Improvement of Color Mura by Using a Triple-Zero-Birefringence Polymer Film

Shizuki Sasaki [1], Yasuhiro Koike [1,2]

koike@appi.keio.ac.jp
[1]Graduate School of Science and Technology, Keio University, Kawasaki, Japan
[2]Keio Photonics Research Institute (KPRI), Kawasaki, Japan
Keywords: Zero birefringence polymer; Polarizer protective film; Color mura; LCD; OLED display.

ABSTRACT

This study proposes triple-zero-birefringence polymer (TZBP) to prevent color mura due to birefringence of polymer films used in displays. Chromaticity measurements of the display clarified the advantage of the TZBP film to prevent the color mura and reproduce an actual color of the displays.

1 Introduction

Polarizer is an essential component in liquid-crystal displays (LCD) and organic light-emitting diode (OLED) displays. To protect the polarizer, tri-acetyl cellulose (TAC) films have been used because it has low birefringence and high light transmittance [1]. Nowadays, poly(ethylene terephthalate) (PET), acrylic polymer, and cyclo olefin polymer (COP) are considered as the replacement of the TAC film because of low cost and size stability [2–4]. However, a slight amount of birefringence of the polymer causes color mura on the displayed image even if the display is seen by naked eyes [3,4]. To prevent the color mura, we previously proposed two approaches: zero-birefringence polymer [5] and high retardation polymer [6].

In this study, we propose triple-zero-birefringence polymer (TZBP) [7,8] to prevent the color mura. Our TZBP does not exhibit two types of birefringence: orientational birefringence and photoelastic birefringence. Figure 1(a) shows the orientational birefringence as a function of a degree of orientation of the polymer main chain, and Fig. 1(b) shows the photoelastic birefringence as a function of an applied stress to the polymer film. The orientational and photoelastic birefringence of the TZBP is nearly zero, compared with poly(methyl methacrylate) (PMMA). Figure 1(c) shows the temperature dependency of the intrinsic birefringence. The birefringence of the TZBP satisfies a negligible level over the wide temperature range. Furthermore, this TZBP achieves high heat resistance (glass transition temperature: 194 °C), high transparency (total light transmittance: 91.0%, haze: 0.65%), and sufficient mechanical strength (tensile strength: 35–46 MPa) [8]. In this paper, we investigate the mechanism of the color mura and evaluate the color mura of an LCD with a uniaxially drawn TZBP film, comparing with a PET film. The evaluation of the color mura by measuring chromaticity values will clarify the advantage of the TZBP to reproduce an actual color of the display.

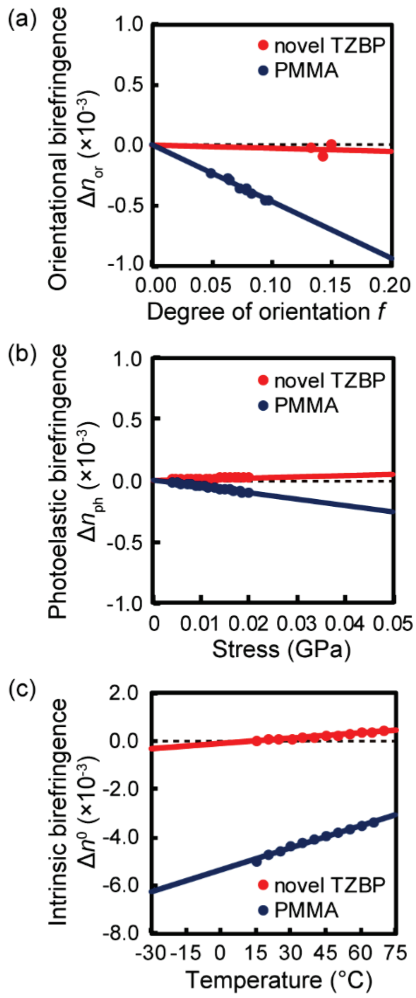

Fig. 1 Birefringence properties of TZBP and PMMA. (a) Orientational birefringence, (b) photoelastic birefringence, and (c) temperature dependency of the intrinsic birefringence [8].

2 Mechanism of Color Mura

The color mura can be seen when an LCD is viewed at an oblique angle. In this study, the viewing angle is defined by a polar angle θ and an azimuthal angle φ, as shown in Fig. 2(a). The sample film is attached to the surface of the LCD so that the slow axis of the film is parallel to the transmission axis of the top polarizer inside the LCD.

The color mura of the display is caused by two factors. The first factor is a difference of transmittance between P- and S-waves [3]. When the light is incident to the sample film as shown in Fig. 2(b), the transmittance of P-wave t_p and S-wave t_s at each interface is expressed by using Fresnel equations as follows:

$$t_p = 1 - \left(\frac{n_B\cos\theta_A - n_A\cos\theta_B}{n_B\cos\theta_A + n_A\cos\theta_B}\right)^2, \quad t_s = 1 - \left(\frac{n_A\cos\theta_A - n_B\cos\theta_B}{n_A\cos\theta_A + n_B\cos\theta_B}\right)^2, \tag{1}$$

where n_A and n_B are refractive indices of air and the sample film, respectively. θ_A and θ_B are incident and refraction angles between air and the film, respectively (see Fig. 2(b)). When n_A=1.00 and n_B=1.60, t_p and t_s is calculated as shown in Fig. 3. Difference of transmittance between P- and S-waves depends on θ_A. From t_p and t_s, a degree of polarization (DOP) of the light transmitted through the first interface is calculated as follows:

$$\mathrm{DOP} = \frac{|t_p\sin^2\varphi - t_s\cos^2\varphi|}{t_p\sin^2\varphi + t_s\cos^2\varphi} \times 100, \tag{2}$$

where $\sin^2\varphi$ and $\cos^2\varphi$ express the incident light intensity of P- and S-components, respectively. Figure 3 shows DOP when φ=65°. This suggests that the light transmitted through the film is partially polarized depending on the viewing angle θ and φ.

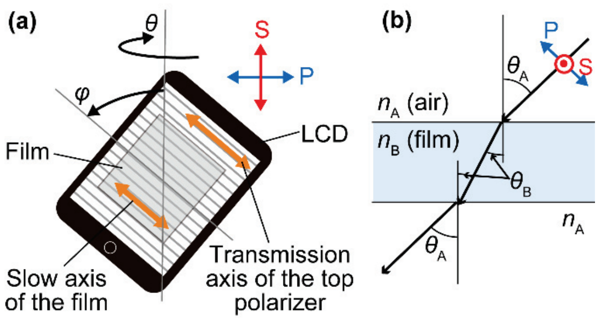

Fig. 2 Definition of the polar angle θ and the azimuthal angle φ. (a) Viewing angle of an LCD with a sample film. (b) Refraction between air and the film.

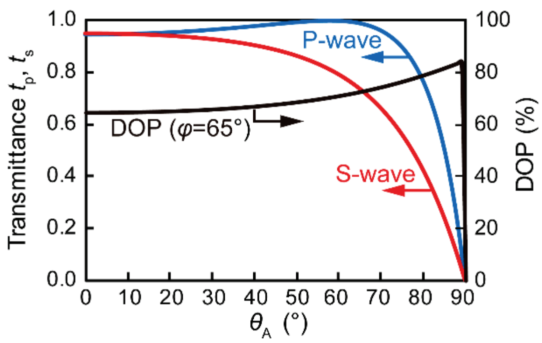

Fig. 3 Transmittance of P-wave t_p and S-wave t_s, and DOP of the light transmitted through the first interface as a function of the incident angle θ_A (n_A=1.00, n_B=1.60, φ=65°).

The second factor of the color mura is retardation of the film, which is defined as the product of the birefringence and thickness. A stretched polymer film generally has a three-dimensional refractive index, and the thickness of the film is proportional to 1/cosθ. Thus, the retardation depends on θ and φ. Owing to this retardation $R(\theta, \varphi)$, the intensity of P- and S-polarization components changes while the light passes from the first interface to the second interface. Transmittance of parallel polarization components $t_{/\!/}$ (P to P, S to S) and crossed polarization components $t_\perp$ (P to S, S to P) are expressed as follows:

$$t_{/\!/} = 1 - \sin^2 2\varphi \sin^2\frac{\pi R(\theta, \varphi)}{\lambda}, \quad t_\perp = \sin^2 2\varphi \sin^2\frac{\pi R(\theta, \varphi)}{\lambda}, \tag{3}$$

where λ is wavelength of the light. Accordingly, the transmittance of the film for P-wave T_p and S-wave T_s is calculated by using t_p, t_s, $t_{/\!/}$, and $t_\perp$ as follows:

$$T_p = \left(t_p t_{/\!/}\sin^2\varphi + t_s t_\perp\cos^2\varphi\right) t_p, \quad T_s = \left(t_s t_{/\!/}\cos^2\varphi + t_p t_\perp\sin^2\varphi\right) t_s. \tag{4}$$

Figure 4 shows T_p and T_s if θ=65°, φ=65°, and R=1590 nm. The transmittance spectrum of the light seen by naked eyes is expressed as T_p+T_s. As shown in Fig. 4, T_p+T_s exhibits wavelength dependency. This is the reason why the color mura can be seen by the naked eyes when the display is viewed at the oblique angle. Thus, zero birefringence polymer such as the TZBP is required for the polarizer protective film.

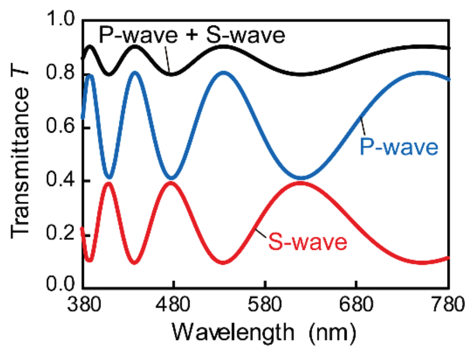

Fig. 4 Transmittance spectra of P-wave T_p, S-wave T_s and the light seen by naked eyes T_p+T_s (θ=65°, φ=65°, R=1590 nm).

3 Experiment

We evaluated the color mura of an LCD by using each of TZBP and PET films. Because the commercial PET films are usually stretched, the TZBP film was uniaxially heat-drawn above its glass transition temperature (draw ratio: 2.6, draw speed: 120 mm/min). Table 1 lists the thickness and retardation of the films. The retardation of the TZBP film was measured using a birefringent measurement system (ABR-10A-EX, Uniopt Co., Ltd.), and the retardation of the PET film was measured using an optical birefringence analyzer (KOBRA-WPR, Oji Scientific Instruments).

Table 1 Thickness, in-plane retardation R_0, and out-of-plane retardation R_{th} of the TZBP and PET films used in this study.

Sample	Thickness (µm)	R_0 (nm)	R_{th} (nm)
TZBP	17	0.73	-
PET	12	570	1750

The color of an LCD was evaluated by measuring chromaticity values (u', v'). The chromaticity values were measured using a spectroradiometer (CS-2000A, Konica Minolta, Inc.) as shown in Fig. 5(a). First, the chromaticity values were measured at various viewing angles θ, φ. When θ was varied from 0° to 80°, φ was fixed at 65°, and when φ was varied from 0° to 90°, θ was fixed at 65°. Next, the chromaticity change $\Delta u'v'$ between two viewing angles was measured for 24 colors of Macbeth chart (Fig. 5(b)). $\Delta u'v'$ was defined as

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}, \qquad (5)$$

where (u'_1, v'_1) and (u'_2, v'_2) are the chromaticity values measured at each of two viewing angles.

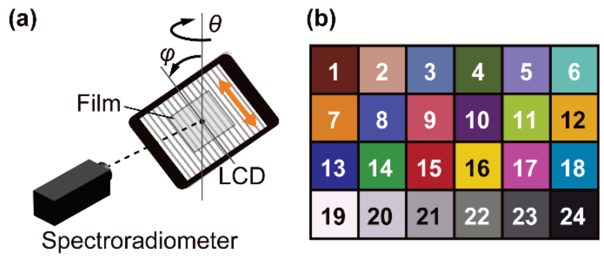

Fig. 5 (a) Schematic diagram of the experimental setup used to measure the chromaticity values. (b) Macbeth chart. Each color in this chart was displayed on the LCD shown in Fig. 5(a).

4 Results and Discussion

Figure 6(a) shows the chromaticity of the LCD with each of the TZBP and PET films for θ of 0°–80° and φ of 65°, and Fig. 6(b) shows the chromaticity for θ of 65° and φ of 0°–90°. These color maps indicate that the color of the LCD with the PET film changed when the viewing angle changed. Especially when φ changed from 55° to 65° (Fig. 6(b)), $\Delta u'v'$ for the PET film was 0.02, which means humans can recognize the color shift. In contrast, the chromaticity of the LCD with the TZBP film was almost the same as that without a film at all viewing angles. The TZBP film achieved smaller color shifts because the retardation is nearly zero as shown in Table 1.

Because the PET film exhibited large color shift when φ changed from 55° to 65° as shown in Fig. 6(b), we measured $\Delta u'v'$ from φ=55° to 65° while θ was fixed to 65°.

Figure 7 shows $\Delta u'v'$ of the LCD with the TZBP and PET films for each color in the Macbeth chart. The numbers 1–24 surrounding the graph correspond to the color numbers in Fig. 5(b). The chromaticity change increases as the points move further inwards along the radius. According to ISO 9241-303:2011(E), humans cannot distinguish two colors when $\Delta u'v'$ is less than 0.02 (indicated by the area outside the circular dashed line in Fig. 7). The LCD with the PET film exhibited $\Delta u'v'$ more than 0.02 for some colors. In contrast, $\Delta u'v'$ of the LCD with the TZBP film was less than 0.02 for all 24 colors and the same as $\Delta u'v'$ of the LCD without a film. This suggests that the TZBP did not change the color of the displayed image. Therefore, the TZBP is suitable for the polarizer protective film to prevent the color mura.

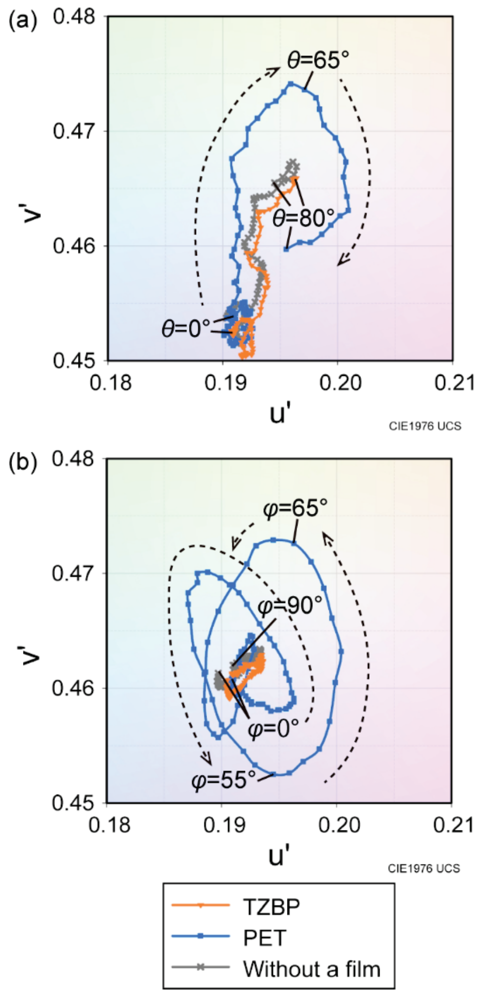

Fig. 6 Chromaticity (u', v') of the LCD with the TZBP and PET films, and without any film. The viewing angle was (a) θ=0°–80°, φ=65° and (b) θ=65°, φ=0°–90°. The arrows indicate the color shift caused by the PET film.

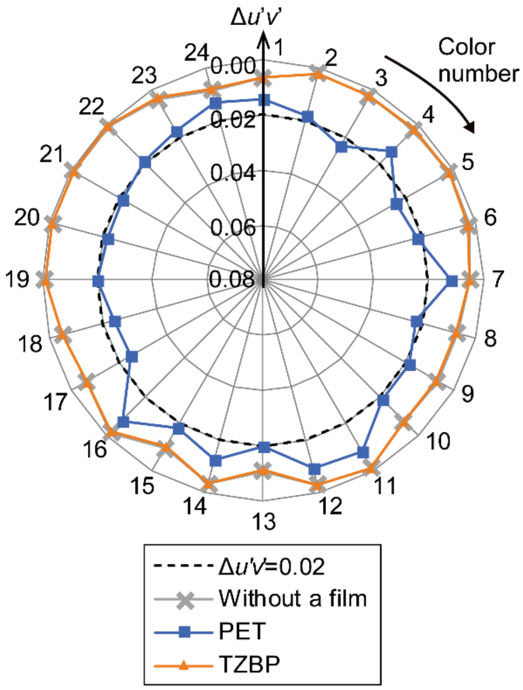

Fig. 7 Chromaticity change Δ*u*'*v*' between *φ*=55° and 65° for 24 colors in the Macbeth chart. The dashed line indicates Δ*u*'*v*' of 0.02, the maximum value that humans cannot distinguish two colors.

5 Conclusions

To prevent the color mura of the LCDs and OLED displays, we proposed the TZBP that achieves not only zero birefringence but also high heat resistance, high transparency, and sufficient mechanical strength. The color mura observed at the oblique angle is caused by the difference of transmittance between P- and S-waves, and the retardation of the polymer film. For these reasons, the LCD using the PET film with the in-plane retardation of 570 nm showed the color shift that humans can recognize as the LCD rotated. In contrast, the LCD with the uniaxially drawn TZBP film exhibited almost the same color as the LCD without a film because the retardation of the TZBP was nearly zero even if the film was drawn. Furthermore, by using the TZBP film, the chromaticity changes of the LCD at the oblique angles were less than 0.02 for all 24 colors in the Macbeth chart. Therefore, the TZBP is beneficial to reproduce an actual color of the displays and can be a strong candidate for the polarizer protective film.

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