Improving Image Quality with Surface-Treated Random Depolarization Films

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Abstract

Our random depolarization film (RDF) randomizes polarization by birefringent dopant particles, thereby resolving color degradation of displays. To further improve image quality with RDFs, this paper designs the RDF with surface treatments. The RDF achieved practical contrast ratios with anti-reflection treatment and sharp images by utilizing directional forward light scattering. Therefore, the designed RDF has high practicality for existing displays and effectiveness in realizing real-color displays.

Author Keywords

Depolarization; Polymer film; Birefringence; Reflection; Image quality.

1. Introduction

At present, liquid-crystal displays (LCDs) and organic light-emitting diode (OLED) displays are widely used outdoors, such as in mobile phones, automotive instrument panels, car navigation systems, and digital signage. Since these displays utilize polarizers to output images or to eliminate internal reflection, linearly polarized light is emitted from the displays, which causes blackout and color degradation of displays.

The blackout problem occurs when someone wearing polarized sunglasses sees a display that emit linearly polarized light. When a transmission axis of the sunglasses is perpendicular to the polarization direction of the light from the display, the displayed image will be completely invisible. As a conventional approach to address this blackout problem, quarter-wave plates (QWPs) have been used in existing displays. The QWP converts linearly polarized light into circularly polarized light using the retardation of a quarter wavelength. However, owing to imperfect wavelength dispersion of the QWP, color of the image changes depending on the angle of the transmittance axis of the polarized sunglasses [1].

In addition, even when displays are viewed without polarized sunglasses, polymer films used in the displays, such as polarizer protective films, can cause severe color degradation owing to their birefringence [2, 3]. This color degradation is seen at the oblique viewing angles because the transmittance difference between P- and S-waves makes interference colors of the polymer films visible.

To address aforementioned issues related to the polarization, we proposed the random depolarization film (RDF) [1, 3−6]. The RDF consists of a polymer film doped with birefringent microparticles. Owing to the birefringence of the dopant particles, RDFs converts linearly polarized light into randomly polarized light. Figure 1 shows an RDF placed on an LCD viewed in a crossed-polarizer state. While the image without the RDF looks completely black, the image with the RDF is visible. Figure 2 shows an LCD with a QWP and the RDF viewed in a parallel-polarizer state. While the image with the QWP looks yellowish, the image with the RDF hardly shows any color change. As shown in Figs. 1 and 2, the RDF addresses the polarization problems, thereby realizing real-color displays.

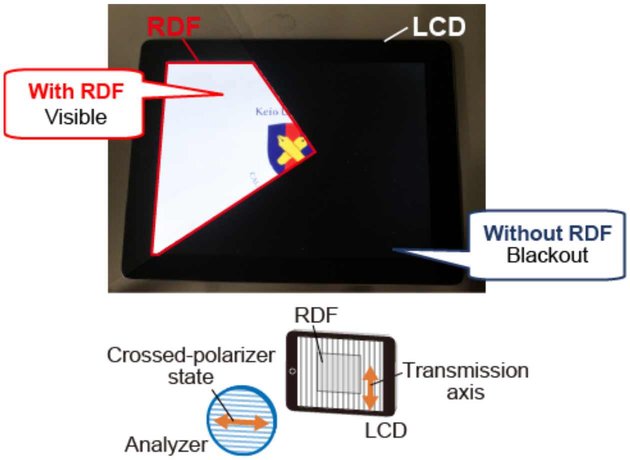

Fig. 1 Solving the blackout problem by the RDF. This photograph is taken in a crossed-polarizer state.

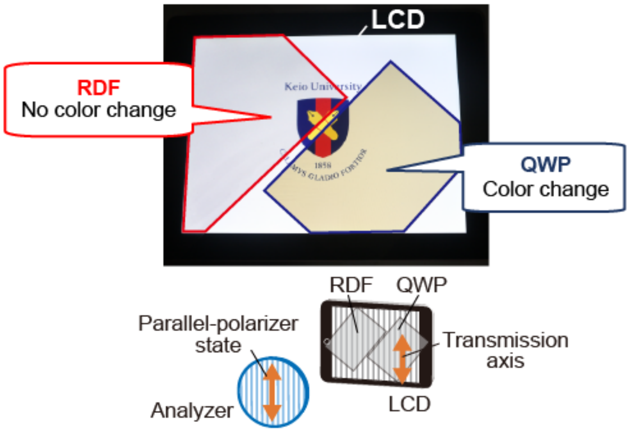

Fig. 2 Preventing the color change by the RDF. This photograph is taken in a parallel-polarizer state.

To further improve image quality, especially in ambient light environments, this study designs RDFs with anti-glare (AG) and anti-reflection (AR) treatments. Properties of surface reflection and light scattering significantly affects the image quality such as contrast ratios, image sharpness, and color [7−9]. In this study, a practical RDF is designed by considering the surface reflection of the AG and AR films and light scattering by the birefringent dopant particles in the RDF. The visual quality of the image with the RDFs is evaluated by measuring the contrast ratios and observing the image sharpness. Furthermore, the depolarization effects of the RDFs are evaluated by measuring the color changes of the displayed image.

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2. Experimental Methods

2.1 Configuration of Samples

Commercial AG film (LCD-MB133, Sanwa Supply Inc.) and AR film (JAR, MeCan Imaging Inc.) were attached on RDFs, which are referred to as "AG+RDF" and "AR+RDF", respectively. The substrate of both AG and AR films is poly(ethylene terephthalate) (PET), and the total thickness of the AG and AR films are approximately 180 and 120 μm, respectively. To evaluate light-scattering effect of the dopant particles in the RDFs, reference samples were prepared using polycarbonate (PC) films instead of the RDFs (referred to as "AG+PC" and "AR+PC").

2.2 Measurement of Reflectance

The relative reflectance spectra of the samples were measured using a spectrophotometer with an integrating sphere (UV-3600 Plus, Shimadzu Corp.). In this measurement, black tapes were attached to the back side of the sample films to minimize back-side reflection. The measured reflectance spectrum $R(\lambda)$ was converted into luminous reflectance R_L by the following equation [7]:

$$R_L = \frac{\int_{360}^{800} V(\lambda)S(\lambda)R(\lambda)d\lambda}{\int_{360}^{800} V(\lambda)S(\lambda)d\lambda}, \tag{1}$$

where $V(\lambda)$ is the spectral luminous efficiency of the human eye and $S(\lambda)$ is the spectrum of standard illuminant D65.

2.3 Evaluation of Image Quality

The quality of the displayed images with the samples was evaluated by comparing dynamic contrast ratio (CR) and image sharpness. The sample films were attached with an IPS LCD surface using immersion oil (refractive index: 1.518) to minimize the refractive index disparities. The CR is defined as L_W/L_K, where L_W and L_K are luminance for full-screen white and black, respectively. The luminance was measured using a spectroradiometer (CS-2000A, Konica Minolta, Inc.) in a darkroom. The original CR of the LCD used in this study was 1831:1.

2.4 Evaluation of Depolarization Effects of RDFs

The depolarization effect of the RDFs was evaluated by measuring chromaticity changes $\Delta u'v'$ of the LCD with the RDFs. $\Delta u'v'$ is defined as the distance between the chromaticity coordinates in the crossed-polarizer state (u'_{90°, v'_{90°) and parallel-polarizer state (u'_{0°, v'_{0°) on CIE 1976 UCS diagram. This can be expressed as

$$\Delta u'v' = \sqrt{(u'_{0^\circ} - u'_{90^\circ})^2 + (v'_{0^\circ} - v'_{90^\circ})^2}. \tag{2}$$

The experimental setup for measuring chromaticity was composed of an LCD with the sample film, an analyzer, and a spectroradiometer (CS-2000A, Konica Minolta, Inc.). The fast axis of the PET layer in the AG and AR films was fixed parallel to the transmission axis of the top polarizer in the LCD to minimize the effect of birefringence of the PET film.

3. Results and Discussion

3.1 Luminous Reflectance of the Sample Films

Table 1 shows the relative luminous reflectance of the sample films. In this measurement, a mirror (TFA-2535R05-10, SIGMAKOKI Co., Ltd.) was used as a standard sample. Table 1 indicates that applying the surface treatments to the RDFs, especially the AR treatments, reduced the reflectance. The difference in the reflectance between the PC and RDF were less than 0.1%, indicating that the internal light scattering by the dopant particles in RDFs has little effect on the total reflectance.

Table 1 Relative luminous reflectance of the sample films and the reflectance difference between the PC and RDF.

	PC	**RDF**	AG+ PC	**AG+ RDF**	AR+ PC	**AR+ RDF**
R_L (%)*	6.5	**6.5**	5.6	**5.7**	1.5	**1.6**
Diff. (%)	±0.0		+0.1		+0.1	

To evaluate the scattering effect, diffuse reflectance R_{Ld} was also measured (Table 2). In this measurement, a barium sulfate plate was used as a standard sample. Without surface treatment and with AR treatment, the RDFs exhibited 0.3–0.7% higher diffuse reflectance than the PC films, suggesting that the dopant particles in RDFs slightly diffuse the reflected light.

Table 2 Relative diffuse reflectance of the sample films and the reflectance difference between the PC and RDF.

	PC	**RDF**	AG+ PC	**AG+ RDF**	AR+ PC	**AR+ RDF**
R_{Ld} (%)*	1.1	**1.8**	4.0	**4.1**	0.5	**0.8**
Diff. (%)	+0.7		+0.1		+0.3	

3.2 Contrast ratio of the LCD

Table 3 shows the CR of the LCD using the sample films. Owing to the light scattering and absorption by the dopant particles, the CR for the RDFs was 9–10% lower than that for the PC films. Nevertheless, the CR mainly depended on the surface treatment. As a result, AR+RDF exhibited higher CR than AG+PC, which suggests that AR+RDF achieved a practical CR for use in existing displays. Taking account of ambient illumination, ambient contrast ratio (ACR) can be expressed as follows [7]:

$$ACR = \frac{L_W + L_{ambient} \cdot R_L}{L_K + L_{ambient} \cdot R_L}, \tag{3}$$

where $L_{ambient}$ is the ambient illuminance on the display. Equation 3 shows that the ACR is highly dependent on R_L for higher $L_{ambient}$. As shown in Table 1, using the RDF has little effect on R_L. Therefore, Eq. 3 suggests that the difference in the contrast ratio with and without the dopant particles will be smaller under stronger ambient light, such as in outdoor environments.

Table 3 Contrast ratio of the LCD with the sample films and the difference in contrast ratios between the PC and RDF.

	AG+PC	**AG+RDF**	AR+PC	**AR+RDF**
CR	1551:1	**1409:1**	1810:1	**1626:1**
Diff.	−142 (−9.2%)		−184 (−10.2%)	

3.3 Image Sharpness under Ambient Light

Figure 3 shows the LCD images with the sample films, taken under room light (~470 lx). Comparing the PC and RDF, the light scattering by the dopant particles in the RDF hardly reduced the image sharpness even under ambient light. This maintenance of sharpness is attributed to minimizing difference in refractive index between the matrix and dopants and optimizing the dopant particle size. Microparticles larger than the wavelength of visible light scatter the light strongly forward [5]. The directional forward scattering is effective in maintaining the image sharpness.

Furthermore, the room-light reflection, surrounded by the dashed line in Fig. 3, was slightly diffused by the RDF. This improvement was likely due to the increase in diffuse reflectance by RDFs shown in Table 2. Increasing diffuse reflectance and reducing specular reflectance prevents undesirable mirror-like reflection [9]. Therefore, taking into account all of contrast ratio, image sharpness, and reflection, we conclude that the RDF with AR coating has a great advantage in achieving superior image quality.

Our previous work showed that the sharpness depends on the pixel pitch of displays [5]. The pixel pitch of the LCD shown in Fig. 3 is 157 μm, which corresponds to a 27-inch screen for 4K resolution and a 54-inch screen for 8K resolution. This result suggests that the RDF is particularly suitable for displays with medium- and large-sized screen such as monitors, automotive instrument panels, and digital signage.

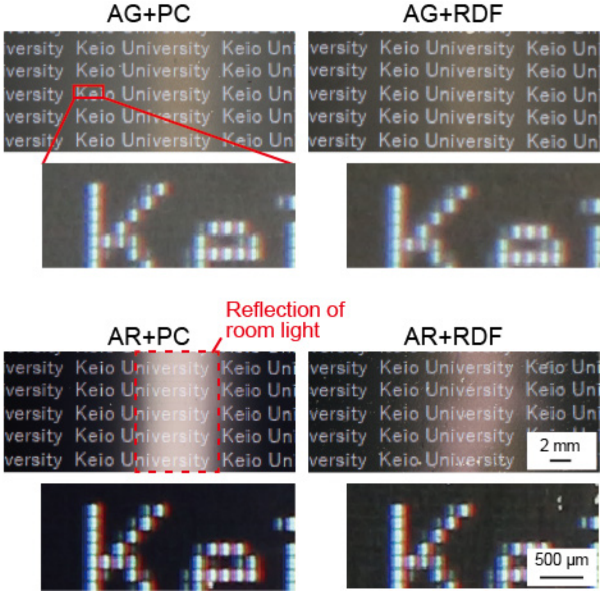

Fig. 3 Photographs of LCD images with each sample film, taken under the room light.

3.4 Color change of the LCD

The depolarization effects of AG+RDF and AR+RDF were evaluated by measuring the chromaticity changes $\Delta u'v'$. For comparison, the QWP with normal dispersion shown in Fig. 2 was also evaluated. Figure 4 shows $\Delta u'v'$ for 24 colors of Macbeth chart. Owing to the random depolarization by the RDF, both AG+RDF and AR+RDF exhibited much lower $\Delta u'v'$ than the QWP. According to ISO 9241-303:2011, humans cannot recognize the difference between two colors when $\Delta u'v'$ is less than 0.02. Both RDFs achieved $\Delta u'v'$ less than 0.02 for all colors of the Macbeth chart, indicating that the high depolarization effect is maintained even when AG and AR coatings are applied.

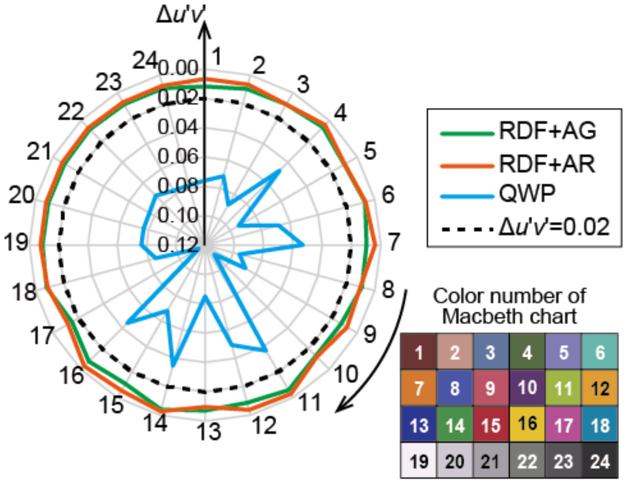

Fig. 4 Chromaticity changes $\Delta u'v'$ of the LCD image for each color in Macbeth chart.

4. Conclusion

The RDF, which randomly depolarizes light by birefringent dopant particles, resolves blackout and color degradation issues in existing LCD and OLED displays. To further improve image quality with RDFs, the AG and AR films were applied to the RDFs. With the AR treatment, which significantly reduced the total reflectance, the RDF achieved a practical contrast ratio. Furthermore, by utilizing directional forward light scattering, the RDFs maintained the image sharpness even under ambient light and reduced undesirable mirror-like reflection. Even after applying the surface treatments, the high depolarization effect of the RDF was maintained. Therefore, the RDF with AR coating has a great advantage in achieving superior image quality. We believe that the designed RDF is highly effective in realizing real-color displays and is highly practical for various outdoor displays such as mobile monitors, automotive instrument panels, and digital signage.

5. Impact of This Research

Polarization phenomena have been utilized in most LCDs and OLED displays to produce images and improve image quality through complex polarization controls such as polarizers and retardation films. However, even with such add-on technologies, color degradation remains unresolved in existing displays. Our proposed RDF addresses this issue by converting the polarized light from displays into randomly polarized light, as if it reverted to “natural light.” In our previous study [6], we demonstrated that the random depolarization by RDFs effectively resolves the blackout and color degradation issues caused by the polarization of existing displays. However, light scattering by the dopant particles in RDFs can reduce the image quality of the displays such as the contrast ratio and image sharpness. To address this, this study designed the RDF with surface treatments. By designing surface reflection and light scattering, we realized the RDF that achieves sufficient contrast ratio and sharpness while maintaining its depolarization effect. In the conference, we will present a prototype of an LCD using the surface-treated RDF. By observing the prototype, participants can confirm high effectiveness of the random depolarization by the RDFs and good visibility of the LCD image with the RDFs.

6. References

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