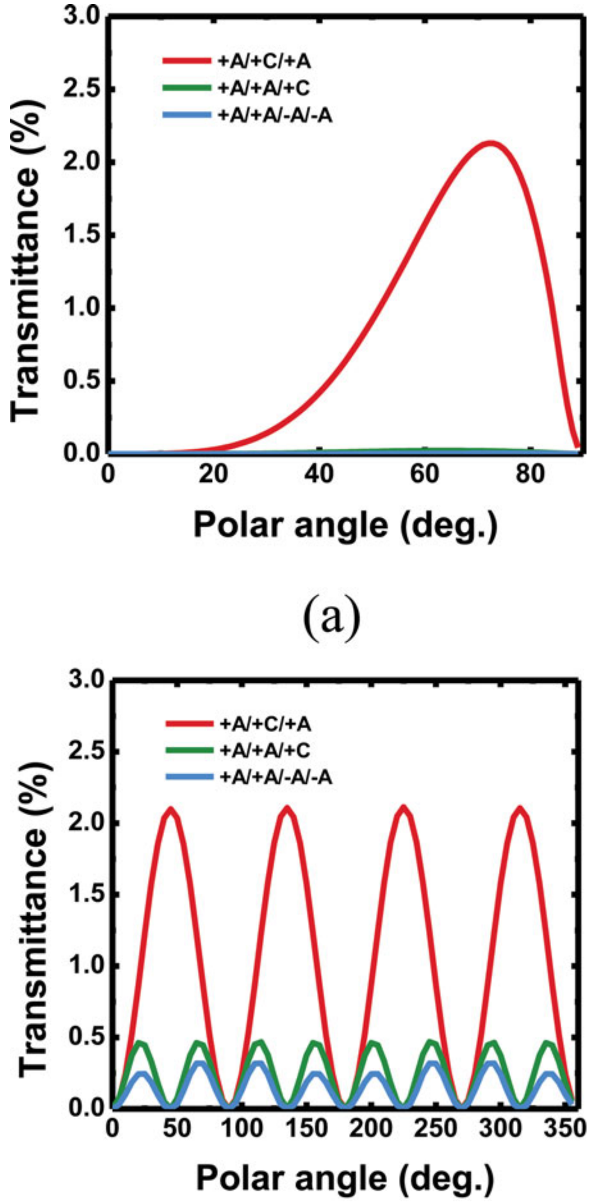

Figure 4. Dependence of the light leakage (a) on θ at $\phi = 45°$ and (b) on ϕ at $\theta = 70°$.

a maximum dark state light leakage of 0.0476% at azimuthal angles of 20°, 65°, 115°, 155°, 200°, 245°, 295°, and 335°. Although the light leakage at $\varphi = 45°$ is eliminated, light leakage still exists at other azimuthal angles. The blue line represents the light leakage in the +A/+A/−A/−A configuration, which shows a maximum dark-state light leakage of 0.0318% at an azimuthal angle of 65°, 115°, 245°, and 295°. It is approximately 33% lower

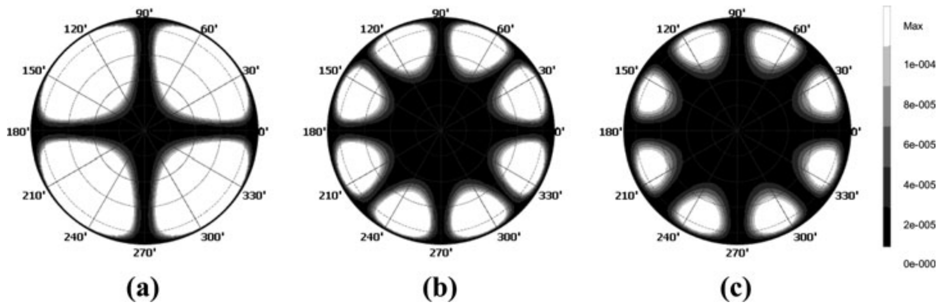

Figure 5. Iso-luminance contours of the dark states: (a) +A/+C/+A, (b) +A/+A/+C, and (c) +A/+A/−A/−A configurations.

than that in the +A/+A/+C configuration. This difference is attributed to the symmetrical rotation of the polarization state on the Poincaré sphere, as shown in Fig. 3, which results in a high contrast ratio over the entire viewing cone for the white light, which also helps reduce the color shift in low gray-level images [19].

We calculated the iso-luminance contour of the dark state using the simulation program "TechWiz LCD 2D," and we assumed that the LCs have a zero pre-tilt angle, as shown in Fig. 5. Light leakage higher than 0.002% is observed at a polar angle of ±20° in the +A/+C/+A configuration, but light leakage in the +A/+A/+C configuration is still less than 0.002% at a polar angle of ±40°. Light leakage is smaller than 0.002% at a polar angle of ±45° in the +A/+A/−A/−A configuration. These results indicate that the dark-state light leakage for the white incident light can be eliminated over the entire viewing cone using normal dispersion of the films and symmetric configurations. The contrast ratio also is calculated assuming a zero pre-tilt angle of the LC layer. The viewing angle with a contrast ratio of 2400:1 in the +A/+C/+A configuration is ±35°, as shown in Fig. 6(a). The +A/+A/+C configuration shows a wider viewing angle of ±50°, as shown in Fig. 6(b). The viewing angle of the +A/+A/−A/−A configuration is much wider than that of the +A/+A/+C configuration because of the lower off-axis dark-state light leakage, as shown in Fig. 5(c). The viewing angle of the +A/+A/−A/−A configuration with a contrast ratio of 2400:1 is over ±60° irrespective of the azimuthal angle, as shown in Fig. 6(c).

To study the effect of the pretilt angle and polarizer, the light leakage for a pretilt angle of 2° with real polarizers is shown in Fig. 7. In all cases, the effect of the pretilt angle and

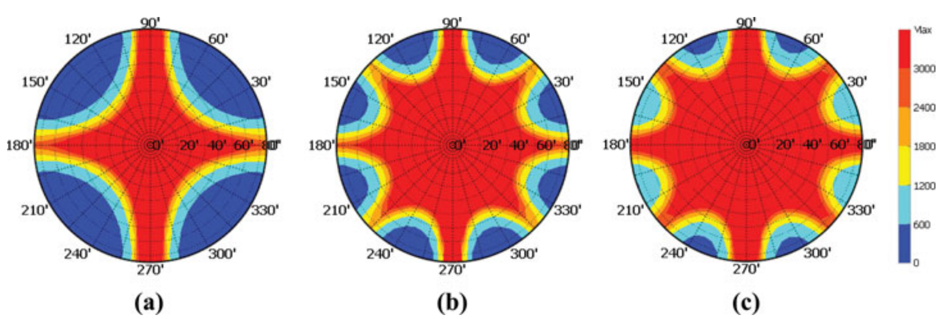

Figure 6. Iso-contrast contours obtained assuming zero pre-tilt angle of LC: (a) + A/+C/+A, (b) +A/+A/+C, and (c) + A/+A/−A/−A configurations.

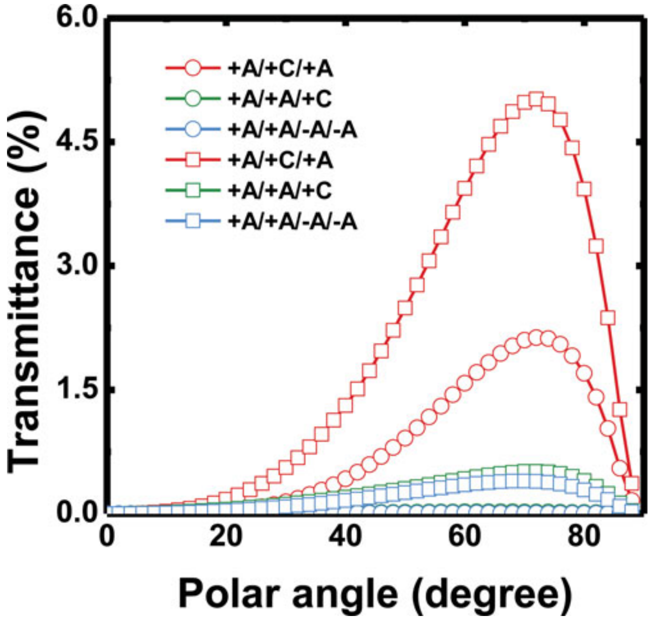

Figure 7. Dependence of the light leakage on θ at $\varphi = 45^\circ$. Squares represent results for the pretilt angle of 0° with ideal polarizers and circles represent results for the pretilt angle of 2° with real polarizers.

polarizer results in an increase in the light leakage. However, the proposed method still shows a significant improvement over the previous technologies although the remaining light leakage is not negligible. These results indicate that lowering of the pretilt angle is essential for complete elimination of the off-axis light leakage. Because obtaining a zero pretilt angle using the rubbing technique is difficult, employing non-contact alignment techniques might be preferable, such as the photo alignment and ion-beam alignment [20–24], to realize a wide-viewing-angle LCD.

Conclusions

We have proposed achromatic compensation configurations using normal dispersion films to eliminate the dark state light leakage over the entire polar and azimuthal angles. The light leakage in the proposed +A/+A/−A/−A configuration was 33% lower than that in the +A/+A/+C configuration. The contrast ratio of the +A/+A/−A/−A configuration for white light is higher than 2400:1 at a polar angle of ±60° and is irrespective of the azimuthal angle. All the films we used have normal wavelength dispersion, which can be easily fabricated at a relatively low manufacturing cost.

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