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Optical design of low-cost polarizer without chromatic fringe pattern

Bong Choon Kim,[1] Young Jin Lim,[1] Seung Hee Lee,[1,a)] and Gi-Dong Lee[2,b)]
[1]*Department of BIN Fusion Technology and Department of Polymer Nano Science and Technology, Chonbuk National University, Jeonju, Jeonbuk 561-756, South Korea*
[2]*Department of Electronics Engineering, Dong-A University, Pusan 604-714, South Korea*

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Recently, polyethylene terephthalate (PET) has been considered as a substitute material for a protection film in a polarizer in order to reduce the cost. However, PET film exhibits high retardation intrinsically due to the stretching process, which induces a chromatic fringe pattern so called a color mura in oblique viewing angle directions, associated with a strong wavelength dispersion. Based on simulation and experimental results, placing an optic axis of PET film in plane can suppress the color mura without the need to use any compensation films; the film thus exhibits high performance as well as low cost. © *2013 AIP Publishing LLC*.
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Liquid crystal displays (LCDs) are widely used in all display applications and dominate the flat panel display market. Many types of liquid crystal modes such as twisted nematic,[1–3] in-plane switching,[4–6] fringe-field switching,[7–9] patterned vertical alignment (VA),[10–13] multi-domain VA,[14,15] and polymer-stabilized VA[16–20] have contributed to present commercialized LCDs which show high image quality comparable to that of emissive displays. Nevertheless, nonemissive LCD has recently been challenged by emissive displays such as organic light emitting devices. Therefore, the performance of LCDs needs to be further improved, and the cost needs to be more competitive in order to maintain a dominant position in the market. At present, all LCDs require two polarizers whose transmittance axes are orthogonal to each other, and a birefringent uniaxial liquid crystal medium is required between the polarizers to control the polarization of incident light. In general, the polarizer with either protective or compensation film determines the light efficiency and contrast ratio of the display.[21] In addition, as the display size increases for television application, the cost of the polarizer is greatly increased, creating a strong demand to develop a low cost polarizer.[22–24] The conventional polarizer is made of a stretched polyvinyl alcohol (PVA) film with adsorbed iodine ions so that protection films are required at both sides of the PVA film. Tri-acetyl cellulous (TAC) is mainly applied to the protection film because it exhibits optically almost zero retardation, high light transmittance, and reliability. Notwithstanding its excellent optical performance, the cost of TAC is very high and is consequently being challenged by its replacement of a polyethylene terephthalate (PET) film to reduce the cost. However, the PET film exhibits high retardation in the process of stretching, which may cause deterioration of optical performances such as color shift and viewing angle in an oblique viewing direction. This is because the light from the backlight can be polarized due to the use of the dual brightness enhancement film (DBEF) in the backlight module. In the previous report, we used randomly oriented liquid crystal film utilizing reactive mesogen (RM) to depolarize a polarized light.[25] The optical performance of the LCD using the film was excellent; however, this method increases not only the thickness of the polarizer but also the cost because of the use of the expensive RM.

In this paper, we propose a high performance low-cost polarizer without showing any colorful fringe pattern (known as "color mura") by controlling the optical parameters of the PET film without using any RM film. Generally, the PET film is made through double stretching processes such that the film is initially stretched in a machine direction (MD) and then in a transverse direction (TD). In this way, the PET film used for this study has a refractive index of the negative biaxial plate ($n_x > n_y > n_z$) which is an anisotropic birefringent film with two optic axes.

Figure 1 shows the optical configuration of the VA cell applying a PET film in the polarizer. The refractive index of the ellipsoid of the PET film is similar to a negative biaxial plate. In the device, the PET film is used for protection of the PVA films, while cyclo olefin copolymer (COP) films, which act as compensation films, were used on one side of the PVA film to suppress light leakage of the VA cell in oblique viewing directions. In the PET film, the stretched level is higher in TD than MD, that is, TD is the slow axis of the film. In the normal direction, the slow axis is exactly parallel to the transmittance axes of the PVA film and DBEF so that the polarization state of a linearly polarized incident light coming from DBEF is not affected by the PET film. However, the polarization state of an incident light changes in the oblique viewing direction because the parallel condition between the transmittance axes of the PVA film and DBEF and the slow axis of the PET film is no longer valid. In addition, the change in the polarization state also depends on the wavelengths so that the transmittance level via the top polarizer becomes wavelength dependent, resulting in the color mura. At off the normal axis, the color mura is associated with slow axis change and retardation change of the PET film according to the viewing angle. The optical properties of the film associated with the in-plane retardation value (R_o) and parameter of the refractive index (N_z)[26] for a biaxial film are described as follows:

a)Electronic mail: lsh1@chonbuk.ac.kr
b)Electronic mail: gdlee@dau.ac.kr

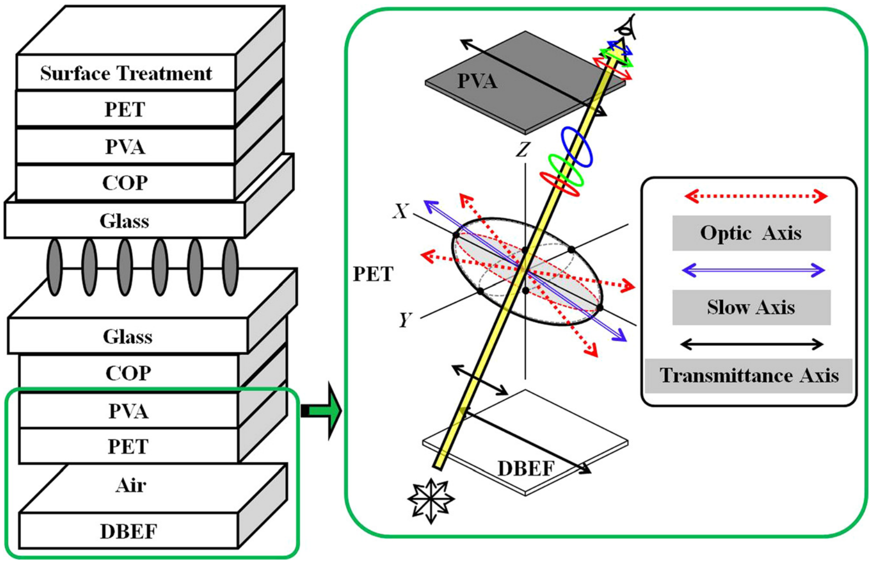

FIG. 1. Optical configuration of the film compensated VA cell and optic refractive index ellipsoid of PET similar to a negative biaxial plate with a schematic drawing of the polarization state of an incident light in the oblique viewing direction.

$$R_0 = (n_x - n_y) \times d, \tag{1}$$

$$N_Z = \frac{n_x - n_z}{n_x - n_y}, \tag{2}$$

where d is the film thickness and n_x, n_y, and n_z are the refractive indices in the x, y, and z directions, respectively. However, the phase retardation value (R) of the light passing through a biaxial film depends mainly on the polar (θ) and azimuthal (ϕ) angles in the spherical coordinates and is defined as follows:

$$R = (n_e(\theta, \phi) - n_o(\theta, \phi)) \times OPL, \tag{3}$$

$$OPL = \frac{n_x + n_y + n_z}{3} \times d(\theta, \phi), \tag{4}$$

where n_e and n_o are the large and small refractive indices, respectively, and OPL is an optical path length in off normal directions.

For calculations of the optical properties in the proposed structures shown in Fig. 1, a commercially available simulation tool "TechWiz LCD" (Sanayi-system, Korea) has been used, while the patterned VA mode is used as a LC cell. In the cell, the LC is vertically aligned in a dark state and then tilts downward in four different ϕs to give a wide viewing angle in a white state. The DBEF is used in the backlight unit (BLU), which means that the light after passing through the DBEF is also polarized, as shown in Fig 1.

Figure 2 shows the calculated iso-luminance with wavelength dependency and the iso-R contour of the patterned VA cell using the polarizer with PET film. Here, R_o and N_z of the PET film are 750 nm and 3 at 589 nm, respectively. According to the iso-luminance contour, no color mura is present within the oblique viewing angle ($\theta = 40°$) in all directions. However, when θ becomes larger than 40°, wavelength dependency in the luminance appears, causing color mura as shown in Fig. 2(a). Comparing the color mura with a symmetric luminance distribution in Fig. 2(a) and iso-R contour of Fig. 2(b), both have a similar appearance. The color mura is strongly associated with the wavelength-dependency of R. The R of the PET film, similar to the negative biaxial plate, has a normal wavelength dependency characteristic such that the phase differences are high and low in short and long wavelengths, respectively. Thus, the ratio of the phase difference between short and long wavelength increases in oblique viewing directions, and the color mura then becomes stronger. For a negative biaxial plate, two optic axes exist at two different directions: $\theta = 60°$, $\phi = 0°$ and $\theta = 60°$, $\phi = 180°$, and we notice that the strong color mura has occurred around the optic axes. In such large oblique viewing directions, the slow axis

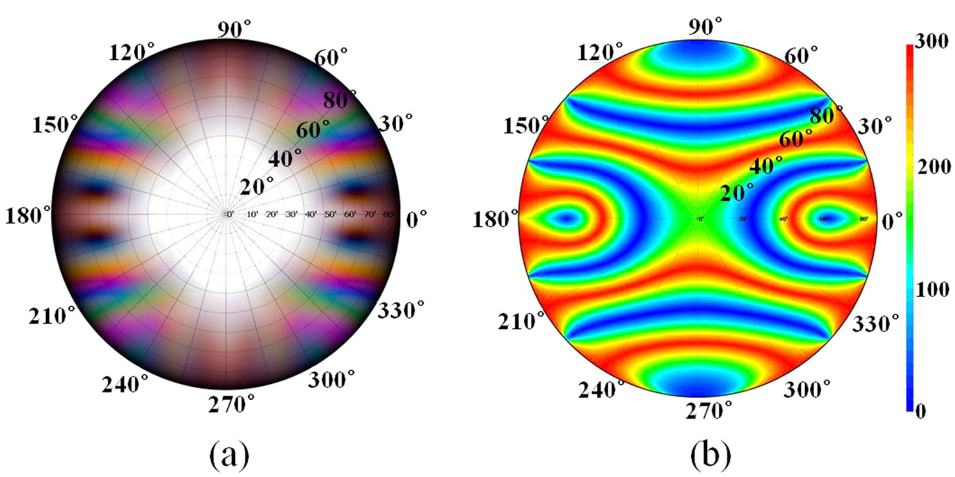

FIG. 2. Calculated (a) iso-luminance contour with color and (b) retardation contour of patterned VA cell with the polarizer using PET film ($N_z = 3$) in BLU with DBEF.

of the negative biaxial plate-PET film and the transmittance axis of DBEF or the absorption axis of PVA cannot be either parallel or perpendicular to each other, and also the change in the phase difference becomes very large over 360°, resulting in the color mura. Therefore, the origin of the color mura comes from two conditions that the slow axis of the film and the polarized light of DBEF are neither parallel nor perpendicular to each other (condition 1), and the change in phase retardation exceeds one wavelength (condition 2). Consequently, two conditions are required to generate the color mura. In other words, the slow axis as well as refractive index associated with Nz of the film should be optimized to remove the color mura, and if the optic axis of the PET film lies in plane, one of two conditions would not be satisfied so that the color mura disappears.

In general, the number of an optic axis and its direction and the direction of slow axis depend on the type of film and N_z values, as shown in Fig. 3. A negative biaxial ($n_x > n_y > n_z$) plate is stretched in the x- and y-axes, and two optic axes then exist out of plane and $N_z > 1$ from Eq. (2). When a positive A ($n_x > n_y = n_z$) plate is stretched in the x-axis, it becomes a uniaxial plate with one optic axis in plane and $N_z = 1$. When a biaxial plate ($n_x > n_z > n_y$) is stretched in the x- and z-axes, two optic axes exist in plane and $0 < N_z < 1$. When a negative A ($n_x = n_z > n_y$) plate with one optic axis is stretched in the y-axis, the optic axis exists in plane and $N_z = 0$. When a positive biaxial ($n_z > n_x > n_y$) plate is stretched in x- and y-axes, two optic axes exist out of plane and $N_z < 0$. Considering the required conditions for the color mura, positive and negative biaxial plates satisfy conditions 1 and 2 so that the color mura is generated. On the other hand, the biaxial plate does not satisfy condition 2, and positive and negative A plates do not satisfy condition 1 so

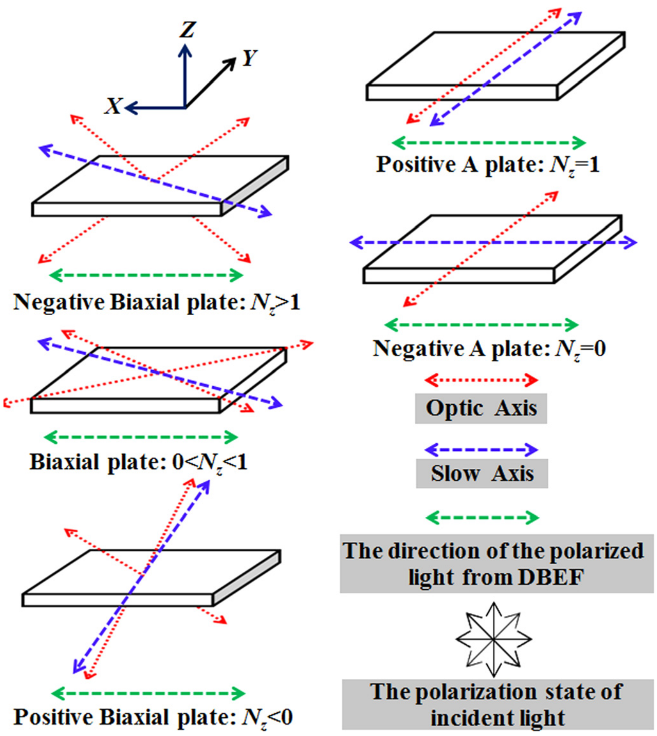

FIG. 3. Schematic diagram of the direction of optic and slow axes on several retardation films.

they do not generate the color mura. Conclusively speaking, in order for the proposed PET film not to satisfy one of these two conditions, the optic axis should exist in plane.

In order to confirm our assumed theory, a calculation has been performed. Figure 4 shows the calculated color contour with the brightness and retardation contours of the PVA cell, using the low-cost polarizer according to N_z of the PET film. All conditions are the same as those in Fig. 2. From Fig. 4(a), we can demonstrate that the color mura of a positive A plate, biaxial plate, and negative A plate with its optic axis in plane is minimal compared with a positive biaxial plate with optic axes out of plane. As clearly indicated in Fig. 4(b), the change in R, according to viewing directions, is greatly reduced when the optic axis exists in plane. From the results, we understand again that the color mura has occurred when an optic axis exists out of plane with $N_z < 0$ or $N_z > 1$. To confirm the dependence of slow axis on the color mura, the direction of the slow axis has been changed to 0°, 45°, and 90° but all cases show that the symmetry axis of the color mura changes as the direction of slow axis changes, while still showing unwanted color mura.

In general, the PET film has a positive refractive index characteristic such that the stretching direction has the highest refractive index. When the film is stretched to MD only, a positive A plate is formed, whereas a negative biaxial plate can be formed by stretching the film to TD after stretching to MD. In addition, when it is stretched to MD and then more to TD, a biaxial plate with high N_z is formed. Therefore, the film should be stretched to MD at first and then shrunk to TD to form the desired biaxial plate. The shrinking method of the polymer film is such that once the film is stretched to TD, a pair of stretched polymer films is laminated together and the heat is then applied, resulting in shrinking in TD. However, the biaxial film formed by the proposed method is quite expensive because it is difficult to form using the two polymer films and pressure sensitive adhesive for the attachment process. On the other hand, a material with a negative refractive index characteristic such that the stretching direction has the lowest refractive index should be applied to produce a negative A and a positive biaxial plate. A typical example of film with a negative refractive index is I-Film (Zeon, Japan). It is composed of two layers of polymethyl methacrylate (PMMA) and one layer of modified polystyrene (PS) in which PS is located between two PMMA layers. The change of R according to stretching strength is primarily generated by a modified PS layer. With this approach, a negative A plate and positive biaxial plate can be made, that is, a negative A plate cannot be made with the PET film. Conclusively speaking, the only color mura free retardation plates that can be fabricated in a low cost practical way using the PET film is the positive A plates, though the film made with this approach with conventional fabricating machine has a limitation to make the film with wide width because it is stretched to only MD.

Figure 5 shows the comparison of color mura in the 4 domain VA LC cell using the low-cost PET films (see Fig. 1 for optical configuration). At a normal direction, the color mura is not shown when either the TAC film or PET films with different Nz are used. However, when the PET negative biaxial plate with $N_z = 3$ is used at both sides, the strong

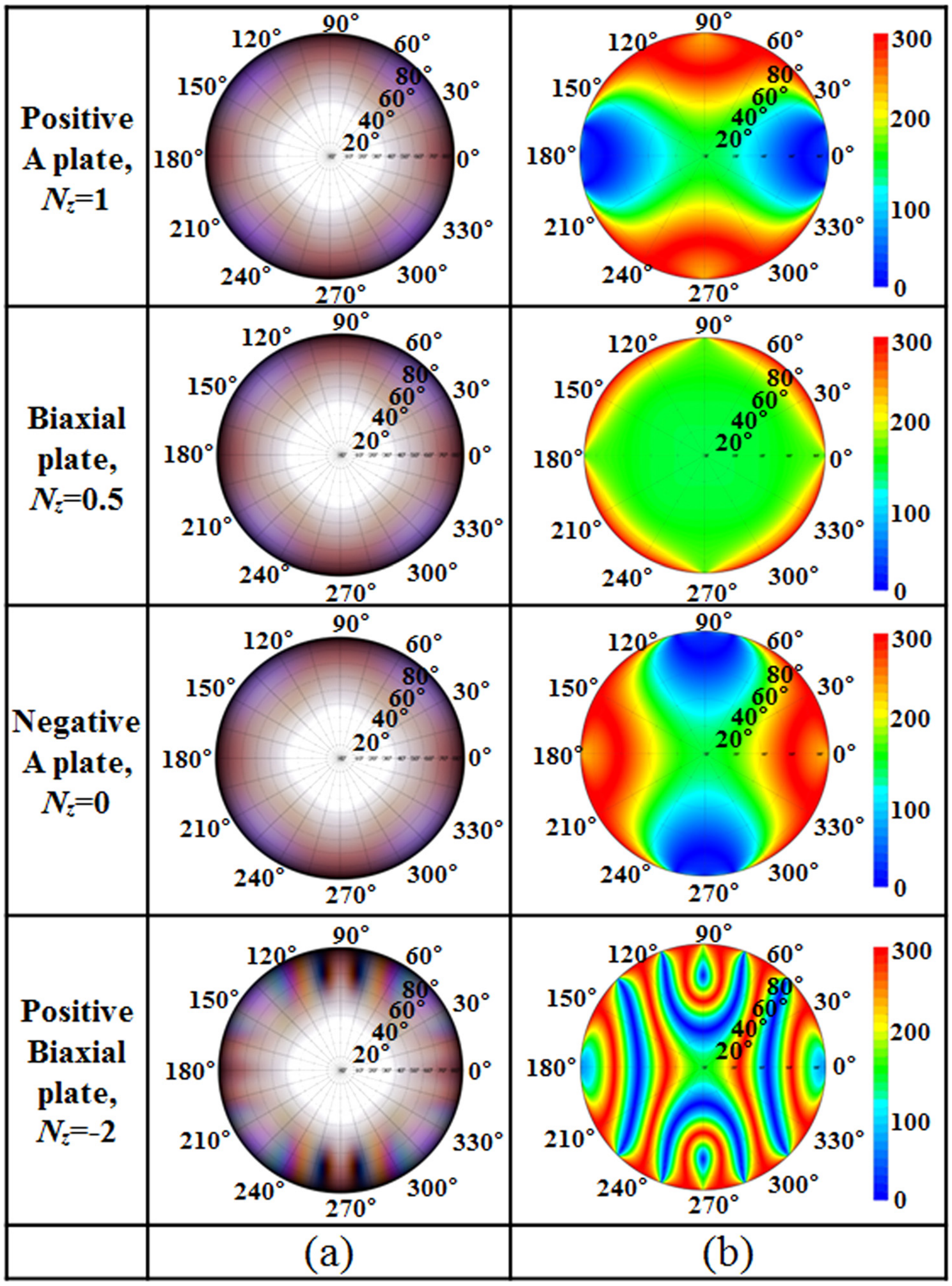

FIG. 4. Calculated (a) iso-luminance contour with color and (b) retardation contour of the low-cost polarizer according to *Nz* of the PET film in BLU with DBEF.

color mura appears in an oblique viewing direction ($\phi = 0°$, $\theta = 60°$). Interestingly, when the PET positive A film with $N_z = 1$ is used on both sides, the mura clearly disappears. From the results, we could confirm that the experimental results are strongly consistent with the calculated results shown in Fig. 2.

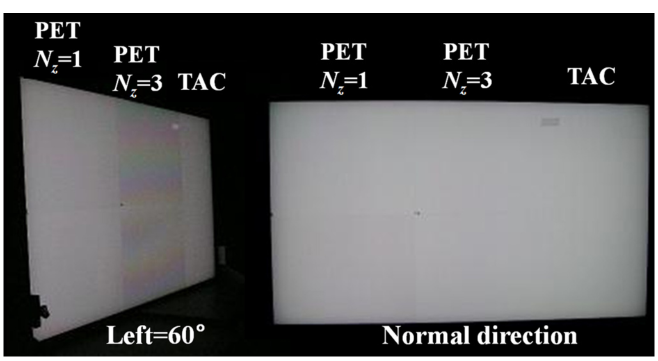

FIG. 5. Comparison of the photographs of 4 domain VA LCDs applying the TAC film and PET films with positive A ($N_z = 1$) and negative biaxial ($N_z = 3$) plates in the normal and oblique directions ($\theta = 60°$ at $\phi = 0°$).

In summary, we have developed a low cost polarizer using PET as the protection film. The color mura is generated on the off normal axis by using the conventional PET negative biaxial film due to optical characteristics such as high retardation and existence of an optic axis out of plane. Our studies clearly show that the mura can be disappeared with the use of the PET positive A film whose optic axis exists in plane.

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