Journal of Information Display, 2015
http://dx.doi.org/10.1080/15980316.2014.1003252

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INVITED ARTICLE

Optical compensation methods for the elimination of off-axis light leakage in an in-plane-switching liquid crystal display

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(*Received 20 November 2014; accepted 12 December 2014*)

Optical compensation to improve the wide-viewing-angle characteristics in a liquid crystal display (LCD) is essential for high-quality dark images, especially from the bisector direction of the crossed polarizers. This paper reviews optical compensation schemes for the elimination of off-axis light leakage in an in-plane-switching LCD. A uniaxial film with normal dispersion commonly increases the dark-state light leakage, but it can be used in the opposite manner to remove the dark-state light leakage at off-axis viewing angles. Using symmetrical rotation of the polarization state on the Poincaré sphere, the dark-state light leakage over the entire viewing cone for white light can be effectively eliminated.

Keywords: polarizers; liquid crystal devices; dark states; light leakage; optical compensation

1. Introduction

Application of liquid crystal displays (LCDs) has been expanded to various devices, such as smartphones, tablet PCs, automotive displays, PCs, and TVs. This expansion is attributed not only to the rapid reduction of the fabrication cost but also to the rapid improvement in the display quality. The desired characteristics of an LCD include a wide viewing angle, high brightness, and a high contrast ratio. Among the various LCD modes, the in-plane switching (IPS) mode exhibits the widest viewing angle because the liquid crystals (LCs) are initially homogeneously aligned and rotate within a plane parallel to the substrates when an in-plane field is applied [1–4]. Further improvement is needed, however, to view high-quality dark images from the bisector direction of the crossed polarizers. Several compensation schemes have been proposed to eliminate off-axis light leakage [5–11]. Although a 100:1 iso-contrast contour at a 550 nm optimized wavelength can cover the entire viewing cone, the light leakage at other wavelengths (e.g. red and blue) remains very severe.

The polarization state of light that has passed 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. A trade-off exists between the performance and cost of the compensation films in choosing a compensation scheme. Moreover, the 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 being developed, but they are not yet widely used because of their high manufacturing cost.

In this article, the developed optical compensation schemes are reviewed in detail. In the following sections, the phase compensation principles are first analyzed using a Poincaré sphere representation [12–15]. Then the research on the achromatic compensation configuration for a perfect dark state is summarized. To verify the performance of the proposed optical configuration, its optical characteristics were calculated using the simulation program TechWiz LCD (Sanayi System, South Korea).

2. Off-axis light leakage in an IPS LC cell

The viewing direction can be represented by the polar angle θ and the azimuth angle ϕ, where the polar angle θ is the angle between the k-vector of the incident light and the z-axis, and the azimuth angle ϕ is the orientation angle of the projection of the k-vector on the xy-plane measured from the x-axis. The major cause of light leakage in an LCD is the change in the effective angle between the absorption axes of the two crossed polarizers when viewed

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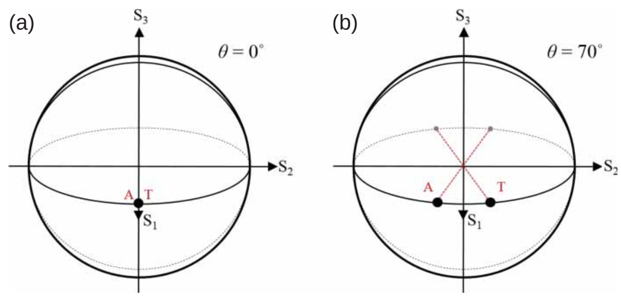

Figure 1. Demonstration of crossed polarizers on the Poincaré sphere under (a) normal view and (b) oblique view.

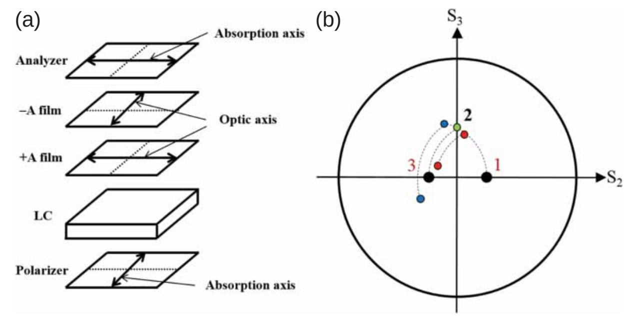

Figure 2. (a) $+$A/$-$A configuration. (b) Polarization change in each color on the Poincaré sphere for the $+$A/$-$A configuration. Viewing angle: $\theta = 70°$; $\phi = 45°$.

from oblique directions, especially from the bisector of the crossed polarizers. The absorption axes of the two crossed polarizers make an angle of $2\tan^{-1}(\cos\theta)$, which depends on polar angle θ. As θ increases, the angle between the two crossed polarizers deviates further from 90°. As a result, the light leakage increases along with the polar angle.

As shown in Figure 1(a), under the normal view, both the transmission axis of the polarizer (point T) and the absorption axis of the analyzer (point A) are located at the S_1 axis of the Poincaré sphere. Point T, at which the light is linearly polarized after passing through the polarizer, exactly overlaps the absorption axis of the analyzer, resulting in complete light absorption and no light leakage from the normal viewing direction. Under an oblique view from the bisector of the crossed polarizers, however, points T and A are no longer located on the S_1 axis of the Poincaré sphere. Instead, point T is located between the S_1 and S_2 axes, whereas point A is located between the S_1 and negative S_2 axes, as shown in Figure 1(b). As point T no longer overlaps point A, light leakage occurs from the bisector viewing direction of the crossed polarizers. To obtain an excellent dark state at off-axis angles, the polarization states for all the visible wavelengths must be moved from the transmission axis of the polarizer (point T) to the absorption axis of the analyzer (point A). The introduced compensation film should improve the off-axis viewing performance but should not affect the on-axis viewing performance.

3. Optical compensation schemes using uniaxial films

Several compensation schemes using uniaxial films, such as $+$A/$-$A [9], $+$A/$+$C/$+$A [10], and $+$A/$+$C [6,7], have been proposed to eliminate the light leakage associated with crossed polarizers. These configurations using uniaxial films are used to move the polarization state from the transmission axis of the polarizer to the absorption axis of the analyzer to eliminate off-axis light leakage, although the rotation routes of the polarization state on the Poincaré sphere are not the same.

An approach using two $\lambda/6$ plates will first be described [9]. Figure 2(a) shows a compensation scheme using one positive A plate and one negative A plate. The retardation value of both plates is 92 nm. More specifically, the optical axis of the positive A plate is parallel to the absorption axis of the analyzer whereas the optical axis of the negative A plate is parallel to the absorption axis of the polarizer. Figure 2(b) shows the calculated Poincaré sphere representation at the 70° polar angle and the 45° azimuth angle for the $+$A/$-$A configuration. Although the green light can be moved from the transmission axis of the polarizer to the absorption axis of the analyzer, the red and blue lights deviate from the absorption axis of the analyzer. Moreover, although the fabrication techniques for a C plate and a positive A plate are relatively mature, those for negative A plates have not been well explored [16].

A different compensation scheme involving the use of two positive A plates and a positive C plate [10], as shown in Figure 3(a), is considered. The retardation values of the positive A plates and the positive C plate are 152 and 92 nm, respectively. The optical axis of the first positive A plate is parallel to the absorption axis of the analyzer whereas the optical axis of the second positive A plate is parallel to the absorption axis of the polarizer. Although this compensation method requires three uniaxial films, it does not use a negative A plate. The positive C plate can be combined with a negative C plate used in the vertical alignment (VA) mode. Figure 3(b) shows the calculated Poincaré sphere representation at the 70° polar angle and

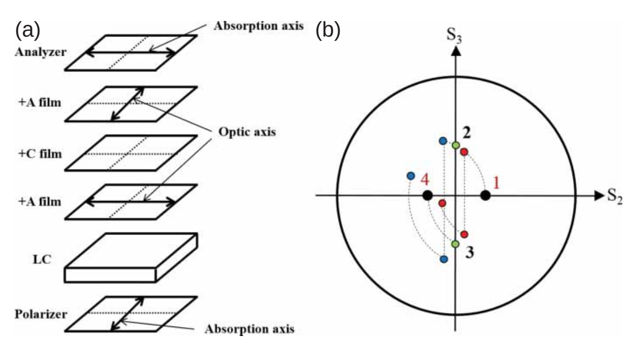

Figure 3. (a) $+$A/$+$C/$+$A configuration. (b) Polarization change in each color on the Poincaré sphere for the $+$A/$+$C/$+$A configuration. Viewing angle: $\theta = 70°$; $\phi = 45°$.

the 45° azimuth angle for the +A/+C/+A configuration. Although the green light can be moved from the transmission axis of the polarizer to the absorption axis of the analyzer, the red and blue lights deviate from the absorption axis of the analyzer.

Now, a compensation scheme involving the use of a positive A plate and a positive C plate [6,7], as shown in Figure 4(a), is considered. The retardation values of the positive A plate and the positive C plate are 138 and 86 nm, respectively. The optical axis of the positive A plate is parallel to the absorption axis of the analyzer. There is no negative A plate. The positive C plate can be combined with a negative C plate used in the VA mode. Figure 4(b) shows the calculated Poincaré sphere representation at the 70° polar angle and the 45° azimuth angle for the +A/+C configuration. Although the green light can be moved from the transmission axis of the polarizer to the absorption axis of the analyzer, the red and blue lights deviate from the absorption axis of the analyzer.

The iso-luminance contour of the dark state was calculated using the simulation program TechWiz LCD 2D, assuming that the LCs have a zero pretilt angle, as shown in Figure 5. More than 0.01% light leakage was observed at the ±34.6, ±33.1, and ±34.0° polar angles in the +A/−A, +A/+C/+A, and +A/+C configurations, respectively. The light leakage in an LC cell remaining after compensation is caused mainly by the fact that the retardation value of a uniaxial film is a function of the wavelength λ of the incident light. Although the green light is moved from the transmission axis of the polarizer to the absorption axis of the analyzer, the red and blue lights deviate from the absorption axis of the analyzer because of the $1/\lambda$ dependence of the phase retardation. As the light leakage caused by the wavelength dependence of the phase retardation cannot be removed using additional uniaxial films or by changing the film configuration, it remains a major cause of off-axis light leakage in LCDs. Moreover, although the compensation films are optimized to suppress the light leakage at $\phi = 45°$, the polarization state of the green light is not moved to the absorption axis of the analyzer, and the light leakage increases at other azimuth angles.

4. Optical compensation scheme using biaxial films and films with negative dispersion

Light leakage in a pair of crossed polarizers at large viewing angles can also be eliminated using a single biaxial film, as shown in Figure 6(a). Such a compensation scheme was first proposed by Saitoh *et al*. [5]. The retardation value and refractive index parameter N_z of the biaxial film are 275 nm and 1.0, respectively. N_z is defined as

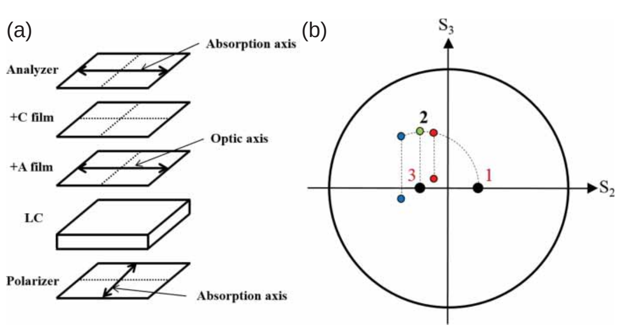

Figure 4. (a) +A/+C configuration. (b) Polarization change in each color on the Poincaré sphere for the +A/+C configuration. Viewing angle: $\theta = 70°$; $\phi = 45°$.

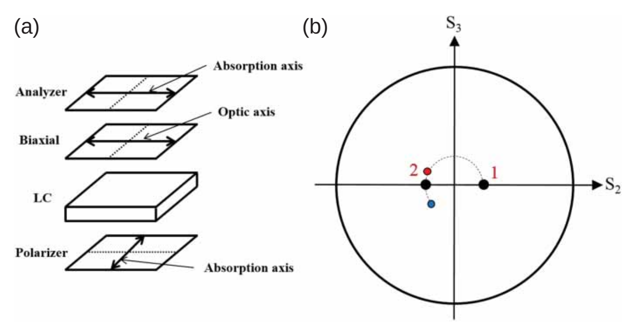

Figure 6. (a) Compensation scheme using a single biaxial film. (b) Polarization change in each color on the Poincaré sphere for the compensation scheme using a single biaxial film. Viewing angle: $\theta = 70°$; $\phi = 45°$.

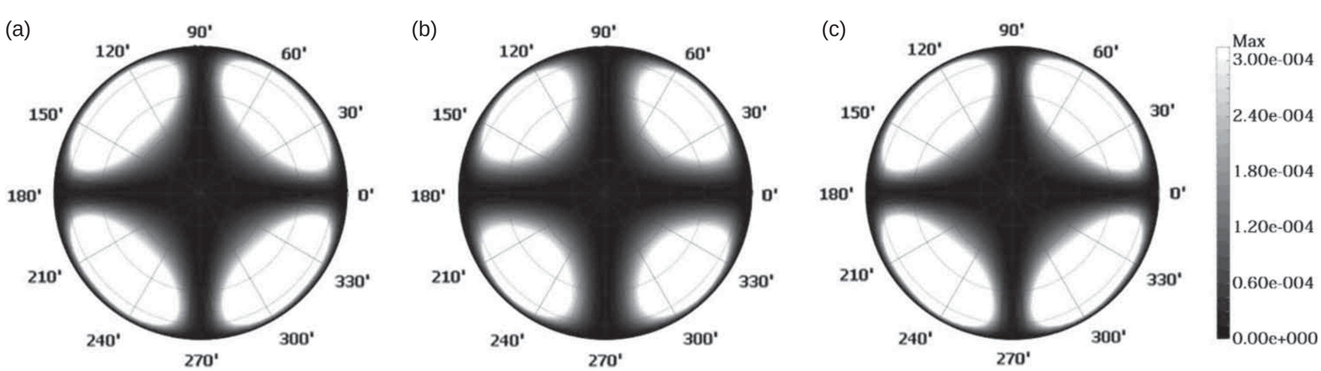

Figure 5. Iso-luminance contours of the dark states of the (a) +A/−A, (b) +A/+C/+A, and (c) +A/+C configurations.

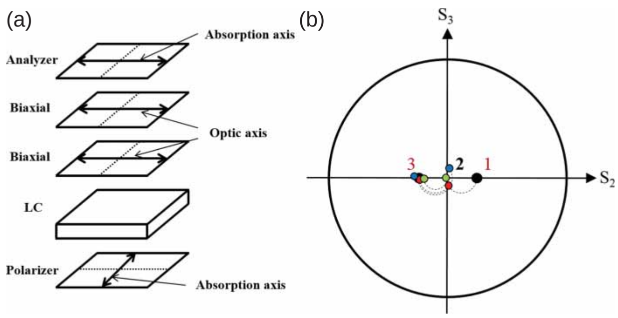

Figure 7. (a) Compensation scheme using two biaxial films. (b) Polarization change in each color on the Poincaré sphere for the compensation scheme using two biaxial films. Viewing angle: $\theta = 70°$; $\phi = 45°$.

$N_z = n_x - n_z/n_z - n_y$ (here, n_x, n_y, and n_z are the refractive indices in the x, y, and z directions, respectively). The optical axis of the biaxial film is parallel to the absorption axis of the polarizer. Figure 6(b) shows the calculated Poincaré sphere representation at the 70° polar angle and the 45° azimuth angle for the compensation scheme using a single biaxial film. This compensation scheme outperforms that using uniaxial films because the deviation at each wavelength is reduced by the small radius of rotation of the polarization states on the Poincaré sphere.

The light leakage in a pair of crossed polarizers at large viewing angles can also be eliminated using two biaxial films, as shown in Figure 7(a). Such a compensation scheme was first proposed by Ishinabe *et al.* [8]. Both biaxial films have a 270 nm retardation value. The N_z values of the first and second biaxial films are 0.35 and 2.375, respectively. The optical axes of both biaxial films are parallel to the absorption axis of the polarizer. Figure 7(b) shows the calculated Poincaré sphere representation at the 70° polar angle and the 45° azimuth angle for the compensation scheme using two biaxial films. This compensation scheme outperforms that using a single biaxial film because the use of two biaxial films can effectively eliminate the wavelength dependence through the symmetrical rotation of the polarization state by each biaxial film. This scheme, however, can be very expensive for practical display applications.

The iso-luminance contour of the dark state was calculated using the simulation program TechWiz LCD 2D, assuming that the LCs have a zero pretilt angle, as shown in Figure 8. More than 0.01% light leakage was observed at the $\pm 37.7°$ polar angle in the compensation scheme using a single biaxial film, but the light leakage in the compensation scheme using two biaxial films was less than 0.01% at the $\pm 40.0°$ polar angle. The performance of the compensation methods that use one or two biaxial films is much better than that of the compensation methods using uniaxial films because the deviation at each wavelength is reduced by the small radius of rotation of the polarization state or by the symmetrical rotation of the polarization state on the Poincaré sphere. Compensation using biaxial films, however, can be too expensive for practical display applications. Among the compensation schemes, a trade-off exists between the performance and cost of the compensation films.

If films with negative dispersion whose refractive index is proportional to the wavelength are used, the light leakage for blue or red light may become as small as that at the 550 nm design wavelength. Negative-dispersion films can be fabricated using multilayers of normal-dispersion films or twist-oriented reactive mesogens [17,18]. Several reports on single-layer negative-dispersion films using copolymers or reactive mesogens were recently published [19–21].

The iso-luminance contour of the dark state was calculated using the simulation program TechWiz LCD 2D, assuming that the LCs have a zero pretilt angle, as shown in Figure 9. More than 0.01% light leakage was observed at the $\pm 54.6°$ polar angle in the compensation scheme using a single biaxial film with ideal negative dispersion. The light leakage in the compensation scheme using a single biaxial film with real negative dispersion, however, was less than 0.01% at the $\pm 50.8°$ polar angle because the dispersion was similar to the ideal one for

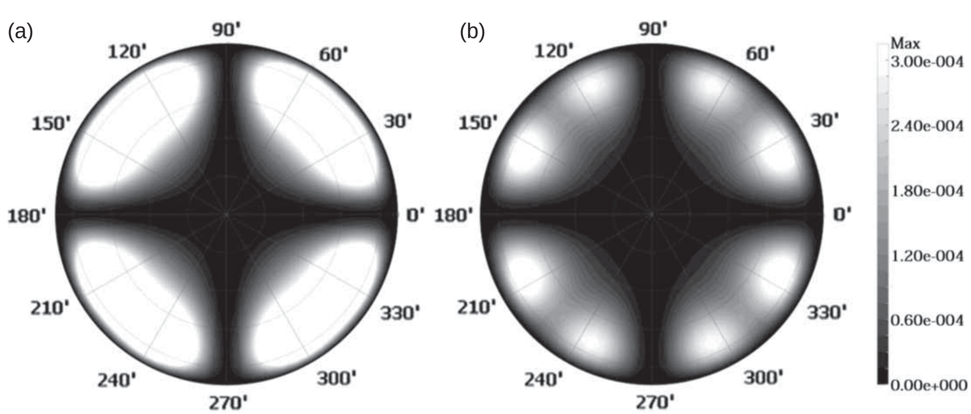

Figure 8. Iso-luminance contours of the dark states for the compensation schemes using (a) a single biaxial film and (b) two biaxial films.

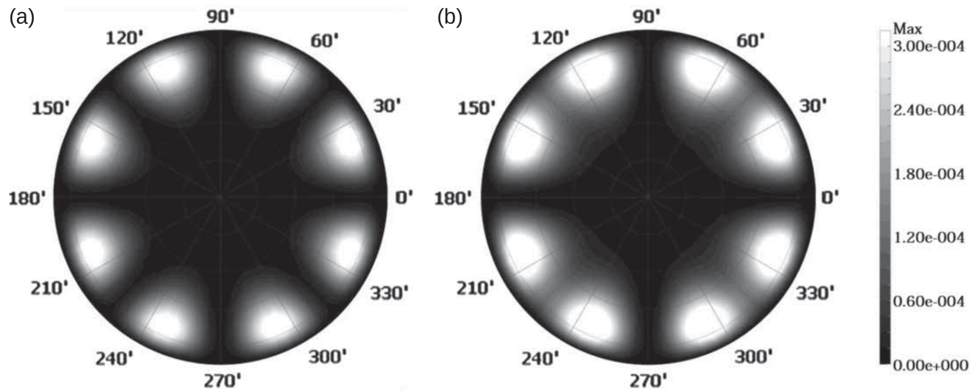

Figure 9. Iso-luminance contours of the dark states for the compensation scheme using a single biaxial film: (a) ideal negative-dispersion film; and (b) real negative-dispersion film [17].

450 nm $< \lambda <$ 600 nm, but it deviated at the other wavelengths [17]. Moreover, although a biaxial film has ideal dispersion and is optimized to suppress the light leakage at $\phi = 45°$, the polarization state of the green light did not move at the absorption axis of the analyzer, and the light leakage increased at the other azimuth angles, as shown in Figure 9(a). Furthermore, a film with zero or negative dispersion can be much more costly than a film with normal dispersion because the former is difficult to fabricate. Among the compensation schemes, a trade-off again exists between the performance and cost of the compensation films.

5. Optical compensation scheme with normal-dispersion films

In the authors' previous papers, normal-dispersion uniaxial films were used. A uniaxial film with normal dispersion commonly increases the dark-state light leakage, but it was used in the opposite manner to remove the dark-state light leakage at off-axis viewing angles. An attempt was made to dissociate the deviation in the retardation value with the wavelength in terms of the inclination angle Φ (the azimuth angle on the Poincaré sphere) and the ellipticity angle Θ (the polar angle on the Poincaré sphere) for the polarization ellipse [13]. Then the deviations in the inclination and ellipticity angles were individually eliminated. The polarization states for all visible wavelengths can be gathered at the absorption axis of the analyzer through the sequential reduction of the deviations in the inclination and ellipticity angles. The dispersion can be effectively removed by setting the plates' degrees of dispersion such that the first A plate (which has a high retardation value) has weak dispersion and the second A plate (which has a low retardation value) has strong dispersion. As the slow axes of the two A plates are orthogonal, the rotations of the polarization state caused by each A plate (on the Poincaré sphere) are in opposite directions; thus, the wavelength dispersion is canceled out by the two orthogonal A plates.

The $+A/+A/+C$ configurationand its detailed compensation mechanism can be explained using the Poincaré sphere at $\phi = 45°$ and $\theta = 70°$, as shown in Figure 10 [22]. The optic axis of the first (second) positive A plate is parallel to the absorption axis of the second (first) polarizer. The retardation values of the first positive A plate, the second positive plate, and the positive C plate are 185, 38, and 125 nm, respectively. The dispersion can be effectively removed by setting the degrees of dispersion of the plates so that the first A plate has weak dispersion and the second has strong dispersion. The positive C plate is used to convert the polarization states of the light that has passed through the two A plates into linear polarization along the absorption axis of the analyzer (point 3). Finally, the polarization states at all visible wavelengths are effectively accumulated at the absorption axis of the analyzer.

Although the compensation films are optimized to suppress the light leakage at $\phi = 45°$, the polarization states are not accumulated at the absorption axis of the analyzer, and light leakage remains at other azimuth angles. Furthermore, a positive C plate with zero wavelength dispersion is required because a plate with normal dispersion cannot completely cancel out the deviation in the ellipticity angle. A zero-dispersion film, however, imposes a high cost because it is not easy to fabricate.

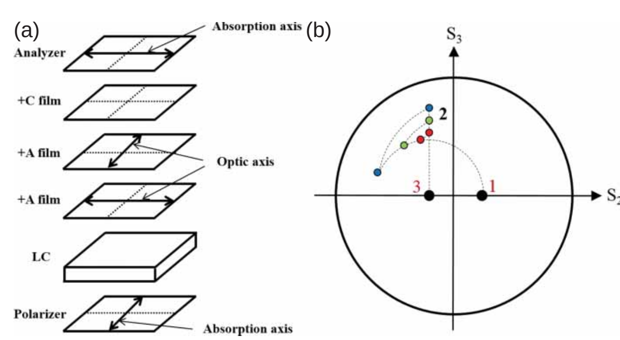

Figure 10. (a) $+A/+A/+C$ configuration. (b) Polarization change in each color on the Poincaré sphere for the $+A/+A/+C$ configuration. Viewing angle: $\theta = 70°$; $\phi = 45°$.

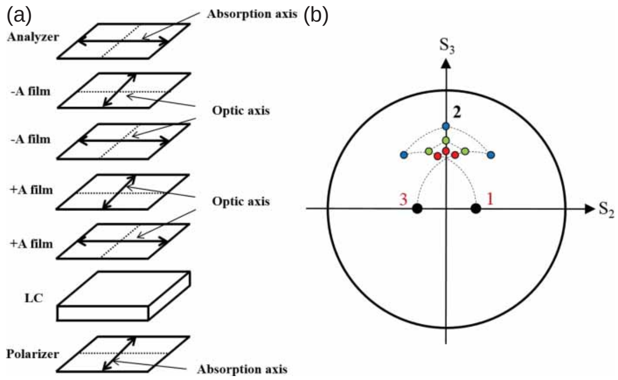

Figure 11. (a) $+A/+A/-A/-A$ configuration. (b) Polarization change in each color on the Poincaré sphere for the $+A/+A/-A/-A$ configuration. Viewing angle: $\theta = 70°$; $\phi = 45°$.

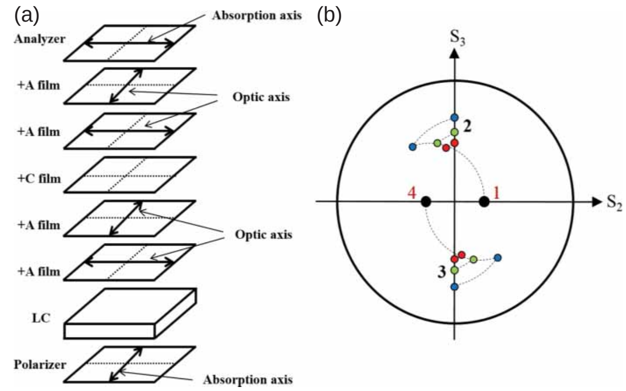

Figure 12. (a) $+A/+A/+C/+A/+A$ configuration. (b) Polarization change in each color on the Poincaré sphere for the $+A/+A/+C/+A/+A$ configuration. Viewing angle: $\theta = 70°$; $\phi = 45°$.

The $+A/+A/-A/-A$ configurationand its detailed compensation mechanism can be explained using the Poincaré sphere at $\phi = 45°$ and $\theta = 70°$, as shown in Figure 11 [23]. The optic axis of the first (second) positive A plate is parallel to the absorption axis of the second (first) polarizer. The two positive A plates, whose slow axes are orthogonal, convert the polarization state of the light passing through them into another elliptical polarization state at point 2, whose azimuth angle is on the S_1 axis. As the slow axes of the two A plates are orthogonal, the rotations of the polarization state caused by each A plate (on the Poincaré sphere) are in opposite directions; thus, the wavelength dispersion is canceled out by the two orthogonal positive A plates. The dispersion can be effectively removed by setting the plates' degrees of dispersion such that the first A plate has weak dispersion and the second has strong dispersion. If the retardation values and degrees of dispersion of the two negative A plates are the same as those of the two positive A plates, the motion of the polarization state is exactly symmetric with respect to the absorption axis of the analyzer. Finally, the polarization states at all visible wavelengths are effectively accumulated along the absorption axis of the analyzer at point 3.

Although the compensation films are optimized to suppress the light leakage at $\phi = 45°$, and the polarization change on the Poincaré sphere exhibits rotational symmetry, the polarization states are not accumulated at the absorption axis of the analyzer, and light leakage remains at other azimuth angles. Furthermore, the scheme requires negative A plates, which are not yet widely used because of their high manufacturing cost.

The $+A/+A/+C/+A/+A$ configuration using two sets of orthogonal positive A plates and a positive C plate, as shown in Figure 12(a), was proposed for the perfect elimination of the dark-state light leakage over the entire viewing cone in an IPS LC cell [24]. The use of two orthogonal positive A plates allows for the symmetrical rotation of the polarization state on the Poincaré sphere. The two positive A plates, whose slow axes are orthogonal, convert the polarization state of the light that passes through them into another elliptical polarization state at point 2, whose azimuth angle is the same as that of the S_1 axis. As the slow axes of the two A plates are orthogonal, the rotations of the polarization state caused by each A plate (on the Poincaré sphere) are in opposite directions; thus, the wavelength dispersion is canceled out by the two orthogonal A plates. The dispersion can be effectively removed by setting the degrees of dispersion of the plates so that the first A plate has weak dispersion and the second has strong dispersion. The positive C plate with normal dispersion converts the polarization state at point 2 into that at point 3, which is symmetrical to point 2 with respect to the S_1 axis. If the retardation values and degrees of dispersion of the two A plates above the C plate are the same as those of the two A plates below the C plate, the movement of the polarization state is exactly symmetrical with respect to the absorption axis of the analyzer. Finally, the polarization states at all visible wavelengths are effectively accumulated at the absorption axis of the analyzer at point 4. As the rotation of the polarization states has rotational symmetry on the S_2–S_3 plane of the Poincaré sphere, the light leakage at any polar or azimuth angle can be effectively eliminated. The path difference on the northern hemisphere can be canceled out by that on the southern hemisphere. Moreover, zero- or negative-dispersion films, which are incidentally difficult to fabricate and very expensive for practical display applications, are not used.

The wavelength dependence of the polarization change on the Poincaré sphere for the $+A/+A/+C/+A/+A$ configuration is shown in Figure 13. The polarization states at all visible wavelengths are accumulated at the absorption axis of the analyzer, irrespective of ϕ, because of the rotational symmetry in the polarization rotation route. The path difference on the northern hemisphere can be perfectly canceled out by that on the southern hemisphere.

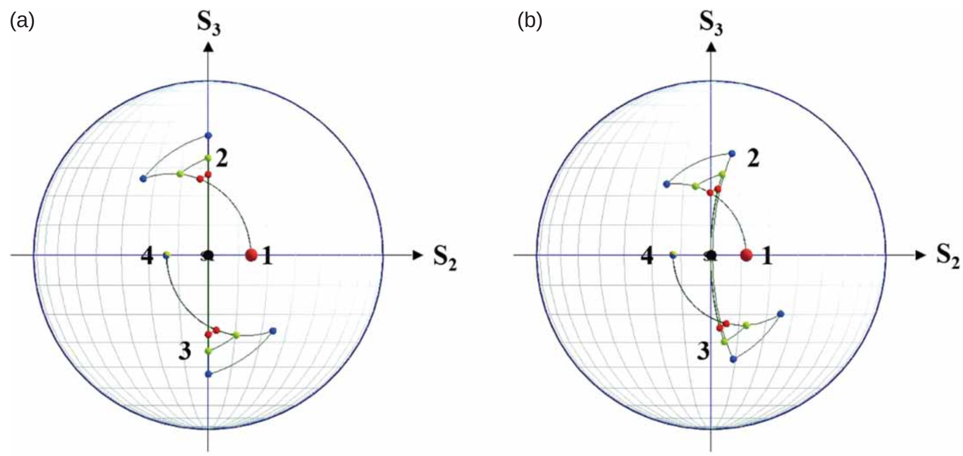

Figure 13. Wavelength dependence of the polarization change in each color on the S_2–S_3 plane of the Poincaré sphere at $\theta = 70°$ for the $+A/+A/+C/+A/+A$ configuration. (a) $\phi = 45°$; and (b) $\phi = 30°$.

The iso-luminance contour of the dark state was calculated using the simulation program TechWiz LCD 2D, assuming that the LCs have a zero pretilt angle, as shown in Figure 14. More than 0.01% light leakage was observed at the $\pm 33.1°$ polar angle in the $+A/+C/+A$ configuration, but the light leakage in the $+A/+A/+C$ configuration was still less than 0.01% at the $\pm 52.6°$ polar angle. Although the off-axis light leakage was reduced in the $+A/+A/-A/-A$ configuration because of the rotational symmetry on the S_2–S_3 plane of the Poincaré sphere, the path differences cannot be canceled out. Thus, the light leakage in the $+A/+A/-A/-A$ configuration was still less than 0.01% at the $\pm 57.1°$ polar angle. The light leakage was smaller than 0.01% over the entire viewing cone in the $+A/+A/+C/+A/+A$ configuration. These results indicate that the dark-state light leakage for white incident light can be eliminated over the entire viewing cone using films with normal dispersion and a symmetric configuration.

6. Numerical results and discussion

The dark-state light leakage was calculated using the simulation program TechWiz LCD 1D. In this numerical calculation, it was assumed that the pretilt angle of the LC layer was 0°. To demonstrate the compensation performance, the light leakage over the entire range of polar angles at $\phi = 45°$ was calculated, as shown in Figure 15. Strong off-axis light leakage was observed at any polar angle in the configurations using uniaxial films and the compensation scheme using a single biaxial film. The compensation scheme using two biaxial films, the $+A/+A/+C$, $+A/+A/-A/-A$, and $+A/+A/+C/+A/+A$ configurations, showed little light leakage over the entire visible spectrum.

The light leakage as a function of ϕ at $\theta = 70°$ was also calculated, as shown in Figure 16. Strong off-axis light leakage was observed at the 45, 135, 225, and 315° azimuth angles in the configurations using uniaxial films and the compensation scheme using a single biaxial film. The pink line represents the light leakage in the compensation scheme using two biaxial films, which shows a maximum dark-state light leakage of 0.0413% at the 25, 155, 205, and 335° azimuth angles. The yellow line represents the light leakage in the $+A/+A/+C$ configuration, which shows a maximum dark-state light leakage of 0.0476% at the 20, 60, 115, 155, 200, 245, 295, and 335° azimuth angles. The dark-blue line represents

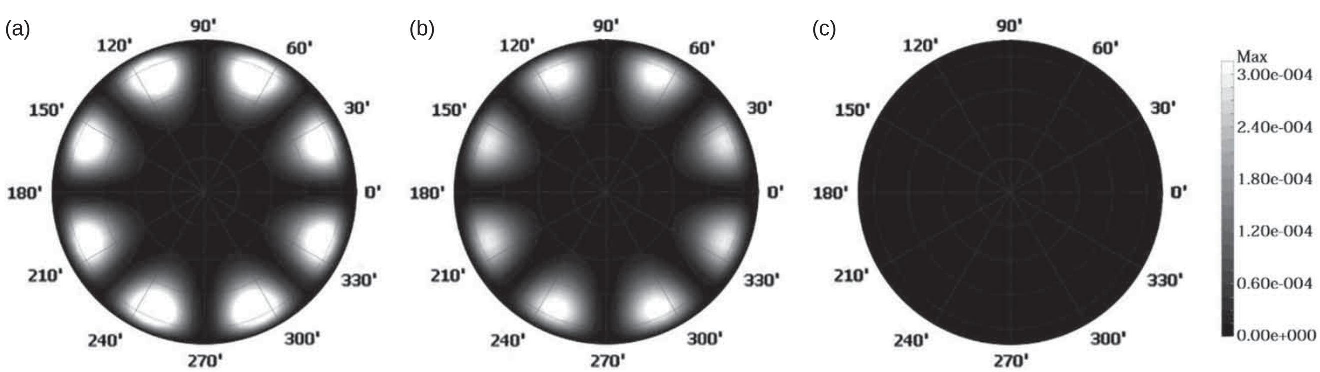

Figure 14. Iso-luminance contours of the dark states for the (a) $+A/+A/+C$, (b) $+A/+A/-A/-A$, and (c) $+A/+A/+C/+A/+A$ configurations.

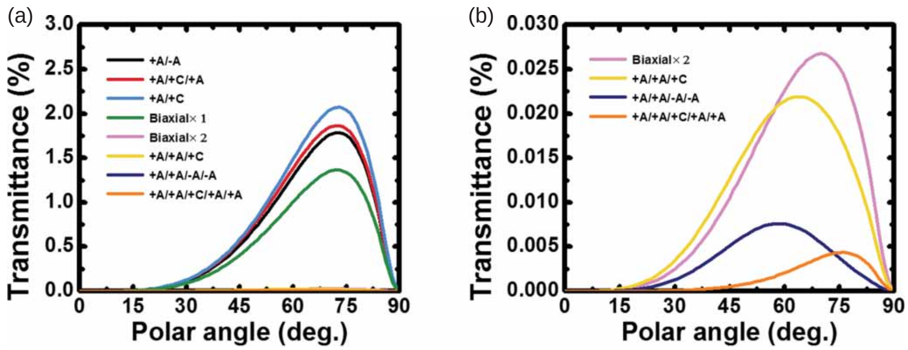

Figure 15. Dependence of the light leakage on θ at $\phi = 45°$.

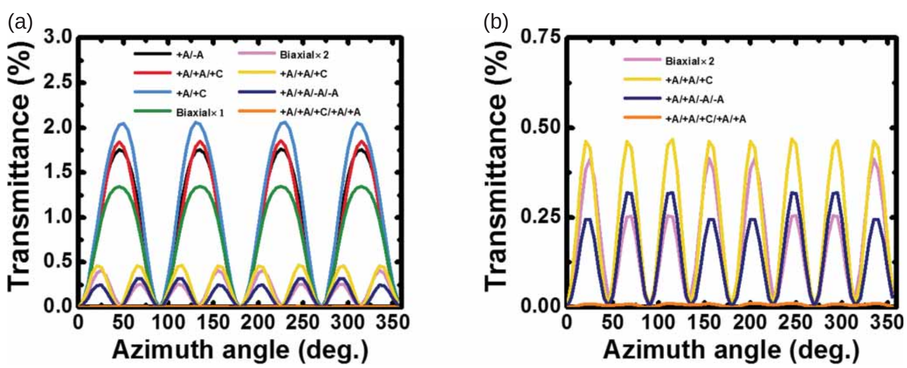

Figure 16. Dependence of the light leakage on ϕ at $\theta = 70°$.

the light leakage in the $+A/+A/-A/-A$ configuration, which shows a maximum dark-state light leakage of 0.0318% at the 65, 115, 245, and 295° azimuth angles. Although the light leakage at $\phi = 45°$ was eliminated in the compensation scheme using two biaxial films, the $+A/+A/+C$ and $+A/+A/-A/-A$ configurations, light leakage still existed at the other azimuth angles. The orange line {represents} the light leakage in the $+A/+A/+C/+A/+A$ configuration, which showed a maximum dark-state light leakage of 0.0011% at the 115° azimuth angle. This is approximately 35 times lower than that in the $+A/+A/-A/-A$ configuration. This difference is attributed to the symmetrical rotation of the polarization state on the Poincaré sphere; this results in a high contrast ratio over the entire viewing cone for white light, which also helps reduce the color shift in low-gray-level images [25].

Although the proposed compensation method showed excellent viewing angle characteristics when the pretilt angle of the LC layer was 0°, achieving a zero pretilt angle may not be easy. In all optical compensation configurations, a non-zero pretilt angle increases the light leakage [24,26]. The proposed method, however, still showed an improvement over the previous technologies, although the remaining light leakage was not negligible. These results indicate that lowering the pretilt angle is essential for the complete elimination of off-axis light leakage. As obtaining a zero pretilt angle using the rubbing technique is difficult, employing non-contact alignment techniques such as photo and ion-beam alignment [27–30] might be preferable for realizing a wide-viewing-angle LCD.

7. Summary

Optical compensation schemes for the elimination of off-axis light leakage in an IPS LCD were analyzed using a Poincaré sphere representation. The concept of achromatic compensation using normal-dispersion films to eliminate the dark-state light leakage was also reviewed. The normal dispersion of a uniaxial film commonly increases the dark-state light leakage, but it can be sued in the opposite manner to remove the dark-state light leakage at off-axis viewing angles. Using symmetrical rotation of the polarization state on the Poincaré sphere, the dark-state light leakage over the entire viewing cone for white light can be effectively eliminated. All the films that were used in this study had normal wavelength dispersion and could thus be easily fabricated at a relatively low manufacturing cost. It may be noted that all the results and discussions on the IPS mode in this paper can be equally applicable to the fringe-field switching mode because such mode may be considered a kind of IPS mode.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2014R1A2A1A01004943).

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