Realization of specific illuminance distributions of OLED lightings using inverted microlens films

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ABSTRACT
The illuminance distribution of flat organic-light-emitting diode (OLED) lightings combined with inverted microlens arrays was investigated through both an experiment and simulation. Two inverted prism films on the OLED surface produced a fourfold symmetry in the illuminance distribution caused by the refraction at the lower and the upper interfaces with air. A simple simulation model could reliably reproduce the experimental distribution. Other specific illuminance distributions, such as the ring-shaped one, were formed in terms of inverted ellipsoidal and pyramid microlens arrays. These results suggest that specific illuminance distributions can be realized by combining inverted microlens arrays with flat OLED lightings, which may be useful for special lightings such as decoration or exhibition lightings.

1. Introduction

The application field of organic-light-emitting diode (OLED)-based displays is rapidly expanding in small-size displays and is beginning to make inroads on large-size displays and general lightings. OLED is a self-emitting device without any color filter, which is a favorable condition for attaining a high contrast ratio and a wide color gamut. Moreover, OLED lighting itself is a truly two-dimensional flat light source showing a nearly Lambertian distribution. This new and unique form factor cannot be found in other light sources because light-emitting diodes (LEDs) or fluorescent lamps need additional optical components for realizing a two-dimensional homogeneous emitting condition. The emitting area of the conventional OLED lightings, however, which can be purchased in the market, is still small, and the cost is much higher than the other light sources of similar lumen outputs.

The typical OLED lightings generally consist of several organic layers, electrodes, and a glass substrate. The refractive indices of organic layers and the transparent electrode are higher than that of the glass substrate. A large portion of the light generated in the middle of the organic layers is trapped due to the total internal reflection (TIR) at the interface between the transparent electrode and the glass substrate [1,2]. Moreover, part of the light guided in the glass substrate is reflected at the glass–air interface due to the TIR. Much effort has been made to improve the outcoupling efficiency of OLEDs by modifying their optical structure [3–5].

The viewing-angle distribution of the luminance or intensity is another important performance characteristic of OLED lightings. The angular distribution of the luminance of flat OLED lightings is usually Lambertian or close to it. The luminance distribution can be modified using various methods. Shaping the emitting surface of OLED by, for example, putting a microlens array thereon [6–9] is one way of modifying the luminance distribution as well as of increasing the outcoupling efficiency. The adoption of a periodic structure, such as photonic crystal [10–14], generally induces specific intensity distributions and color separation depending on the viewing angle. In the field of lighting technology, the illuminance distribution on an illuminating plane is one of the crucial characteristics. In a particular environment, such as a museum, a specific illuminance distribution is required for illuminating exhibition objects. The illuminance is determined in terms of the intensity distribution of the light source. Thus, to achieve the targeted illuminance distribution over a specific plane and the objects on it, it is necessary to realize the appropriate intensity distribution of the light source.

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In previous studies, microlenses have been integrated in the OLED lighting only as a part of the structure [6–9]. It was shown in the authors’ previous study that the luminance distribution of OLED lightings can be easily controlled by applying independent microlens array films to the planar OLED panel [15]. The effect of the thin air gap between the OLED and the microlens film on the luminance distribution was found to be substantial. In the present study, the authors’ previous study was extended by carrying out an experiment and simulation to investigate the effect of inverted microlens films applied to the planar white OLED lightings on the illuminance distribution. Optical films have been widely used in various fields, such as in backlight technologies for liquid crystal displays, prism films [16–17], combinations of optical films for edge-lit backlights [18–19], and reflective polarizers [20–21]. Applying inverted prism films on the light guide plate is very effective for achieving narrow viewing-angle characteristics. In this study, it was shown that putting inverted microlens films on white OLEDs is one way of realizing specific illuminance distributions on the illuminating surface.

2. Experiment and simulation

Commercial OLED panels (PT-530, Oless) with an emitting area of 50 cm² and a correlated color temperature of ~3000 K were purchased. These panels were manufactured by LG Chemical Company and were the same panels that were used in the authors’ previous study [15]. A conventional spectroradiometer (PR-670, Photo Research) and an illuminance meter (TES-1332A, TES Co.) were used to evaluate the luminance, the color coordinates, the spectrum of the OLED panel, and the illuminance distribution on a plane at a vertical distance of 0.5 m. Figure 1(a) shows the luminance distribution of the OLED panel as a function of the viewing angle. The inverted ‘W’-shaped luminance distribution is close to the Lambertian one and is more suitable for achieving a homogeneous illuminance distribution [15].

The conventional one-dimensional prism films (PF, HLAS1.20H, Kumho Electric), which are shown in Figure 1(b), were used for the experiment in this study. The pitch and the apex angle of the prism film were 25 μm and 90°, respectively. One or two films were inverted and attached to the OLED panel, that is, the prism grooves

Figure 1. (a) Angular distribution of the luminance of the OLED panel used in this study, taken from Ref. [15]. (b) Photographs of the prism films and the cross-section showing the dimensions of the prism grooves. The ‘OLED’ in (a) indicates that the luminance was measured on the OLED panel without any optical film.
were put toward the emitting surface of the OLED. When two prism films were attached, the prism grooves were orthogonal to each other. The illuminance of the OLED panel with or without prism films was measured on a monitor plane with an area of 300 mm × 300 mm positioned at a vertical distance of 0.5 m from the OLED panel. A total of 169 points on the plane with equal distances from one another were investigated to obtain the illuminance distribution. Figure 2(a) is a photograph showing a schematic experimental setup. The OLED panel was aged for at least 30 min before measurement, which is necessary for luminance stabilization. A sticky tape was used to fix the edges of the inverted prism films on the OLED panel.

Optical simulation for the OLED lighting based on a ray-tracing technique was carried out for comparing its results with those of the experiment. A commercial software (LightTools, Synopsys) was used for the simulation. Figure 2(b) shows a schematic drawing of the simulation model where the OLED panel and the plane on which the illumination distribution was investigated are included. A detailed description of the simulation model of the OLED panel is included in the next section.

3. Results and discussion

Figure 3(a–c) shows the illuminance distribution on the monitor plane formed by the OLED panel without any film, with one inverted horizontal prism film, and with two inverted, crossed prism films, respectively. The illuminances of a total of 13 × 13 = 169 data points were colored according to their values, as shown in the color bars. The illuminance on the plane beneath the OLED panel at a vertical distance d satisfies the cos^4θ law. Here, θ indicates the angle between the illuminating direction from the OLED panel to the monitor plane and the normal direction with respect to the emitting surface. Therefore, the luminous intensity should increase as the viewing angle increases, to make the illuminance uniform on a wide area below the light source. Figure 3(a) shows that the illuminance is highest at the center and then decreases towards the edge of the monitor plane. The approximate Gaussian distribution of the illuminance seems to be consistent with the quasi-Lambertian distribution of the luminance of the OLED panel.

Figure 3(b) shows that the horizontal inverted prism film disperses the incident light toward the upper and lower regions of the monitor plane. The apex angle of the prism groove is 90°; thus, the prism surfaces of the inverted grooves form ±45° with respect to the horizontal direction. These two inclined surfaces tend to refract the light incident from air toward directions closer to the horizontal plane according to Snell’s law, at the air–prism groove interface as well as the substrate–air interface. Therefore, the illuminances at the center and at the horizontal area near it are lower than those of the upper and lower regions. This result is in contrast to the case of the upright prisms on the OLED panel, where the emitted light is collimated toward the normal direction [15]. Figure 3(c) displays the result of the effect of the two inverted prisms orthogonally positioned over the OLED panel on the illuminance distribution. The four inclined planes disperse the incident light toward the up–down and left–right directions; thus, a cross-shaped dark area is formed, and four bright spots appear along
Figure 3. Illuminance distributions of the OLED on the monitor plane (a) without any film, (b) with one inverted horizontal prism film, and (c) with two inverted prism films, respectively, obtained from the experiment.

The four diagonal directions. This kind of illuminance distribution may be appropriate for special exhibition places where one flat light source needs to illuminate four objects positioned on the angular points of a square.

The experimental investigation in terms of the inverted prism films is not enough to reveal the possibility of forming various illuminance distributions using inverted microlens arrays. In this context, optical simulation is a powerful tool in searching for the optimized optical structure for realizing specific illuminance distributions. A commercial ray-tracing software (LightTools) was used to simulate an OLED panel, inverted prism films, and a monitor plane, as schematically shown in Figure 2(b). The simulation model of the OLED panel consisted of two electrodes (ITO anode and Al cathode), an organic layer between the two electrodes, and a glass substrate, which was the same as that used in Ref. [15], except for the emitting area. The area of the panel was 50 cm² in the present case; the same as that of the OLED panel that was used in the experiment. Fresnel conditions were applied to each interface. Nine isotropic point sources positioned at equal distances from one another in the middle of the organic layer were used as light sources. The area of the monitor plane in the simulation model was enlarged to $600 \times 600$ mm² to obtain a more detailed illuminance distribution. The detailed information of the simulation model is summarized in Table 1.

The effects of three inverted microlens arrays on the illuminance distribution were investigated using optical simulation: prism, pyramid, and ellipsoidal lenses. The ellipsoidal lens can be described by the equation $x^2/a^2 + y^2/a^2 + z^2/c^2 = 1$, with the $z$-axis in the normal direction with respect to the substrate. Thus, the cross-section of the ellipsoidal lens is an ellipse, and the base shape is a circle. The substrate consists of two layers: a base layer (thickness: 12.6 µm; refractive index: 1.667) and an intermediate layer (thickness: 2.5 µm; refractive index: 1.59). The height of all the microlenses was 2.5 µm, except when the aspect ratio of the ellipsoidal lenses was changed. The apex angle of the one-dimensional prism array was first set to $90^\circ$. The pyramid and elliptical lenses were positioned on a square and a hexagonal lattice, respectively. The lateral dimension of these two microlenses was fixed at 5 µm. The apex angle of the prism and pyramid lens arrays was changed from 70 to $120^\circ$. The aspect ratio of the ellipsoidal lenses (i.e. the ratio between the diameter of the base circle and the height) was changed from 0.5 to 2.0.

Figure 4(a–c) displays the illuminance distribution on the monitor plane formed by the OLED panel without any film, with one inverted horizontal prism film, and with two inverted prism films, respectively, obtained from the simulation. The quasi-Lambertian distribution in Figure 4(a) changed into the bimodal and then multimodal distributions in terms of the inverted prism films, as shown in Figure 4(b,c). The similarity between the experiment and simulation results suggests that the present simulation model reliably predicts the illuminance distribution caused by various inverted microlens arrays. Figure 5(a–d) shows the illuminance distribution for the 0.5, 1.0, 1.5, and 2.0 aspect ratios of the

| Table 1. Thickness, refractive index, and other characteristics of each component of the OLED panel and the inverted microlens arrays studied through optical simulation in this study. |
|---|---|---|---|
| Thickness (µm) | Refractive index | Remark |
| Reflector | 10 | – | Aluminum |
| Organic layer | 20 | 1.75 | – |
| ITO | 10 | 1.82 | Indium tin oxide |
| Glass | 30 | 1.48 | – |
| Substrate (base) | 12.6 | 1.667 | Substrate of the film |
| Substrate (intermediate) | 2.5 | 1.59 | Intermediate layer of the film |
| Microlenses | 2.5 | 1.59 | Microlens height: 2.5 µm |

The pyramid and elliptical lenses were positioned on a square and a hexagonal lattice, respectively.
**Figure 4.** Illuminance distributions of the OLED on the monitor plane (a) without any film, (b) with one inverted horizontal prism film, and (c) with two inverted prism films, respectively, obtained from the simulation.

**Figure 5.** Illuminance distribution of the OLED combined with the inverted elliptic microlenses with the aspect ratios of (a) 0.5, (b) 1.0, (c) 1.5, and (d) 2.0.

Inverted ellipsoidal microlenses, respectively. When the aspect ratio is small (e.g. 0.5), the degree of refraction at the surface of the microlens is also small, and the overall illuminance distribution is not much different from the Lambertian distribution. When the aspect ratio becomes 1.0, the inverted hemispheres refract the incident light towards high viewing angles. Figure 5(b) exhibits six-fold symmetry in the illuminance distribution caused by the hexagonal lattice structure. When the aspect ratio becomes larger than 1, a large portion of the refracted rays will enter the neighborhood lenses, and thus, the star-shaped illuminance distribution disappears. Instead,
Figure 6. Illuminance distribution of the OLED combined with two crossed and inverted prism films at the apex angles of (a) 70°, (b) 80°, (c) 90°, (d) 100°, (e) 110°, and (f) 120°.

Figure 7. Illuminance distribution of the OLED combined with one inverted pyramid film at the apex angles of (a) 70°, (b) 80°, (c) 90°, (d) 100°, (e) 110°, and (f) 120°.

ring-shaped illuminance distributions, such as those in Figure 5(c,d), appear.

To search for the additional possibility of realizing other illuminance distributions, the apex angle of the prism and pyramid arrays was changed to a wide range. Figure 6(a–f) shows the illuminance distribution of the OLED combined with two crossed and inverted prism films at the 70, 80, 90, 100, 110, and 120° apex angles, respectively. The characteristic fourfold illuminance distribution appears clearly only from the condition of the 90° apex angle. At other angles, the illuminance distribution is neither concentrated nor homogeneous. Figure 7(a–f) shows the illuminance distribution of the OLED combined with one inverted pyramid film at the
70, 80, 90, 100, 110, and 120° apex angles, respectively. All the distributions exhibit nearly fourfold symmetry caused by the same rotational symmetry of the inverted pyramid film. Similar to the inverted prism films, the distribution exhibits rather concentrated regions along four diagonal directions at the 90° apex angle. This shows that the effect of one inverted pyramid film is similar to that of the two inverted and crossed prism films. The degree of homogeneity of the former, however, is inferior to that of the latter.

4. Summary

The effect of inverted microlens films on the illuminance distribution of the OLED lighting was investigated through an experiment and simulation. The illuminance distribution on a monitor plane separated from the OLED with an emitting area of 50 cm² was close to the Gaussian distribution. One and two crossed inverted prism films caused a twofold and fourfold illuminance distribution, respectively, due to the refraction at the 45°-inclined surfaces of the prism grooves. These illuminance patterns were exactly reproduced in the optical simulation based on the ray-tracing technique. The OLEDs combined with other inverted microlens arrays, such as ellipsoids and pyramids, exhibited various illuminance distributions depending on the shape parameters (e.g. aspect ratio, apex angle). The present results indicate that the combination of OLED and inverted microlens arrays can be used to realize specific illuminance distributions appropriate for special lightings, such as decoration lightings in museums or exhibition spaces.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

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