1. Introduction

Reflective displays use ambient light, such as sunlight or indoor lighting, as a light source; they do not require a backlight, and have low power consumption1)-3). The brighter the ambient light, the brighter the display and, the better the visibility of these displays. These characteristics are difficult to achieve in transmissive liquid crystal displays (LCDs) and organic electroluminescence displays (OLEDs); reflective displays are therefore more suitable for applications that are often used outdoors or where a reduction in the number of charging is desirable.

Figure 1 shows the structure of a reflective LCD using a light-diffusing film. In the optical design of a reflective display, it is important that ambient light incident from various angles is effectively diffusely reflected toward the observer in front of the display. Several light diffusing materials, such as surface relief-patterned diffusive mirrors and particulate diffusers, have been proposed4)-6). However, these diffusing materials do not work effectively in environments with obliquely incident ambient light. In such cases, the diffused light luminance directed toward a viewer in front of the display becomes low and the image becomes dark. Therefore, we focus here on the use of refractive index distribution-type light diffusing films with high controllability of the diffused light distribution7, 8). We have optimized the diffused light distribution by controlling the tilt angle and thickness of the refractive index distribution structure formed inside the film, and have demonstrated application to nonrotating reflective displays such as smart watches and signages9) -10).

Considering further expansion of applications, there are displays such as tablets and smartphones where the screen can be rotated to allow either portrait or landscape viewing. If a reflective display can be adapted to screen rotation, its use may be further widened.

In this scenario, the mirror electrode and light-diffusing film must be able to reflect and diffuse light to the front of the display, regardless of the azimuth of the incident ambient light. The wider the diffusion area, the more light can be diffused to the front, even if the azimuth changes; however, if the diffusion area is too wide, the overall brightness will be reduced and the image will be blurred. Therefore, we optimized the diffuse reflection characteristics while taking into account lowering

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Abstract  We examined anisotropic light-diffusing films for reflective displays to realize a wide viewing angle for a rotating screen such as a tablet. By orthogonally laminating 60-µm-thick anisotropic light diffusing films having bent columnar structure, we were able to demonstrate uniform diffuse reflection characteristics for a point light source polar angle of 30° from various azimuth angles. Then, we showed that image blur could be suppressed by narrowing the gap between the reflector and the diffusing layer, such as by grinding the top cell glass.

Keywords: Reflective display, wide diffusing region, Anisotropic light diffusing film, Refractive index distribution, Columnar polymer structure, UV curing.
brightness and image blur. Based on the above, several light-diffusing films with a bent columnar structure were prepared, and their diffuse reflection luminance distributions were measured when a point light source was incident at a polar angle of 30° for each of the four azimuthal angles. The results are reported with respect to polarization retention and image blur.

2. Preparation of light diffusing films

Light-diffusing films were prepared such that the front brightness and viewing angle do not change even when the display is rotated. In addition, a wide viewing angle is needed to support a large device.

A spherical silica filler with a diameter of 4.5 µm was added to an acrylic pressure-sensitive adhesive (PSA) at 60 wt% to prepare particulate diffusion film A for comparative purposes. The film thickness was adjusted to 35 µm, and the haze was 95%.

Figure 2 shows the materials used for fabrication of the anisotropic light diffusing film B. The larger the difference in refractive index between the high refractive index bent columnar structure formed inside the film and the low refractive index binder, the better the diffusion performance. Accordingly, ethoxylated o-phenylphenol acrylate with a refractive index of 1.577 (@ 589 nm, 25°C) before curing and a urethane methacrylate oligomer with a refractive index of 1.455 were used as the main materials. Equal amounts of each main material were heated and mixed at 70°C, and a 7.4 wt% photoinitiator (Fig. 2 (c)) and a 0.074 wt% ultraviolet (UV) absorber (Fig. 2 (d)) were added to obtain a coating liquid.

The resulting coating liquid was applied to a 100-µm-thick release film treated on one side of a polyethylene terephthalate (PET) film with a silicone release agent to form a 110-µm-thick coated layer. Next, a release film having a thickness of 38 µm was laminated on the surface. This sample was placed on a conveyor and moved under UV light at a speed of 0.2 m/min. A high-pressure mercury lamp with a main wavelength of 365 nm and subwavelengths of 254, 303, and 313 nm was used. Furthermore, this UV light source was collimated using an optical lens incident on the sample at an angle of 5°. The illuminance was 1.06 mW/cm² and the light intensity was 43.7 mJ/cm².

We propose the following structure formation mechanism for the diffusion film. When the resin mixture is initially irradiated with collimated UV light, low molecular weight and highly reactive monomers selectively react to form ball lens-like polymerized aggregates with a high refractive index. The continuously irradiating UV light is focused under the ball lens and grows downward while forming a columnar structure in the direction of the angle of the UV light.

The experimental results indicate that when the UV illuminance is high, the curing speed is also high, and a linear columnar structure is formed along the angle of the UV light refracted when it is incident on the coated layer. When a resin mixture containing a small amount of UV absorber is used, UV light is absorbed within the coated layer, and the illuminance decreases toward the bottom. By intentionally reducing the illuminance within the coated layer, it is possible to obtain a structure that is bent in the middle, similar to that obtained with low illuminance irradiation.

Figure 3 shows the cross-section of Diffuser B in the direction of machine movement, which was observed using an optical microscope (VHX-1000; KEYENCE). A bent columnar structure is evident due to the added UV absorber, and the tilt angle of the structure changes.
above and below the diffusion layer.

The angle of incidence of UV light was set to 5°, to widen the diffusion angle region while suppressing changes in brightness and viewing angle with respect to the rotation of the display. However, since the inclination of the bent columnar structure is uniaxial, there is a possibility that it will expand only along one axis. Therefore, to diffuse the ambient light incident from the four directions assumed in the tablet, Diffuser C was prepared by orthogonally stacking Diffuser B using a 25-µm-thick acrylic PSA.

In a light-diffusing film with a bent columnar structure, the difference in film thickness mainly affects the uniformity of the brightness of the diffused light in the diffusing region. Uniformity improves with increasing film thickness. However, it is necessary to determine the optimum thickness because it also affects the decrease in polarization retention and image blur. Therefore, we prepared Diffuser D, which was orthogonally laminated by reducing the film thickness of Diffuser B to 60 µm. Table 1 summarizes the light diffusing-films used in this study.

### 3. Diffuse reflection property

The diffuse reflection properties of each light diffusing film were measured using a conoscope (Autronic-Melchers GmbH). Figure 4 (a) shows a model of the light diffusing film with the bent columnar structure used for Diffuser D, in which the direction of inclination is the moving direction of the conveyor, indicated by arrows. Figure 4 (b) shows a sample configuration for conoscopic measurement, which was laminated on a mirror (BV2; JDSU) via a clear acrylic PSA. In the case of orthogonal lamination, the directions of the arrows were unified as shown. For each sample, a point light source was individually incident at a polar angle of 30° from azimuthal angles $\phi = 0, 90, 180,$ and $270^\circ$, and the diffuse reflected light was measured.

Figure 5 (a) shows the result of diffuse reflected light obtained by entering a point light source at a polar angle of 30° from four directions into a particulate-type Diffuser A. In each of the images, diffuse reflection centered on the specular direction was observed. Therefore, when the point light source is incident at 30°, the brightness of the front is low. The change in diffuse reflection characteristics caused by rotating the display was compared with the luminance distribution in the horizontal direction in front of each measurement result in four directions (Fig. 5 (b)). Data measured with a white reflection standard (WRS) at $\phi = 90^\circ$ and a polar angle of 30° were used for comparison. The change in the luminance distribution between azimuths is very small in Diffuser A, however, the front is the edge of the diffusion region at a polar angle of 30° incidence. So, the brightness is almost the same as the WRS, and the viewing angle is very narrow. This is because particulate diffusers exhibit isotropic diffusion in the direction of the incident angle of light. When the horizontal viewing angle is very narrow, the in-plane luminance distribution of the display may be adversely affected.

Figure 6 (a) shows a distribution image of the diffuse reflected light obtained by entering a point light source from four directions at a polar angle of 30° about Diffuser B using a sheet of anisotropic light diffusing film. In all the images, it can be seen that the front of the display is included in the diffusion region. However, the shape of the diffuse reflected light at $\phi = 0^\circ$ and $180^\circ$ is not circular. According to Fig. 6 (b), Diffuser B shows higher...
luminance than the WRS, but the change in the luminance distribution in the horizontal direction between the azimuthal angles is large. In particular, the distribution at $\phi = 0^\circ$ and $180^\circ$ has no symmetry and exhibits large undulations. We attributed that behavior to a strong dependence of a light-diffusing film with a bent columnar structure on the azimuth angle of the incident light. When applied to a reflective display with a rotated screen, there may be issues with luminance changes at the front and luminance unevenness across the screen.

Figure 7 shows the measurement results for Diffuser C. At a polar angle of 30° from four azimuthal angles, circular diffusion was obtained with the front included in the diffusion region. From Fig. 7 (b), the distribution for each azimuth is almost uniform, and the front luminance change is small. This is attributed to orthogonal stacking of the light-diffusing films, which causes the tilt axis of the bent columnar structure to be coaxial with the light source incident axis in either layer by orthogonally stacking the light diffusing films.

Although the viewing angle is narrower than that of the WRS, due to diffuse reflection with a half-value angle of about ±40°, a brightness of 1.5 times or more can be obtained within the diffusion region. These results show that when Diffuser C is applied to the display, the luminance change and in-plane unevenness are small even when the screen is rotated.

Diffuser C showed good diffuse reflection characteristics that were uniform and symmetric with respect to the light source incident from four directions. However, the thickness of the functional layer is twice that of Diffuser B. There is concern that it may affect the polarization retention and image blur. Therefore, the diffuse reflection characteristics of Diffuser D, which was orthogonally laminated with the thickness of one layer reduced to 60 µm, were evaluated.

Although a slight shoulder peak was observed, it showed a uniform diffuse reflection characteristic with respect to the light source incident from four directions, similar to Diffuser C (Fig.8). With such a change, it can be considered that no degradation in the diffuse reflection characteristics is caused by reducing the thickness of the film.

4. Polarization retention

For displays that use polarized light, such as LCDs, diffusion that does not disturb the polarization state is required. If the polarization is disturbed by using a light diffusing film with low polarization retention, there will be a decrease in contrast. In particular, there is concern about the effect of orthogonally laminating anisotropic light diffusing films. Therefore, the polarization retention of each film was measured using the measurement system shown in Fig. 9. The light diffusing film was placed between the polarizer and the analyzer, and parallel light was made to enter from the normal direction. The luminance $L_p$ measured under parallel nicol and $L_c$ measured under crossed nicol were measured, and the polarization retention $P$ was calculated from Equation (1).

$$P = \frac{(L_p - L_c)}{(L_p + L_c)} \times 100$$ (1)

The results are summarized in Table 2. Diffuser A showed the highest value, however, even though Diffuser C was the thickest due to the lamination of two anisotropic light diffusing films; it exhibited a relatively
high P value of 99.29%. From these results, it was found that P tends to decrease due to the influence of the diffusion region and the increase in thickness, but maintains a high value. The higher the P-value, the more feasible it is to suppress image quality degradation such as "rainbow unevenness", 99.5% is considered the minimum acceptable P value.

5. Image blur

In a reflective display, image blur caused by the diffusing layer thickness, the diffuse reflected light distribution, and the distance to the mirror must be considered. Therefore, the degree of image blur caused by the light diffusing film was compared using the USAF 1951 test target pattern. The gap between the reflection layer (Cr) and the light diffusing film was controlled by changing the thickness of the clear PSA to 100, 200, 300 and 400 µm. This gap simulates the thickness of the top cell glass in a reflective LCD. Figure 10 shows the laminated structure of the evaluation sample. Dark field observation was performed on each sample using the optical microscope.

Consider application to a display such as an 8-inch tablet with an aspect ratio of 4:3 and resolution of 200 ppi. The USAF 1951 test target pattern requires that line 1 of group 2 of the test target is not blurred. We evaluated Diffuser D, which shows the most promise for rotational use.

Figure 11 (a) shows how the image blur differs for PSA gaps of 100 and 400 µm. When the gap is 400 µm, the image blur clearly increases. Next, images were taken for each group / line of the test target, and cross-sections of the three lines were plotted according to the gray scale for each thickness (Fig. 11 (b)).

This figure shows that the distance between the Cr and the diffusing film is correlated with image blur; the distance must be minimized when applying Diffuser D to the reflective LCD.

Recognition was possible up to just before the distinction between light and dark could not be made, as in the 400-µm gap in the Fig. 11 (b), and the resolution value was read at this point. Table 3 summarizes the resolution values for each light diffusing film when the PSA gap was changed. When the gap is 400 µm, the effect of the diffusion angle width for each diffusion film is large, and there is a difference in the resolution value. In this case, the orthogonally laminated Diffusers C and D are strongly blurred. However, when the gap was reduced to 100 µm, the effect of the diffusion region width was weakened, and all exhibited the same

![Fig.9 Measurement system of polarization retention.](image)

![Fig.10 Composition of samples for image blur evaluation.](image)

![Fig.11 Difference in image blur due to PSA gaps and how to determine these.](image)

| Diffuser | Lp (cd/m²) | Lc (cd/m²) | P (%) |
|----------|------------|------------|-------|
| A        | 890        | 0.27       | 99.94 |
| B        | 729        | 1.25       | 99.66 |
| C        | 560        | 1.99       | 99.29 |
| D        | 620        | 1.50       | 99.52 |

![Table 2 Results of polarization retention measurements.](image)

| Diffuser | PSA Gap (100, 200, 300, 400µm) | 100 µm | 200 µm | 300 µm | 400 µm |
|----------|-------------------------------|--------|--------|--------|--------|
| A        | 20.16                         | 17.95  | 14.25  | 10.10  |
| B        | 20.16                         | 17.95  | 12.70  | 8.98   |
| C        | 20.16                         | 11.30  | 8.98   | 4.49   |
| D        | 20.16                         | 12.70  | 10.10  | 5.04   |

![Table 3 Determination of image blur using USAF 1951 test target. (Unit: line pairs per mm)](image)
resolution value. From these results, it is considered that when using Diffusers C and D that are orthogonally stacked, image blurring can be suppressed by reducing the thickness of the top cell glass by grinding.

6. Conclusion

Here, optimization of a light diffusing film under conditions of rotation of a reflective display was studied. It was found that a structure in which an anisotropic light diffusing film with bent columnar structure, formed at a UV incident angle of 5° and orthogonally laminated, was capable of diffuse reflecting in the front direction regardless of the azimuthal angle of the incident external light. Next, polarization retention and image blurring, which were concerns related to expansion of the diffusion angle region and the increase in thickness, were investigated, and it was confirmed the decrease in polarization retention was small, and that image blur could be suppressed by narrowing the gap between the reflector and the diffusing film.

Therefore, good visibility can be obtained by applying the light diffusing film reported in this paper to reflective displays such as tablets or smartphones that are rotated and viewed. It is expected that further applications such as outdoor and educational use will be investigated in the future.

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