

Light extraction from electroluminescent devices using micro-rod array embedded within glass substrate

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Abstract: The total internal reflection (TIR) effect in conventional electroluminescent devices causes a large amount of light energy trapped in the devices and result in heat energy that adversely affects the performance of the device. In order to enhance the light out-coupling efficiency without sacrificing the electrical properties, a micro-rod array (MRA) structure fabricated by a femtosecond laser was demonstrated. Green, blue, and red organic light-emitting diodes were employed to verify the effect of the proposed method, which increases out-coupling efficiencies by a factor of 1.9, 1.7, and 1.82, respectively, compared with conventional devices. This highly effective method is compatible with current device fabrication processes and is applicable to full-color electroluminescent devices.

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1. Introduction

A high optical device efficiency is still hindered by the total internal reflection (TIR) effect owing to the refractive index mismatch at the interface of various functional layers of electroluminescent devices to achieve higher brightness [1–5]. The external quantum efficiency (η_{EQE}) of an optoelectronic device is generally determined by $\eta_{\text{EQE}} = \chi \cdot \eta_{\text{IQE}}$, where the χ is the light-coupling efficiency proportional to the amount of light escaping from the device, and η_{IQE} is the internal quantum efficiency related to the probability of electron–photon conversion in the active region. Nowadays, the internal quantum efficiency of an optoelectronic has been dramatically improved to nearly 100% [6, 7]. Conversely, the light-extraction efficiency is still limited to 20%, which is far below the desired level. Hence, a substantial increase in the external quantum efficiency is essential to enhance the light out-coupling efficiency of electroluminescent devices.

Several techniques have been reported to enhance the light-coupling efficiency of OLED via the internal mechanism or external structure. Internal mechanisms such as a nanofaceted structured layer [8], embedded low-index grids [9], a high-refractive-index resin substrate with diffusive particles [10], a randomly distributed indium tin oxide (ITO) pattern fabricated by maskless wet etching [11], a stamped Bragg grating with a poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) layer [12], two-dimensional photonic crystals [13], nanowire electrodes [14], a micro-cavity [15], surface plasmonic structures [16], and aperiodic dielectric mirrors [17] have already been reported to modify the direction of light propagation or to adjust the refractive-index difference between different functional layers. External structures such as shaped substrates [18], scattering media [19], and micro-lenses [20] have also been used on the back surface of the substrate, which result in a positive effect on the extraction of light out-coupling. These approaches increase the light-extraction efficiency, yet device fabrication complexity, image blur, narrowed viewing angle, altered emission spectrum, and the angular dependency of the emission spectrum are among the drawbacks to limit these methods for practical applications.

In this paper, we present a technique using micro-rod arrays (MRAs) embedded within a glass substrate fabricated by a femtosecond laser to enhance the out-coupling efficiency by more than 90%. Several critical factors for enhancing the optical properties were also investigated. Red, green, and blue organic light-emitting diodes (OLEDs), which are

fabricated on an MRA-glass substrate, exhibited a substantial enhancement in the optical out-coupling. As the patterned MRA-glass can be directly used as a substrate, the proposed method is highly compatible with current fabrication processes of OLEDs.

2. Design and fabrication process

Light trapping is a critical factor that still limits the performance of electroluminescent devices. For example, light extraction from the organic emission layer in conventional OLEDs is still suppressed owing to the waveguide in the multilayered sandwich structures and plasmonic quenching at the metallic cathode. The light-energy proportion in each mode can be approximately calculated by Snell's law with optics modeling according to the refractive indices of the organic emitting layer ($n \sim 1.71$), glass substrate ($n \sim 1.5$), and external ambient condition ($n \sim 1$). As shown in Fig. 1(a), only a fraction of the emitted light, approximately 18.8%, can be directly coupled out into the air. Approximately 35.3% of the light is trapped in the form of a substrate mode, approximately 45.9% is dissipated in the ITO/organic layers in a waveguide mode, followed by the TIR limitation [10]. Extracting light from the ITO/organic layers, which are as thin as 50–100 nm, could result in certain critical issues caused by its thickness. The ITO/organic layers could be harmed and adversely affected by out-coupling treatments to the ITO-organic layer interface, leading to a decrease in electrical performance [11]. On the contrary, the thickness and robustness of the glass substrate enables much easier extraction of light from the substrate compared to the very thin ITO/organic layers. Consequently, an MRA in the substrate is proposed to enhance the out-coupling efficiency without sacrificing the electrical properties of the devices. The MRA structure can alter the optical path of the light propagating in the substrate, break the TIR limitation via multiple refraction, and increase the out-coupling efficiency, as schematically illustrated in Fig. 1(b).

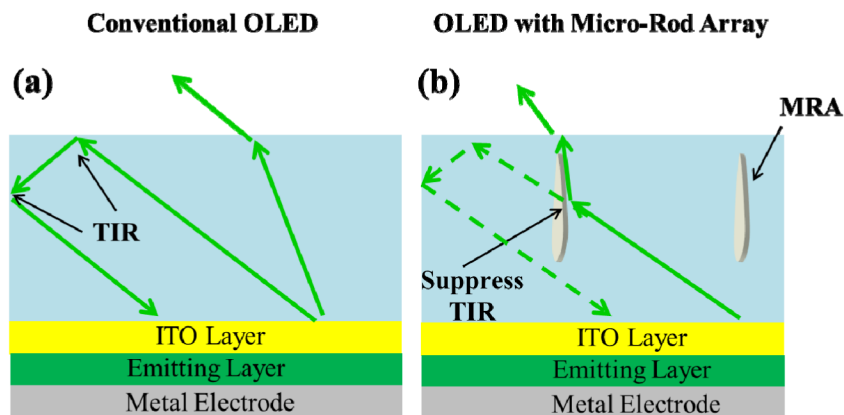


Fig. 1. Schematic of the mechanism for the out-coupling efficiency enhancement: (a) conventional OLED and (b) the proposed method with a micro-rod array (MRA) in a glass substrate.

The micro-rod array was fabricated by a multi-femtosecond-laser scanning array on a motorized x–y–z micro-positioning stage, as shown in Fig. 2. This stage has a 0.01-mm-step motor for precise positioning of the fabricated pattern as pre-design specifications. A laser beam propagated through the substrate in a perpendicular direction and converged inside the glass substrate by a focal lens. As the laser energy reached a certain value at the center of the focus, amount of the free electron were generated and stay localized by the photoionization and electron avalanche processing. The kinetic energy of electron absorbed by the laser energy was transferred to lattice of the glass which results in refractive index changing [21]. After a single pass of the laser irradiation, the refractive index at the center of the focused region increased in a small proportion, approximately 1%, compared with the surrounding glass [22].

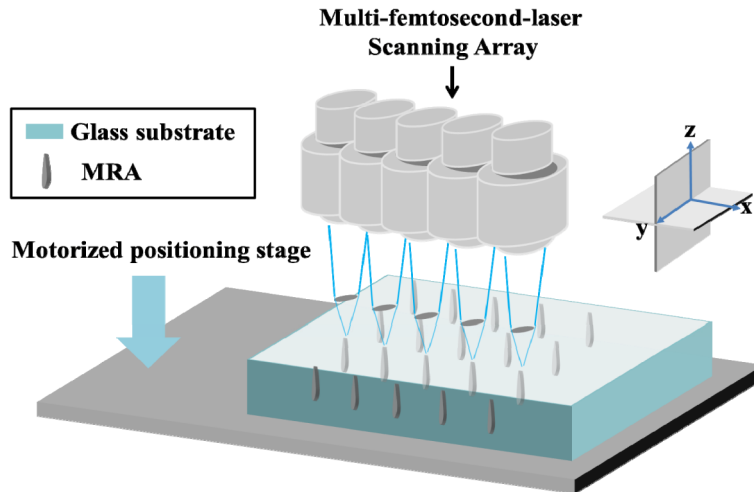


Fig. 2. Schematic illustration of the fabrication process for the pre-design specifications of the MRA structure.

In order to reveal the micro-rod structure in a glass substrate clearly, the glass substrate was cut and coated with a 10-nm-thick layer of platinum to minimize scanning electron microscopy (SEM) imaging problems caused by surface charging and shifting. A cross-sectional SEM image of the micro-rods is shown in Fig. 3(a). A typical profile was observed: many micro-rod structures were produced, as the refractive index of glass was altered by laser irradiation [22]. Laser irradiation with 100- μ J pulses and a 50-MHz repetition rate was employed to form the micro-rods, whose length and diameter were approximately 200 μ m and 20 μ m, respectively, with a 100- μ m pitch, as shown in Fig. 3(a). The profile of the micro-rod can be controlled by the laser pulse energy. Lower-energy-density pulse would lead to shorter micro-rod and make it sphere-like. Here, we define the duty ratio of the MRA as the volume of the MRA divided by the volume of the glass substrate. Therefore, the duty ratio of the MRA can be approximately calculated at 3%. Less than 30 seconds was required to produce a 3% duty ratio for the 1 m \times 1 m MRA-glass substrate by the multi-femtosecond-laser scanning array. Though the duty ratio can be increased by reducing the pitch of the micro-rod, the internal stress of the glass caused by laser irradiation should be carefully taken into account. As the uneven distribution of internal stress continually accumulated with the increasing of duty ratio, the mechanical strength of the glass would be gradually decreased, after exceeding a threshold value, the glass is easily cracked. The threshold value can be improved with the increasing of the glass thickness, which implying that there is a trade off between thickness and duty ratio.

To evaluate the optical characteristics of the fabricated glass, the parameter of haze was used which is defined as the measured diffused transmittance divided by the total transmittance. A haze meter (NDH-5000) was equipped in an integrating sphere so that the total transmitted light after passing through the glass substrate can be gathered. As shown in Table 1, the total transmittance of glass with MRA only declined slightly with the increasing of duty ratio, implying that the MRA structure can alter the optical path without causing obvious light loss. The large haze with the ability of increase the light extraction efficiency was proved by both of simulation and measurement results in later sections. Figure 3(b) shows the parallel transmittance spectrum of the fabricated glass substrate with and without MRA. The spectrums of the three substrates are almost flat which means the transmittance would not be apparently affected in the visible range. The root mean square (RMS) roughness of the MRA-glass and typical glass were measured by an atomic force microscopy (AFM), as illustrated in Figs. 3(c) and 3(d), respectively. It was revealed that the RMS roughness of the

MRA-glass was 5–7 nm, which is same as typical glass, indicating that the MRA is completely embedded within the glass substrate after laser irradiation.

Table 1. Optical characteristics for glass substrate.

	Total Transmittance (%)	Diffused Transmittance (%)	Parallel Transmittance (%)	Haze (%)
Glass w/o MRA	91	0.5	90.5	0.55
3% MRA	90	15.4	74.6	17.1
6% MRA	88.5	18.3	70.2	20.7

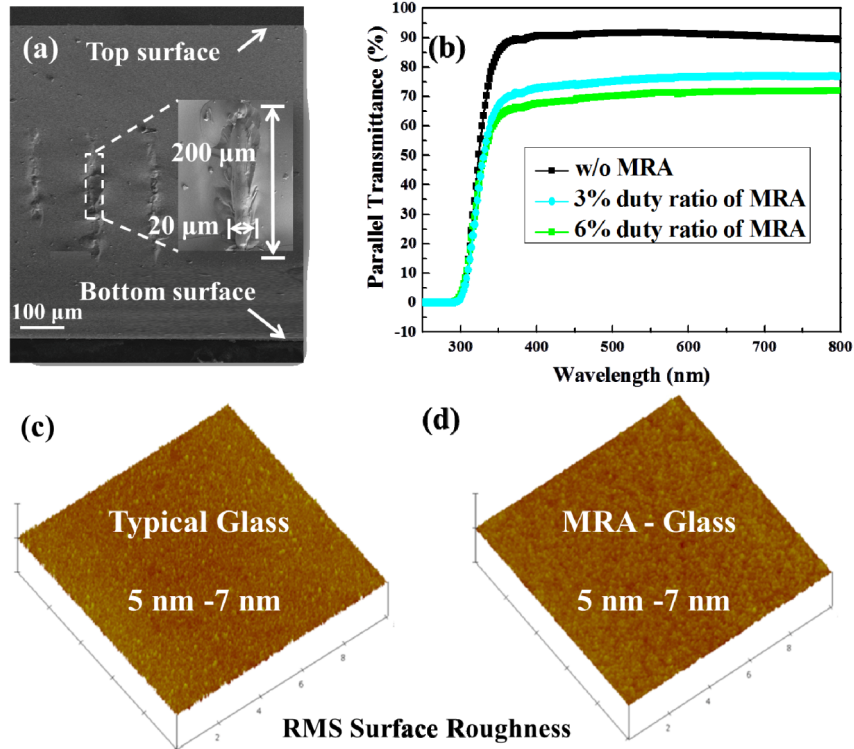


Fig. 3. Properties of the MRA: (a) a cross-sectional view obtained by SEM, (b) parallel transmittance of the glass, (c) the roughness of typical glass, and (d) MRA-glass.

3. Simulation results and analysis

In order to investigate the out-coupling efficiency of the MRA structure, a 3D geometric model of the device was built by Lighttools 7.2 ray-tracing software, which employs the Monte Carlo method [23]. Four main parameters—the arrangement of the MRA, the distance of MRA from glass/ITO interface, the refractive index of the substrate, and the duty ratio of the MRA—account for the enhancement in the out-coupling efficiency. The factors related to the increase in the optical efficiency were simulated and are summarized in Tables 2–5 after normalization. A conventional device without an MRA structure was also calculated as a reference. All the simulation results were only based on ray-optic modeling but excluding the surface plasmonic, interference and micro-cavity effect.

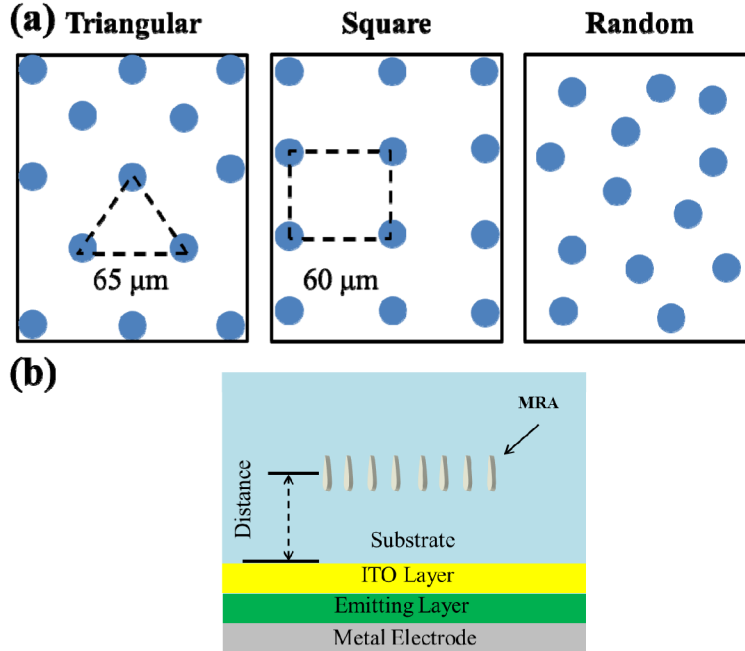


Fig. 4. (a) Different arrangements for the MRA with a 3% duty ratio and (b) distance of MRA from glass/ITO interface.

Table 2. Factor of increase in the optical efficiency for different arrangements of the MRA.

Arrangement of MRA	Triangular	Square	Random
Factor of increase	1.62	1.61	1.62

with a distance 150 μm from glass/ITO interface, a refractive index of 1.5 for the glass substrate and a 3% duty ratio of the MRA

Table 3. Factor of increase in the optical efficiency for different distances of MRA from glass/ITO interface.

Distance(μm)	150	250	350
Factor of increase	1.62	1.63	1.62

with a triangular arrangement, a refractive index of 1.5 for the glass substrate and a 3% duty ratio of the MRA

Table 4. Factor of increase in the optical efficiency for different glass refractive indices.

Refractive index	1.5	1.65	1.8
Factor of increase	1.62	2.21	3.36

with a triangular arrangement, a distance 250 μm from glass/ITO interface, and a 3% duty ratio of the MRA

Table 5. Factor of increase in the optical efficiency for different duty ratios of the MRA.

Duty ratio of MRA (%)	3	6	12
Factor of increase	1.62	2.16	2.81

with a triangular arrangement, a distance 250 μm from glass/ITO interface, and a refractive index of 1.5 for the glass substrate

The different arrangements with a duty ratio of approximately 3% for the MRA are shown in Fig. 4(a). In order to maintain a similar duty ratio, the lengths of the regular triangle and square are set as 65 μm and 60 μm , respectively. As summarized in Table 2, MRAs with different arrangements exhibit a similar increase in the optical efficiency by a factor of 1.62, 1.61, and 1.62, compared with the reference device. It implies that the optical efficiency can be enhanced effectively by the MRA, but it is insensitive to the specific arrangement.

The schematic diagram of distance of MRA from glass/ITO interface is illustrated in Fig. 4(b). The distance of MRA from glass/ITO interface as a function of the optical efficiency was simulated. As summarized in Table 3, the factors of increase in optical efficiency with different distances are almost the same, which indicated that no matter what depth of MRA, the optical efficiency could be enhanced by MRA with similar proportion.

According to classical electromagnetic and refractive-index-matching theory, if the refractive index of a substrate is greater than that of the emitting layer, the ITO/organic waveguide mode can be completely transformed to the substrate mode. A refractive index of 1.8 for the substrate glass, which is higher than that of the organic emission layer ($n \sim 1.7$), was used in our simulation. Thus, the proportion of light trapped in the glass substrate increased from 35.3% to 81.2% using the high-refractive-index glass, with a factor of increase of 4.32 in theory [10]. As summarized in Table 4, more light was coupled to the substrate from the waveguide mode as the refractive index of the glass substrate increased, and the optical efficiency was greatly enhanced by factors ranging from 1.62 to 3.36. Obviously, the combination of a high-refractive-index substrate with an MRA structure can tremendously enhance the optical efficiency.

As summarized in Table 5, the optical efficiencies were improved by factors of 1.62, 2.16, and 2.81 as the MRA duty ratio increased from 3% to 12%. A larger amount of emitted light can be effectively out-coupled by breaking the TIR limitation due to multiple refraction by increasing the duty ratio of the MRA. As the duty ratio of MRA reaches 12%, the factor of increase of 2.81 in the optical efficiency is very close to that of the maximum value in theory (2.88), implying that all of the light trapped in substrate is mostly out-coupled. The 12% duty ratio of the MRA is an optimal value for optical efficiency enhancement.

4. Experimental results and discussion

To verify the proposed method, green OLEDs on a 0.5 mm-thick glass substrate with MRA duty ratios of 0%, 3%, and 6% were fabricated. The current efficiency with its increase factor are shown in Fig. 5(a). With the increasing of current density, the increase factors are gradually stabilized at 1.5 and 1.9 for duty ratios of 3% and 6%, respectively, compared with the reference device. The electrical properties including the voltage versus the current density and voltage versus power efficiency are plotted in Fig. 5(b). The improvement in the optoelectronic properties of the OLED devices should be mostly attributed to the enhancement in the optical efficiency, as the green OLEDs on an MRA-glass substrates have the similar current density compared with the reference device, as shown in Fig. 5(b). Additionally, the increase factor in current efficiency is well matched with the enhancement of power efficiency according to the curves in Fig. 5(b). The MRAs simply increased the light output from the glass substrate but did not affect the electrical properties of the OLEDs. Moreover, when the duty ratio of the MRA changed from 6% to 12%, the pitch of the MRA was decreased from 40 μm to 20 μm , and the uneven distribution of the internal stress in the glass substrate was aggravated by the decreased pitch, which results in cracking, thus, a glass substrate with a 12% duty ratio for the MRA was not yet successfully produced. This issue could be overcome by using glass with a larger thickness to relax the internal stress. If an MRA can be fabricated with the optimized duty ratio of 12%, more light could be extracted from the substrate, and the factor of increase in the optical efficiency can be further improved.

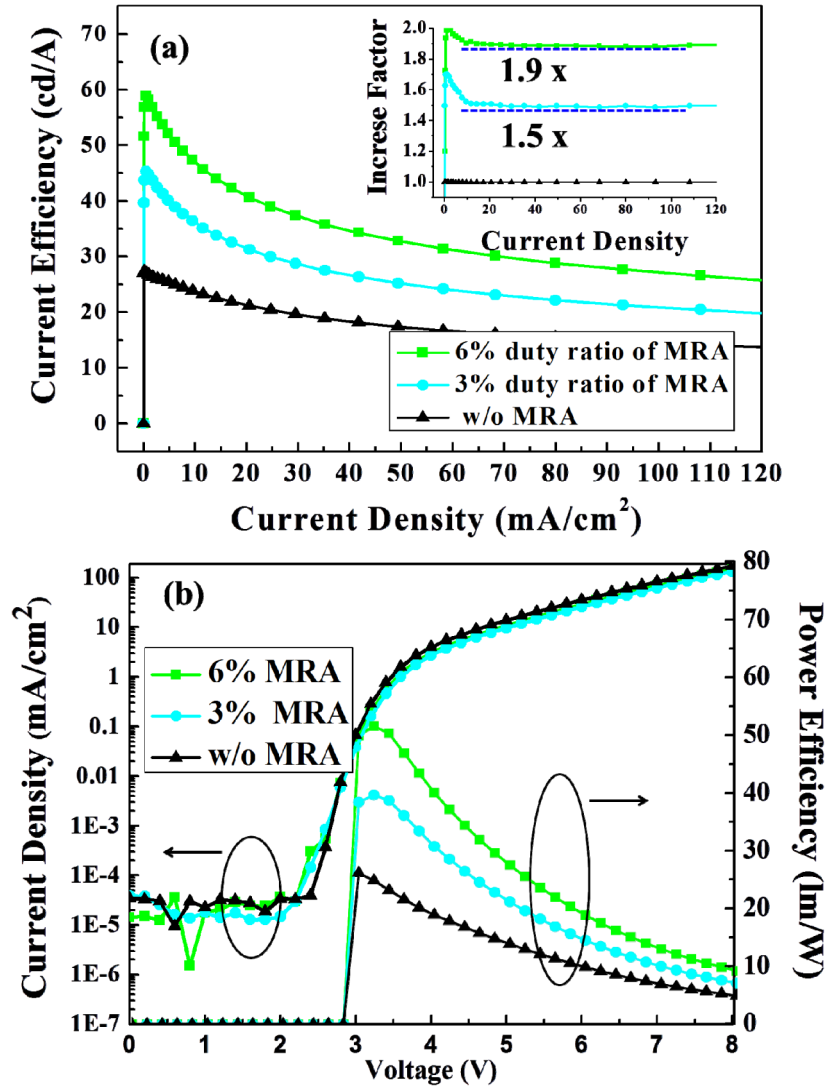


Fig. 5. Photoelectric properties of a green OLED for different duty ratios of the MRA: (a) current density–current efficiency and increase factor of current efficiency and (b) voltage–current density and voltage–power efficiency.

To further investigate the enhancement in the efficiency in the visible-light spectrum, red and blue OLEDs on glass substrates with a 6% duty ratio of the MRAs were also fabricated with a similar device structure as the green OLEDs. The current efficiencies for each color at 10 mA/cm² are illustrated in Fig. 6. The blue and red OLEDs exhibited an enhancement in the current efficiency by a factor of 1.7 and 1.82, respectively, which were very close to that of the green OLED on the MRA-glass substrate with the same duty ratio of the MRAs, indicating that the optical out-coupling efficiency of the full-color OLEDs can be improved by one MRA structure.

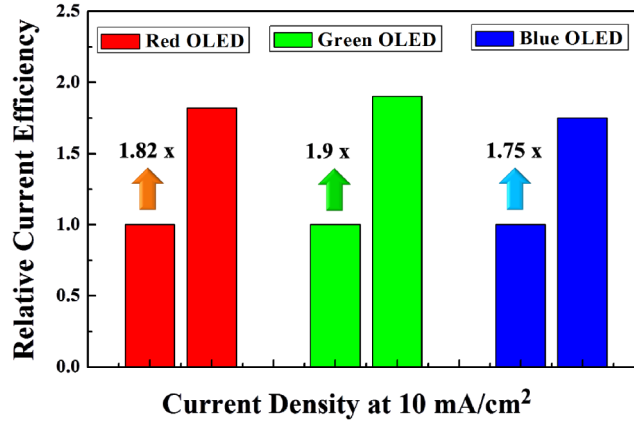


Fig. 6. Optical properties of red, green, and blue OLEDs.

The angular dependencies of green OLEDs with and without an MRA were measured by a spectrophotometer (Konica Minolta CS-2000) and are summarized in Fig. 7 with the simulation results after normalization. The angular distribution of the green OLED with a 6% duty ratio of the MRA had a negligible change compared to those of simulation, and both results were similar to a Lambertian source. The normalized light intensities with and without an MRA were also very similar, indicating that a device with an MRA structure can offer the same functional angular distribution as a conventional one. Compared with conventional structure such as Micro Lens Array (MLA), the OLED with MRA structure shows no light distortion which is essential for display applications [24].

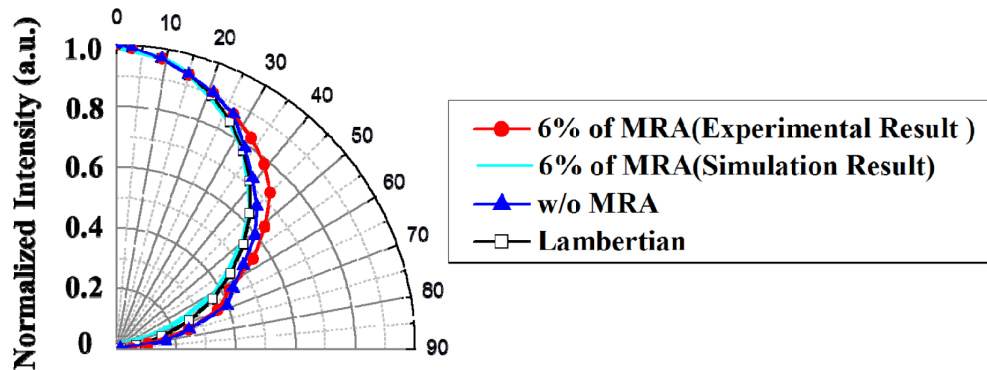


Fig. 7. Angular distributions of the normalized light intensities of devices with and without MRAs compared with a typical Lambertian light source.

5. Conclusions

A novel MRA structure in a glass substrate fabricated by a femtosecond laser was demonstrated to enhance the optical out-coupling efficiency for electroluminescent devices. Green, blue, and red OLEDs on an MRA-glass substrate exhibited an out-coupling efficiency enhancement by a factor of 1.9, 1.7, and 1.82, respectively, at 10 mA/cm² compared to conventional OLEDs. The results indicate that the optical performance can be improved by only one MRA structure for full-color OLEDs. In addition, the device with an MRA substrate is a Lambertian light source. The proposed method, which is compatible with current fabrication processes, effectively enhances optical out-coupling efficiency and shows great potential for next-generation displays and solid-state lighting.

Acknowledgments

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