Luminescence enhancement of OLED lighting panels using a microlens array film

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**ABSTRACT**

The enhancement of the luminance of organic light-emitting diode (OLED) panels with various areas (2.25–6084 mm\(^2\)) using a microlens array (MLA) film was investigated. The luminance enhancement was dependent on the viewing angle, and the largest enhancement (64\%) was observed in the normal direction while 60 and 18\% enhancements were observed at 60 and 30\°, which led to lower enhancement (38\%) of the total luminous flux compared with the luminance enhancement (64\%) in the normal direction. The luminance enhancement with the MLA film also depended on the panel area, and the smaller panels showed lower luminance enhancement than the larger ones. As for the small panels, the straying light beyond the panel areas significantly affected the luminance of the panels, and over 60\% luminance enhancement was observed in the normal direction for the large panels (2500 and 6084 mm\(^2\)) with the MLA film while only 48 and 58\% luminance enhancements were observed at the small panels (2.25 and 70 mm\(^2\)).

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1. Introduction

Organic light-emitting diode (OLED) technologies have matured for lighting application. OLED lighting offers an aesthetic diffusive color spectrum and low thickness. In general, OLED lighting can offer high luminous efficiency, color tunability, flexibility, transparency, low thickness, large luminescence area, etc. [1–3]. In OLED lighting applications, a large illumination area is favored. This is in stark contrast to OLED display applications, where small OLED pixels are operated by individual transistors. Thus, the miniaturization of the pixels is an important point to consider for improving the resolution. To make inroads into the general lighting market, the luminous efficiency has to be higher than that of the conventional lightings. The external quantum efficiency of OLED is limited by the wave-guiding and total internal reflection in the glass substrate, as shown in Figure 1 [4,5]. Various approaches to the improvement of the light extraction from OLEDs have been adopted. Broadly, depending on the position of the light extraction component, the light extraction techniques from OLED can be classified into the internal and external extraction techniques. In the internal extraction techniques, the light extraction component is formed between the substrate (e.g. glass) and the transparent electrode (e.g. indium tin oxide, ITO). In the external extraction techniques, the light extraction component is positioned at the exterior surface of the glass [4,5]. In this work, the external light extraction technology using microlens array (MLA) films was focused on [6–9]. In particular, the area and viewing angle effects on the light extraction using MLA were investigated. In laboratory scale, small-emission-area (e.g. 2 × 2 mm) OLED devices are fabricated and evaluated, but in realistic-lighting OLED applications, a large emission area is required. As MLA can be regarded as a periodic array of half spheres, luminance dependence on the viewing angle may exist. In this work, the area dependence of the MLA in OLED was addressed.

2. Experiment methods

A series of OLED panels were fabricated using the following configuration: glass substrate(0.7 mm)/anode (70 nm)/organic layers(220 nm)/cathode(100 nm), as shown in Figure 1. The dimensions of the fabricated OLED panels were 2.25, 70, 2500, and 6084 mm\(^2\). For the anode ITO electrode, 70 nm thickness was used. The sheet resistance and optical transmittance of the ITO film...
were $\sim 23 \, \Omega/\text{sq}$ and 87% at $\lambda = 550$ nm, respectively, and the cathode was a LiF/Al (100 nm) thin film. The organic electron luminescence (EL) was the fluorescent blue type. The ITO was cleaned via the standard oxygen plasma treatment at a 123 W power level. The OLED-grade materials were purchased and used without further purification. All the organic layers were deposited in a high-vacuum (below $6.7 \times 10^{-5}$ Pa) chamber. The OLED panels with $2500 \times 6084 \text{mm}^2$ areas were furnished with Al (70 nm) auxiliary metal layers to improve the luminance uniformity in the large luminescence area. The OLED panels were transferred from the vacuum into an inert-environment glove box, where they were encapsulated using UV-curable epoxy and a glass cap with a moisture getter.

The MLA film was obtained from MIRAENANTECH Co. The diameter of the microlens was 10 $\mu$m (see Figure 1), the sag was 0.5, and the refractive index was 1.5. The MLA film was attached to the glass substrate of an OLED panel using an optical adhesive whose refractive index matches that of the glass. The refractive index of the glass in this study was $n = 1.46$.

For the optical simulations, a ray-tracing-technique-based commercial ASAP software (Breault Research Org.) was used. The structure and luminescence dimensions of the OLED panels in the simulation models were adjusted to match those of the fabricated OLED panels.

For the case of the $1.5 \times 1.5 \text{mm}^2$-unit OLEDs, the EL spectrum was measured using a Minolta CS-1000. The luminescence-current density ($L-J$) characteristics were measured with a current/voltage source/measure unit (Keithley 238) and a spectroradiometer (Minolta CS-100), respectively. For the case of the larger-luminescence-area OLED panels, the EL spectrum was measured using a spectra colorimeter (Photo Research, PR-650), and the $L-J$ characteristics were measured with a current/voltage source/measure unit (Keithley 2400) and a two-dimensional (2D) luminance colorimeter (Minolta CA-2000), respectively.

The luminous flux of the OLED panel without an MLA film was measured at a constant current driving condition. Stabilization was carried out to obtain stable luminous flux values after switching on an OLED panel. Afterwards, an MLA film was attached to the OLED panel, and the measurement was repeated. The MLA film was removed after the measurement, and the luminous flux was measured again to eliminate the luminance fluctuations during the experiments.

3. Results and discussion

Figure 2 shows the EL spectra of the $2500 \text{mm}^2$-large OLED panel obtained at different viewing angles. The main peak of the blue fluorescent was $\lambda = 465$ nm. In the case of the OLED panel without an MLA film, the appearance of a shoulder around $\lambda = 500$ nm was observed (Figure 2(a)). The shoulder became more noticeable as the viewing angle deviated from the normal direction. With the attachment of an MLA film, the spectral dependence on the viewing angle became negligible (Figure 2(b)). Thus, an externally attached MLA can be understood as having the function of eliminating or reducing the spectral dependence of the OLED panel on the viewing angle.

Figure 3 shows the MLA film effect on the luminance as a function of the viewing angle. Several features are observable. Enhancement of the luminance was observed in the whole viewing angle range. The highest enhancement (65%) was achieved in the normal viewing direction (90°). The luminance enhancement gradually decreased as the viewing angle moved away from the normal direction. The enhancements at the 60 and 30° viewing angles were 60 and 18%, respectively (see Table 1). These results indicate that the MLA film mainly directs the light towards the normal direction. From the
viewpoint of uniform illumination, however, a preferred characteristic of general lighting, such feature is not desirable. The total luminous flux enhancement due to the attachment of an MLA film was 38% in a 2500 mm² panel. As can be seen in Figure 3, without information on the viewing angle dependence, erroneous data on the degree of MLA film luminance enhancement can be easily obtained. To correctly assess the enhancement, information on the viewing angle dependence must be incorporated.

In the next section, the results of the investigation of the effect of the area on OLED panels will be presented. In real-lighting OLED applications, large-area panels rather than small-area ones are used. Figure 4 shows the luminance enhancement variation as a function of the panel area. To verify the measurements, optical simulations were also performed. The overall simulation results matched the trend of the measured results. A closer match between the simulation and measurement results was obtained at the large panel. The discrepancy in the small panel was obtained from the normal direction (Figure 4(a)), and the angle integral total luminous flux (Figure 4(b)) was plotted. For a given area, the angle integral enhancement was always lower than the enhancement obtained from the normal direction.

The angular dependence of the luminance enhancement with the MLA film led to a difference between the luminance enhancement in the normal direction and the total luminous flux enhancement. As shown in Table 2, although the luminance enhancement in the normal direction was 64%, the total luminous flux enhancement was only 38% for the 2500 mm² OLED panel. Therefore, if the light extraction method is applied to the OLED panel to improve the external quantum efficiency or luminous efficacy, the light distribution characteristics should be determined or luminous flux measurement should be carried out to prevent overestimation. The same experiment was also performed for the larger OLED panel (area: 6084 mm²). In this case, similar enhancement factors were observed, and 66% luminance enhancement in the normal direction and 41% luminous flux enhancement were obtained, as shown in Table 2. The enhancement characteristics were also investigated at different luminance values in the 6084 mm² OLED panel. The enhancement characteristics remained

Table 1. Luminance measurement result of the 2500 mm² OLED panel at different viewing angles with and without an MLA film.

| Viewing angle | Luminance (cd/m²) | Luminance with MLA (cd/m²) | Luminance enhancement (%) |
|---------------|------------------|---------------------------|--------------------------|
| 90°           | 302.3            | 496.4                     | 64.2                     |
| 60°           | 308.4            | 492.2                     | 59.6                     |
| 30°           | 326.6            | 383.9                     | 17.6                     |

Figure 2. EL spectra of a 2500 mm² OLED panel obtained at different viewing angles (a) without and (b) with an MLA film.

Figure 3. (a) Luminance at different viewing angle and (b) light distribution diagrams of 2500 mm² OLED panel attached with and without MLA film.

Table 1.
nearly stationary at the more-than-threefold-higher luminance.

From the above results, it seems that the light enhancement characteristics with the MLA film have little correlation with the OLED panel size and luminance. The OLED panel size was found to be dependent, however, on the light enhancement characteristics. The light enhancement characteristics with the MLA film using smaller OLED panels were also investigated. OLED lighting panels with 2.25, 70, 2500, and 6084 mm² luminescence areas, respectively, were fabricated, and their normal-direction luminance values with and without an MLA film were measured and simulated as described in the experiment section. The measurement and simulation areas were limited to the luminescence area of the OLED panel, and a portion of the extracted light from outside the OLED panel was ignored.

As shown in Table 2 and Figure 4, the normal-direction luminance enhancement of the OLED panel with an MLA film increased with increasing luminescence area, and reached a stable value at sufficiently large luminescence areas (2500 and 6084 mm²). For the smallest OLED panel, only 48 and 25% luminance enhancements were obtained in the experiment and simulation results. This luminance size dependence of the luminance enhancement may be related with the stray light extracted from outside the luminescence area. The OLED panels were fabricated on a 0.7-mm-thick glass substrate, and as such, it is expected that some light could be extracted from outside the luminescence area, and that this effect becomes substantial in the small OLED panels.

**Table 2.** Measurement and simulation results of the OLED panels with and without an MLA film.

| Luminescence area (mm²) | Luminance with MLA (cd/m²) | Luminance enhancement (%) | Simulated luminance enhancement (%) | Luminous flux with MLA (lumen) | Luminous flux enhancement (%) |
|-------------------------|---------------------------|---------------------------|-------------------------------------|-------------------------------|-------------------------------|
| 2.25                    | 1933.7                    | 48                        | 25                                  | 3.4                           | 38                            |
| 70                      | 526.2                     | 58                        | 51                                  | 5.9                           | 41                            |
| 2500                    | 497.8                     | 64                        | 66                                  | 8.3                           | 41                            |
| 6084                    | 500.2                     | 66                        | 68                                  | 5.9                           | 41                            |
| 6084                    | 1761.4                    | 66                        | 68                                  | 20.7                          | 40                            |

**Figure 5.** (a) Cross section view of 2−dimensional luminance measurement of 70 mm² OLED panel and (b) 2500 mm² OLED panel at normal direction.
To confirm this effect, the cross-sectional view of the normal-direction luminance with various-sized OLED panels was investigated. As shown in Figure 5, there was some light outside the measurement area in the small OLED panel, which was ignored in the measurement, while the light outside the measurement area was negligible for the large OLED panel. It can be concluded that the ignored light outside the measurement area led to the underestimation of the light enhancement in the smaller OLED panels.

4. Conclusions

The luminance enhancement by the microlens array (MLA) film was found to be strongly dependent on the luminescence area and viewing angles and weakly dependent on the driving condition. Over 60% normal-direction luminance enhancement was achieved. Nevertheless, the total luminous flux enhancement was only about 40% due to the biasing of the MLA film’s light extraction mechanism to the normal direction. The normal-direction luminance enhancement of the small OLED panels was affected by the photons that escaped from the luminescence area. The dependence of the luminance and luminous flux enhancements on the angular distribution and luminescence area would influence the efficiency of the OLED panel.

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