Reshaping the luminance distribution of OLED lighting using optical films

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ABSTRACT

The angular distribution of luminance on a combination of a white organic light-emitting diode (OLED) panel and optical films was investigated through an experiment and through optical simulation. Applying an appropriate combination of separate optical films onto the OLED panel provided a great deal of flexibility in shaping the luminance profile of OLED lighting. This was due to the existence of thin air gaps between the OLED and the optical film on it as well as between the optical films, as supported by optical simulation. This flexibility may supply the OLED lighting with an additional degree of freedom, which is effective in adjusting the luminance profile freely.

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1. Introduction

Display technology based on organic light-emitting diodes (OLEDs) is one of the most representative displays these days, especially in small-sized displays such as mobile phones and tablets. OLED is characterized by several advantages, such as a wide color gamut, low power consumption, and a thin form factor. In addition, white OLED has attracted great attention as a new light source because it is the only true flat light source that by itself emits homogeneous two-dimensional white light. Lighting products based on white OLEDs can be purchased in the market, although the cost is relatively high compared to the LED (light-emitting diode) lighting devices. Similar to semiconductor LEDs, OLED has outcoupling issues for the generated light due to the total internal reflection (TIR) caused by the differences in the refractive index between several interfaces [1,2]. Extensive and thorough studies have been carried out to improve the outcoupling efficiency of OLEDs [3–5].

Another performance issue of OLED lighting is the intensity (or luminance) distribution – i.e. the viewing angle characteristics. The luminance distribution of flat OLEDs is close to the Lambertian one. The adoption of a certain outcoupling structure modifies this Lambertian distribution. For example, the microlens arrays on the glass substrate of the bottom-emitting OLEDs reshape the luminance distribution and enhance the on-axis luminance in general [6–9]. On the other hand, applying photonic crystals to the OLED induces the characteristic symmetry property in the intensity distribution and may also cause color separation [10–13]. These results indicate that the outcoupling structure is one of the critical factors that determine the luminance distribution as well as the color uniformity of white OLED lighting [14].

The angular distribution of luminance of OLED is important to realize the appropriate viewing angle characteristics for lighting applications. The luminance distribution of OLED lighting, however, cannot be modified once the optical structure of the white OLED, including the outcoupling structure, is determined. It is sometimes necessary and cost-effective, however, to modify the viewing angle characteristics of planar lighting devices by applying external optical components to the same OLED panel. In this study, the effect of thin optical films on the luminance distribution of white OLEDs was investigated through both an experiment and simulation. This approach is similar to the case of the backlight units used for liquid crystal displays (LCDs), where several optical films are used to improve and modify the optical performances of LCDs [15–17]. Especially, the role of the air gap between the OLED panel and the upper optical film from the viewpoint of the viewing angle characteristics, and the efficiency, were focused on.
2. Experiment and simulation

The OLED panel that was used in this study was taken from a commercial lighting product (PT-530, Ocless) with an emitting area of 50 cm² and a correlated color temperature of ~3000 K. This panel was manufactured by LG Chemical Company and can be controlled to have three steps of luminance. A conventional spectroradiometer (PR-670, Photo Research) was used to evaluate the luminance and the color coordinates of the OLED panel. Figure 1(a) shows the viewing angle dependence of the luminance of the present OLED panel turned on at the highest luminance level. The angular distribution of the luminance exhibits an inverted 'W' shape, displaying minimum luminance toward the normal direction while showing maximum luminance at ~60°. Figure 1(b) indicates the color coordinates of the panel on the chromaticity diagram, which corresponds to the correlated color temperature of ~3000 K.

Two kinds of optical films were used: one-dimensional prism films (PF, HLAS1.20H, Kumho Electric) and diffuser films (DF, LMS325EF02-D, Kumho Electric) with randomized hemispherical lenses. Figure 2(a, b) shows the top views of the prism and diffuser films, respectively. The prism film is the more conventional one, consisting of a straight one-dimensional prismatic structure with a 25 μm pitch and a 90° apex angle. The circles on the diffuser film denote the hemispherical lenses positioned randomly on the substrate. The average diameter of the lens is approximately 10 μm. Randomization of microlenses is important for preventing any possible formation of Moiré patterns caused by interference between the periodic structures of the optical films. These optical patterns are usually formed on a substrate whose thickness is in the order of 100 μm. Figure 3(c) is the scanning electron microscope (SEM) image of typical prism films taken from the authors’ previous publication (Ref. [18]), which shows both the substrate and the prism array of the film. Two sets of experiments were carried out for the OLED panel. First, the optical film was attached onto the panel with index-matching liquid being inserted between them, and then the angular distribution of the luminance was measured. Second, a certain combination of optical films was put on the panel without using any index-matching liquid. A sticky tape was used on the edge of the optical films to hold the OLED and the optical films together. This is nearly the same situation as that of the backlights where a side mode holds the optical films on the light guide or diffuser plate. This indicates that a very thin air gap remains between the panel and the optical film on it, as well as between the different optical films. The comparison of these two experiments is expected to reveal the role of the air gap in reshaping the luminance distribution. Liquid paraffin (LP100F, Kukdong Oil & Chemicals Co.) was used as the index-matching liquid because it is transparent, inert, and non-volatile. The refractive index of LP100F is known to be 1.467 at 20°C, which is very close to those of the typical optical films.

Optical simulation based on the ray-tracing technique was carried out for comparison with the experiment results, and thus for constructing a reliable simulation model. A commercial software (LightTools, Synopsys) was used for the simulation. A detailed description of the simulation model for the OLED panel was included in the next section.

3. Results and discussion

Figure 3(a) shows the angular distribution of luminance without and with optical films attached on the OLED
Figure 2. (Color online) Photographs of (a) the prism film, (b) the DF used in this study, and (c) the SEM image of typical prism films taken from Ref. [18].

As a next step, the angular distribution of luminance on a combination of an OLED panel and optical films was investigated without using any index-matching liquid. It was indicated that thin air gaps remained between the optical films as well as between the OLED panel and the optical film above it. Figure 4(a, b) shows the dependence of luminance on the viewing angle measured under several conditions without and with normalization, respectively. The DF on the OLED narrows the luminance distribution and increases the on-axis luminance by 26% via the refraction on the surfaces of the semi-spherical microlenses. The addition of a horizontal PF, denoted as PF(H), on the OLED panel significantly increases the on-axis luminance (∼65%) by collimating the light toward high angles. The exact meaning of the horizontal PF indicates that the prism grooves are aligned vertically, thus reducing the viewing angle in the horizontal direction. The combination of DF + PF(H) further narrows the distribution and significantly enhances the on-axis luminance, which amounts to ∼79% compared to that on the OLED panel. An additional luminance gain of ∼13% can be achieved by applying a second vertical PF (the prism grooves are horizontal, thus narrowing the viewing angle in the vertical direction), denoted as PF(V), on the PF(H). This kind of narrow luminance distribution is desirable for developing OLED downlights.
Figure 3. (Color online) (a) Angular distribution of the luminance of the OLED panel without and with optical films where index-matching liquid was used between the panel and the film. (b) Normalized angular distribution of the luminance with respect to the on-axis value on the OLED panel.

Figure 4. (Color online) (a) Angular distribution of the luminance of the OLED panel without and with optical films where index-matching liquid was not used between the panel and the film. (b) Normalized angular distribution of the luminance with respect to the on-axis value on the OLED panel.

The comparison of Figure 3(b) and Figure 4(b) shows that the luminance gain in the normal direction substantially depends on whether index-matching liquid is used or not. This substantial difference is related to the light distribution in the optical film. When index-matching liquid is used, the light distribution formed in the OLED panel does not change even in the substrate of an optical film because there is nearly no difference in the refractive index between the OLED panel and the optical film due to the index-matching liquid. Therefore, the rays propagating at large angles with respect to the normal direction generated from the emission layer may be trapped in the OLED due to the TIR, or may be guided to escape toward the direction of the high viewing angles. This is the reason that all the luminance distributions shown in Figure 3 do not exhibit a large difference from the Lambertian distribution. On the other hand, when index-matching liquid is not used, the propagating direction of the light incident on the bottom surface of optical films is confined within a certain solid angle in the optical film due to the refraction at the interface. Figure 5(a) shows that if the refractive index of the substrate of optical films is \( n \), the ray incident on the bottom surface with an incident angle of 90° (the maximum allowable incident angle) is refracted with a refraction angle of \( \theta \). If the refractive index of the substrate is 1.5, \( \theta \) is 41.8°. This indicates that the directions of the transmitted, and thus, the refracted rays are confined within a cone whose half angle is 41.8°. This confinement is very important for the high luminance gain of microlens films such as prism films because it plays an important role in the angle recycling process for the rays reflected back from the microlenses [19]. In this case, some of the rays that cannot be refracted toward the normal direction at the inclined surface of microlenses may
be reflected back toward the OLED panel via TIR. Then the OLED panel reflects this light again toward the optical film, during which the light direction can change significantly due to the diffuse reflection, making the light escape the optical film in the normal direction. A similar recycling process occurs in the backlight for LCDs, where polarization recycling is very important for the high luminance gain of reflective polarizers [20,21].

To come up with an appropriate simulation model for reproducing the luminance profile, the LightTools software was used to simulate an OLED panel and optical films. Figure 6 shows the cross-section of the present model. The area of the panel was $5 \times 5$ mm$^2$. The OLED panel consisted of two electrodes (Al cathode and ITO anode), an organic layer, and a glass substrate. This OLED model was a simplified one because there was no information about the inner structure of the OLED panel that was used in this study. Hemispherical microlenses were arrayed on a substrate, which was used as a DF. The prism film consisted of a conventional one-dimensional prism array with an apex angle of 90° placed on a substrate. The dimensions, refractive indices, and other information about the simulation model are summarized in Table 1. It should be noted that there were air gaps between the OLED and the optical film as well as between the
Table 1. Thickness, refractive index, and other characteristics of each component comprising the OLED lighting device studied via optical simulation in this study.

| Component       | Thickness (µm) | Refractive index | Remark                          |
|-----------------|----------------|------------------|---------------------------------|
| Reflector       | 10             | Aluminim         |                                 |
| Organic layer   | 20             | 1.75             |                                 |
| ITO             | 10             | 1.82             | Indium tin oxide                |
| Glass           | 30             | 1.48             |                                 |
| DF              | 10             | 1.50             | Diameter (hemisphere): 20 µm    |
| Prism film (H)  | 20             | 1.60             | Height: 10 µm; apex angle: 90°  |
| Prism film (V)  | 20             | 1.60             | Height: 10 µm; apex angle: 90°  |

First, optical simulation was carried out for the model consisting of an OLED panel and only the prism film on it. Two cases were studied, one with and the other without an air gap between the OLED and the prism film. The purpose of this simulation is to reveal the role of the air gap in the formation of the angular distribution of the luminance. Figure 5(b) shows the normalized luminance data obtained from the simulation. As can be seen in the figure, the existence of an air gap has a substantial effect on the angular distribution of the luminance. The overall distribution is very similar to the experiment results shown in Figure 4. It is thought that this is mainly due to the refraction of the incident light at the interface between the air and the substrate of the prism film. It limits the angular range of the light entering the substrate of the prism film, which is more favorable for the light collimation via the prism grooves in the normal direction.

Figure 7 exhibits a far-field luminance distribution in a polar plot for four different combinations of optical films. The luminance distribution on the OLED panel is nearly Lambertian (Figure 7(a)). The addition of DF enhances the on-axis luminance while reducing the luminance along the high viewing angles (Figure 7(b)), which is mainly due to the refraction of the rays occurring on the air gap in the formation of the angular distribution of the luminance. Figure 5(b) shows the normalized luminance data obtained from the simulation. As can be seen in the figure, the existence of an air gap has a substantial effect on the angular distribution of the luminance. The overall distribution is very similar to the experiment results shown in Figure 4. It is thought that this is mainly due to the refraction of the incident light at the interface between the air and the substrate of the prism film. It limits the angular range of the light entering the substrate of the prism film, which is more favorable for the light collimation via the prism grooves in the normal direction.

Figure 7. (Color online) Far-field luminance distribution of the light from the (a) OLED panel; (b) DF; (c) horizontally positioned prism film (PF(H)) and DF; and (d) horizontally positioned prism film (PF(H)), vertically positioned prism film (PF(V)), and DF, which were put on the OLED panel.
the surfaces of the hemispherical microlenses. The one-dimensional PF collimates the light anisotropically, as can be seen in Figure 7(c). Two crossed PFs collimate the light horizontally and vertically, significantly increasing the on-axis luminance. Figure 7(d) shows the highly collimated luminance distribution on the two crossed PFs. Quantitative prediction of the luminance gain is not possible with the present model due to the insufficient information of the commercial OLED panel, but at the qualitative level, the luminance distribution on each condition is consistent with the experiment results. This indicates that an appropriate simulation model that is useful in predicting the luminance distribution under a certain combination of optical films may be constructed.

The kind of luminance reshaping described in the foregoing is very common in many optical devices, the LCD backlight being the most representative [22,23]. The highly directional distribution along large viewing angles on the light guide plate can be controlled by using several optical films, resulting in uniform, bright, and collimated light toward the LCD. When microlenses are applied to the surface of OLED, it is mainly for enhancing the outcoupling efficiency [6–7]. The shape of the microlenses determines the luminance distribution on the OLED lighting, which cannot be adjusted once the outcoupling structure is determined.

The present study showed that applying separate optical films onto the OLED panel has several advantages. The optical films may be combined and fixed on the OLED panel by using, for example, some outer mold frame. First, the luminance distribution can be easily controlled by using different combinations of optical films. Figure 4 shows that a highly directional luminance distribution can be realized by using two crossed prism films. Even an asymmetric luminance distribution, which sheds light in only a certain direction, is possible if anisotropic microlenses will be used. This kind of luminance distribution is desirable for special lighting devices, such as downlightings with a narrow intensity distribution. Second, a comparison of Figures 3 and 4 clearly demonstrates that the luminance profile can be much more flexibly controlled when separate optical films are applied onto the OLED panel without using any index-matching liquid. This was explained based on the role of the air gaps between the devices, which confined the incident light into a certain cone in the substrate, making the angle recycling process more effective. This flexibility may supply the OLED lighting with an additional degree of freedom, which is effective in adjusting the luminance profile freely.

4. Summary

The effect of optical films on the luminance distribution of the organic OLED panel was investigated through an experiment and through simulation. The application of optical films on the OLED panel with index-matching liquid inserted induced a moderate change in the luminance profile and on-axis luminance gain. When index-matching liquid was not used, however, and thus a thin air gap was persistent between the OLED panel and the optical film, the angular dependence of the luminance changed significantly, resulting in a highly collimated profile under crossed prism films, for instance. A simplified simulation model showed luminance distributions consistent with the experiment results. These results indicate that the luminance profile can be much more flexibly controlled when separate optical films are applied onto the OLED panel.

Notes on contributors

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