1. Introduction

In recent years, noticeable progress in optical performance of liquid crystal displays (LCDs) has been made with the huge growth of smart phones and tablet computers. While the resolution of LCDs are progressing, light efficiency is being decreased because of the small aperture ratio of the pixels, therefore the reducing of power consumption has been one of the most important problems in the development of high performance LCDs.

Reflective displays using ambient light are promising candidates as low power displays, and the development of reflective color displays with a high reflectivity, a wide viewing angle range, and a broad color gamut, together with a motion image capability has been expected for next-generation display applications.

However, conventional reflective color LCDs employing diffusive reflective electrodes have problem of low reflectivity because the precise control over the optical diffusion by engineering the surface microstructure of the reflective electrodes is difficult, since these structures are fabricated using conventional photolithography processes. As a result, wide gamut color filters cannot be used because of its low transmittance and the color gamut of the reflective LCD becomes narrow (less than 10% of that required by the NTSC standard) because of the use of narrow gamut color filters. In addition, optical interference due to the periodicity of the surface microstructure is also problem for reflective color LCDs. Therefore, it is important to establish a method controlling the optical diffusion to achieve a high reflectivity for the wide color gamut color filters.

To solve these problems, we have proposed a reflective color LCD using mirror type reflective electrodes and a light diffusion film, demonstrating that this scheme offers the advantages of high contrast ratio and motion image capability while avoiding the optical interference problem of the diffusive reflective electrodes.

In this display system, a light diffusion film is located in the upper part of the liquid crystal cell, therefore it is important to suppress an image blur caused by the light diffusion film, while keeping the high reflectivity. To address this problem, we have developed a directional light diffusion film, which has a limited diffusion angle range as well as a transparent angle range by the internal layer structure with different refractive indices. Light that enters the reflective LCD is diffused once by this directional light diffusion film, as a result, image blur is suppressed even if we use the light diffusion film with high diffusion intensity (see Fig. 1).
However, because of the strong directivity of the diffused light distribution, viewing angle range of reflective LCDs becomes narrow and several light diffusion films with different diffusion angle range are required to improve viewing angle range of reflective LCDs. This results in the increase of thickness and cost of the display panel.

In this paper, we reported the development of the directional light diffusion film with wide diffusion angle range by precisely controlling the internal refractive index distribution and evaluated its polarization maintenance, backscattering characteristics required for the improvement of contrast ratio of reflective LCDs. In addition, we fabricated the reflective color LCD with a high reflectivity, a wide viewing angle range, a wide color gamut and motion image capability by using the single directional light diffusion film.

2. Directional light diffusion film with internal refractive index distribution

We fabricated the directional light diffusion film by exploiting the photo-polymerization-induced phase separation effects. We selected two materials with different refractive index, molecular mobility and reactivity to induce the radical reaction of material with low molecular weight and high reactivity more rapidly than the other material. We used urethane methacrylate oligomer as a low refractive-index material and acrylic monomer as a high refractive-index. The difference of refractive indices between these materials was 0.1. We mixed these materials at equal concentration with a photo initiator and irradiated UV light with integrated amount of 20 to 40 mJ/cm².

We used the diffused and collimated UV light sources for the photo polymerization to control the internal refractive index distribution (see Fig. 2). Figure 3 shows the internal refractive index distribution of our directional light diffusion films in the cross-section of x-z and y-z planes measured by using a laser microscope (Keyence). These samples were fabricated using diffused and collimated UV light respectively. The incident angle of UV lights are normal to the film surface and thickness of each sample were 180 µm and 200 µm, respectively. From Fig. 3, we confirmed that louver and column structures were realized by the diffused UV light and collimated UV light.

Figure 4 shows the distribution of diffused light of our directional light diffusion films. These images were measured by using Conoscope (Autronic-Melchers GmbH). The incident light was normal to the light diffusion film. These figures show that we can control the internal refractive index distribution and the anisotropy of optical diffusion by controlling the diffusion angle of UV light. We can also control the inclination angle of internal layer structure and the angle range of the diffused light by varying the angle of
incidence of the UV irradiation.

3. Design of Directional Light Diffusion Film with Wide Diffusion Angle Range

We optimized the diffusing property of the directional light diffusion film. In order to achieve the reflective LCD with wide viewing angle range, at least two directional light diffusion films with different diffusion angle range by the different inclination angle of internal layer structures are required. Therefore, to achieve the thin light directional diffusion film with wide diffusion angle range, we fabricated two different diffusion layers in a single polymer film by using the two-step UV irradiation process (see Fig. 5).

In general, the layer structure is formed from the middle of the polymer film and there is a non-structured region near the film surface because of the polymerization inhibition by oxygen. Therefore, we fabricated the first diffusion layer in the bottom part of the polymer film and a non-structured region near the film surface by the first UV irradiation. After laminating a PET film to the surface to suppress the polymerization inhibition, the second diffusion layer with different diffusion properties is formed in non-structured region by the second UV irradiation.

Figure 6 shows the internal refractive index distribution of double-layered directional light diffusion film. We confirmed that the two different layer structures with different layer angle was fabricated in a single polymer film.

Next, we examined the effect of internal layer structure on the diffusion property of double-layered directional diffusion films. We prepared several light diffusion films with different combinations of layer angles such as $0^\circ + 20^\circ$, $10^\circ + 10^\circ$ and $10^\circ + 30^\circ$. Measurement result is shown in Fig. 7. The incident angle is $-30^\circ$ to the normal of the film surface.

As a result, we found that the directional light
diffusion film having $0^\circ + 20^\circ$ layer angles has high reflectivity in a wide angle range including a normal direction of the film surface. We considered that the reason for this is that the diffusion angle range by the upper side layer structure was spread by the lower side layer structure. In the case of the directional light diffusion film having $0^\circ + 20^\circ$ layer angles, the diffused light by the layer structure of $20^\circ$ enters the layer structure of $0^\circ$ and is diffused to the normal direction of the film surface, because the diffusion angle range of two layer structure is overlapped.

On the other hand, in the case of the light diffusion film having $10^\circ + 30^\circ$ layer angles, the layer structure of $30^\circ$ diffused the light to the wide angle range and the light enters the diffusion angle range of layer structure of $10^\circ$ is diffused around the direction of $10^\circ$. As a result, the diffusion intensity at normal direction becomes relatively small compared to the $0^\circ + 20^\circ$ layer structures. The $10^\circ + 10^\circ$ layer structure has a single layer angle and diffuses the light around the direction of $10^\circ$, therefore it has a problem of narrow diffusion angle range. As a result, we confirmed that the optical diffusion profile can be controlled by optimizing the combination of the layer structure in the single polymer film.

Figure 8 and Fig. 9 respectively shows the measure result of diffused light distribution of our double-layered directional light diffusion film with $10^\circ + 20^\circ$ layer structures by the Conoscope (Autronic-Melchers GmbH). The incident angle is $-30^\circ$ to the normal to the film surface. We also measured the diffusion property of particulate type light diffusion film for comparison. These figures show that our new light diffusion film has a wider diffusion angle range and higher reflectivity at normal direction of the film surface than the traditional particulate type light diffusion film.

4. Evaluation of the Optical Characteristics of Directional Light Diffusion Film

In the proposed reflective display system, the light diffusion film is located between a polarizer and a LC panel, therefore the light diffusion film is required to have high polarization maintaining property and low backscattering to achieve a high contrast ratio. Hence, we evaluated the polarization maintaining property and backscattering of the light diffusion films. Figure 10 shows the experimental set-up for measurement of polarization maintaining property. Measurements were performed with a background light intensity of less than 0.1 lx.

We prepared the sample of the directional light diffusion film, and the particulate type light diffusion film for comparison. The haze value of these films were 94%. The light diffusion film was sandwiched between two polarizers, and the transmission axis of incident side polarizer $\phi_p$ was set to be parallel to the flow casting direction of the light diffusion film $\phi_D$ during the manufacturing processes. The douser was placed on the surface of light source to collimate the incident light to
the polarizer. By rotating the transmission axis of the output side polarizer $\phi_A$ to $0^\circ$ and $90^\circ$, while $\phi_P$ and $\phi_D$ were set to $0^\circ$, we measured the luminance of transmitted light in parallel and crossed nicol states ($L_P$, and $L_C$) by using a luminance meter CA-2000 (Konica Minolta, Inc.).

The degree of polarization of transmitted light $P$ was calculated by using following equation.

$$P = \frac{L_P - L_C}{L_P + L_C}$$

The measure results of degree of polarization $P$, are shown in Table 1.

| Sample           | $L_P$ (cd/m$^2$) | $L_C$ (cd/m$^2$) | Degree of polarization |
|------------------|------------------|------------------|------------------------|
| Particulate film | 28.79            | 0.35             | 0.9760                 |
| Directional film | 120.24           | 0.88             | 0.9855                 |

The luminance of backscattered light as a function of $\theta_1$ is shown in Fig. 12. We confirmed that the backscattering of our directional light diffusion film was lower than that of the particulate type diffusion film. We considered that the reason why our columnar structured type light diffusion film has high polarization maintenance and low backscattering property compared to the particulate type light diffusion film is that the light passed through the light diffusion film while totally reflecting the internal layer structure of the light diffusion film. As a result, the light was diffused only to the forward direction with the high degree of polarization.

5. Fabrication of Prototype of Reflective Color LCD

We fabricated the reflective color LCD using single directional light diffusion film ($0^\circ$+20') and wide gamut color filters. A photograph of which is shown in Fig. 13.
The reflectivity was 60% of the white standard for the -30° obliquely incident light and the contrast ratio was 50:1. We confirmed that a high quality reflective color LCD with a wide color gamut (50% of NTSC color standards) and wide viewing angle, together with the motion image capability was achieved.

6. Conclusion

We have successfully developed a low-power reflective color LCD with high reflectivity of 60% and a good contrast ratio of 50:1, a wide color gamut of 50% of NTSC color standards, and a wide viewing angle, as well as motion image capability.

We developed a double-layered directional light diffusion film by using two-step UV irradiation process and achieved high reflectivity across a wide angle range. We also clarified that this diffusion layer has advantages of maintaining a high degree of polarization as well as eliminating backscattering.

The power consumption of our display can be further reduced by using oxide thin-film transistor (TFT) and memory-in-pixel (MIP) technology. Our reflective display is suitable for both small and large size display applications, including smart watches, e-book readers, and digital signage and is expected to contribute to the development of future low power display applications.

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