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# Effect of refractive index of packaging materials on the light extraction efficiency of COB-LEDs with millilens array

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**Lens arrays are introduced to diminish the total internal reflection (TIR) that happens at chip-encapsulant and encapsulant-air interfaces of chip-on-board light-emitting diodes (COB-LEDs), so as to improve the light extraction efficiency (LEE) of the COB-LEDs. However, the LEE of COB-LEDs with lens array depends on the refractive index of the encapsulant layer $n_{encap}$ and lens array $n_{lens}$, which was rarely concerned so far. Optical simulations based on a Monte Carlo ray tracing method, and experiments were conducted to investigate the effect of $n_{encap}$ and $n_{lens}$ on the LEE of COB-LEDs with millilens array. The simulated results show that the TIR at chip-encapsulant, encapsulant-lens, and lens-air interfaces can be significantly diminished by regulating the $n_{encap}$ and $n_{lens}$, and the LEE of COB-LEDs decreases as the refractive difference of encapsulant layer and lens array $|n_{lens} - n_{encap}|$ increases. Compared to the COB-LEDs with only a flat encapsulant layer, the LEEs of blue and white COB-LEDs with $n_{lens} = n_{encap} = n_{ITO} = 2$ are enhanced by 246.2% and 50.6%, where $n_{ITO}$ is the refractive index of the top layer of the conventional LED chip. The experimental results agree well with the simulated results with normalized LEE deviation within 7.3%.** 

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## 1. INTRODUCTION

Chip-on-board light-emitting diodes (COB-LEDs) with dozens to hundreds of LED chips have attracted extensive attention in recent years due to their advantages of compact size and high output power [1]. For commercial COB-LEDs, a flat encapsulant layer is coated on the LED chips to protect the chips from oxygen, moisture, and contaminants. However, serious total internal reflection (TIR) happens at both chip-encapsulant and encapsulant-air interfaces due to the refractive index difference of LED chip ($2 \sim 2.5$), encapsulant ($1.4 \sim 1.7$) and air ($=1$), which decreases the LEE of COB-LEDs significantly [2–5]. To diminish the TIR at the two optical interfaces, nanolens [6–9], microlens [10–17], and millilens [18] arrays were introduced on the LED chips and encapsulant layer. For the flat optical interface shown as Fig. 1(a), the light with incident angle exceeding the critical TIR angle $\theta_c$ of $\arcsin(n_1/n_2)$ is totally reflected back, where $n_1$ is the refractive index of the exit layer, and $n_2$ is the refractive index of the incident layer. Part of the reflected light is absorbed by the packaging materials, which causes serious light extraction efficiency (LEE) drop of COB-LEDs. However, when the lens array is imported, more light can emit out from the curved-interface directly shown as Fig. 1(b), and the LEE of COB-LEDs is enhanced significantly.

Previous studies mainly focus on the effect of lens geometry, including lens shape, lens curvature, lens radius, and lens spacing, on the LEE of the LED chips and LED packages [6–19]. By optimizing the lens geometry, the TIR at the lens-encapsulant and lens-air interfaces can be significantly diminished. However, the LED chip, encapsulant, and lens array are usually composed of different materials. Therefore, the refractive index difference of these packaging materials may induce serious TIR at numerous optical interfaces, such as chip-encapsulant, chip-lens, chip-air, encapsulant-lens, encapsulant-air, and lens-air interfaces, which may decrease the LEE of COB-LEDs. However, the effect of the refractive index of these packaging materials on the LEE of the COB-LEDs with lens array was rarely a concern.

In the LED packaging, it is difficult to adjust the refractive index of the LED chip due to the complicated and expensive fabrication process of the LED chip, while the refractive index of the encapsulant layer $n_{encap}$ and lens array $n_{lens}$ can be regulated by using various transparent packaging materials, such as sapphire [9], glass [11,20], indium tin oxide (ITO), GaN [12–14], and transparent resin [15–18]. Therefore, this study

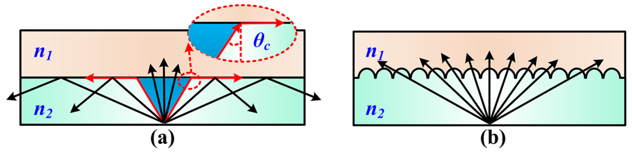


**Fig. 1.** Light propagation at (a) flat optical interface, and (b) curved optical interface.

aims to investigate the effect of the $n_{encap}$ and $n_{lens}$ on the LEE of COB-LEDs with lens array. For this goal, optical simulations based on Monte Carlo ray tracing method and experiments were conducted. In the optical simulations, the $n_{encap}$ and $n_{lens}$ were adjusted as 1 to 2.5 to include the refractive index of typical packaging materials. In the experiments, two typical transparent resins, i.e., OE6550 (Dow Corning) and DC-184 (Dow Corning), were used to fabricate encapsulant and millilens array by the method that is reported in our recent study [18]. The LEE of the COB-LEDs were measured and analyzed, and the accuracy of the simulation was verified with the experimental results.

## 2. METHODOLOGY

### A. Optical Simulation

For COB-LEDs with an encapsulant layer and lens array, there are three important optical interfaces, i.e., chip-encapsulant, encapsulant-lens, and lens-air interfaces. Typically, the refractive index of LED chip, encapsulant layer, lens array, and air are in the order of $n_{chip} > (n_{encap}, n_{lens}) > n_{air}$. Therefore, the TIR happens inevitably at the three optical interfaces, which decreases the LEE of COB-LEDs. $n_{chip}$ and $n_{air}$ are uncontrollable in most LED packages, while $n_{encap}$ and $n_{lens}$ can be regulated by using various transparent packaging materials. Therefore, it is very important to investigate the effect of $n_{encap}$ and $n_{lens}$ on the TIR at the three optical interfaces, and improve the LEE of COB-LEDs by manipulating $n_{encap}$ and $n_{lens}$.

For this goal, optical simulations based on Monte Carlo ray tracing method were conducted by commercial software Tracepro. Figure 2(a) shows the structure of the COB-LEDs used in the optical simulations. It consists of substrate with packaging area of 20 mm × 20 mm, 100 conventional LED chips in 10 × 10 array with chip size and spacing of 1 mm × 1 mm and 2 mm, an encapsulant layer with thickness of 1 mm, and lens array shown as Fig. 2(b). The reflectance and absorptance of the LED substrate were set as 0.92 and 0.08, respectively [18,21]. The structure of a conventional LED chip is shown in Fig. 2(c), and the optical properties of each layer are shown in Table 1 [21]. The encapsulant layer and lens array are usually made up by transparent resin with refractive index of 1.4–1.7, such as OE6550 (Dow Corning) with refractive index of ∼1.41 and DC-184 (Dow Corning) with refractive index of ∼1.53. In some special applications, the sapphire, ITO, and GaN are also used to fabricate the lens array, and their refractive index were shown in Table 1. To include these typical package materials in the simulations, the refractive index of the encapsulant and lens array was adjusted as 1, 1.41, 1.53, 1.77, 2, and 2.5. Both blue and white COB-LEDs were studied. For white COB-LEDs, phosphors was assumed to be embed in the encapsulant layer with mass concentration of 0.03 g: 1 g, and they were assumed to be spherical with diameter of ∼13 µm. To simulate the light conversion process, specific wavelengths of 454 and 570 nm were used to characterize the emission light of the LED chips and phosphor.

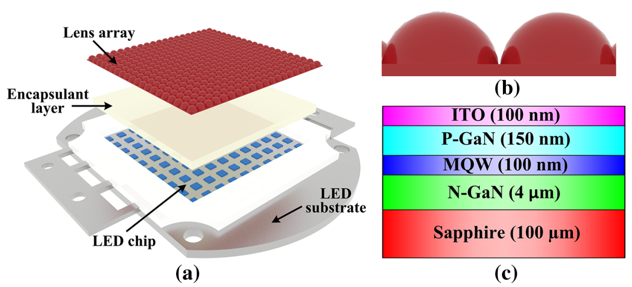


**Fig. 2.** Optical simulation: (a) structure of COB-LEDs, (b) parameters of lens array, and (c) structure of the conventional LED chip.

**Table 1. Optical Properties of the Chip Layers**

| Layers | Thickness (µm) | Wavelength | 454 nm |
|---|---|---|---|
| Sapphire | 100 | Refractive Index | 1.77 |
| | | Absorption Coefficient ($mm^{-1}$) | 0 |
| N-GaN | 4 | Refractive Index | 2.43 |
| | | Absorption Coefficient ($mm^{-1}$) | 2 |
| MQW | 0.1 | Refractive Index | 2.51 |
| | | Absorption Coefficient ($mm^{-1}$) | 8 |
| P-GaN | 0.15 | Refractive Index | 2.43 |
| | | Absorption Coefficient ($mm^{-1}$) | 2 |
| ITO | 0.1 | Refractive Index | 2 |
| | | Absorption Coefficient ($mm^{-1}$) | 0 |

### B. Experiment

Experiments were conducted to characterize the LEE of COB-LEDs packaged with various materials in different packaging structure. Figure 3(a) shows the structure of COB-LEDs used in the experiments, which is the same as that used in the simulations. Figure 3(b) shows the COB-LEDs with encapsulant layer and lens array. The thickness of the encapsulant layer was set as ∼1 mm. The lens array with lens curvature, radius, and spacing of 90°, 1 and 2 mm shown as Figs. 3(c) and 3(d) was fabricated with the complementary printing method that was reported in our recent study [18]. Limited by the experimental conditions and the complementary printing method, only DC-184 and OE6550 were used for fabricating the encapsulant layer and lens array. Under this condition, seven series of LED samples were fabricated, and their packaging structure is listed in Table 2. The optical performance of LED samples was measured by an integrating sphere (ATA-1000, Everfine).

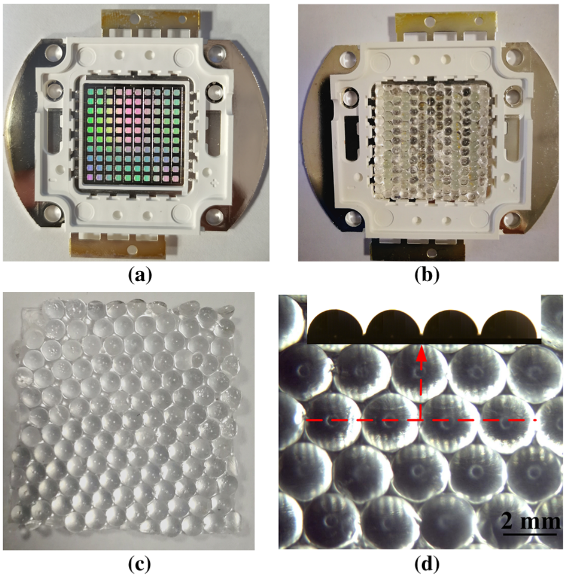


**Fig. 3.** Pictures of (a) structure of COB-LEDs, (b) COB-LEDs with encapsulant layer and lens array, and (c)–(d) lens array with lens curvature, radius, and spacing of 90°, 1 and 2 mm.

**Table 2. Packaging Structure of the Experimental Samples**

| Samples | Encapsulant layer | Lens array |
|---|---|---|
| 1 | | |
| 2 | DC-184 | |
| 3 | OE6550 | |
| 4 | DC-184 | DC-184 |
| 5 | DC-184 | OE6550 |
| 6 | OE6550 | DC-184 |
| 7 | OE6550 | OE6550 |

## 3. RESULTS AND DISCUSSION

The lens radius $R$ and lens curvature $\theta$ could have great influence on the LEE of COB-LEDs [6–19]. Therefore, the effect of $R$ and $\theta$ on the LEE of COB-LEDs was investigated before refractive index optimization. The $\theta$ was fixed as 90° (hemispherical shape) when changing the $R$, and the $R$ was fixed as 0.5 and 1 mm when changing the $\theta$. The $n_{\text{encap}}$ and $n_{\text{lens}}$ were set as 1.41, and the lens arrangement was kept the same with the experimental lens array shown in Fig. 3(d). Figures 4(a) and 4(b) show the normalized LEE of blue COB-LEDs with various $R$ and $\theta$. The normalized LEE is defined as $P_1/P_2$, where $P_1$ represents the light output of COB-LEDs with encapsulant layer or lens array, and $P_2$ represents the light output of COB-LEDs without encapsulant layer and lens array. Figure 4(a) shows the normalized LEE of blue COB-LEDs increases as $R$ increases. As the inset figure of Fig. 4(a) shows, larger $R$ is better for the light extraction at lens-air interface, so the normalized LEE of COB-LEDs increases as $R$ increases. Figure 4(b) shows the normalized LEE of blue COB-LEDs with both $R$ of 0.5 and 1 mm increases with $\theta$ and deceases with $\theta$ when $\theta > 90°$, which indicates that $\theta$ of 90° is optimal for improving the LEE of COB-LEDs.

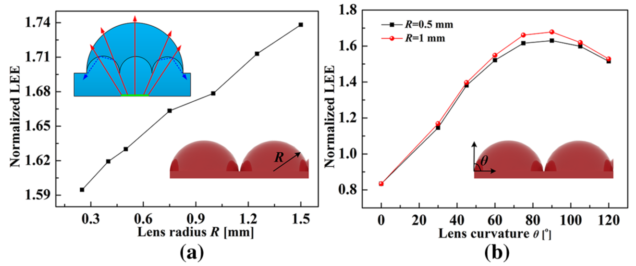


**Fig. 4.** Simulated normalized LEE of blue COB-LEDs with (a) various $R$ when $\theta$ is fixed as 90°, and (b) various $\theta$ when $R$ is fixed as 0.5 and 1 mm.

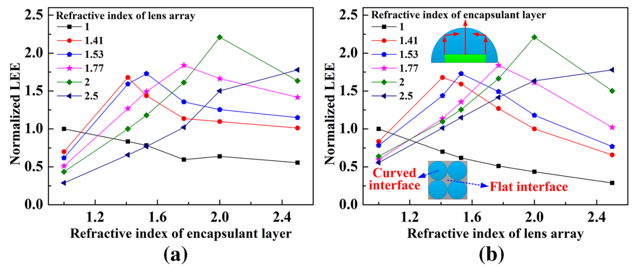


**Fig. 5.** Simulated normalized LEE of blue COB-LEDs as a function of (a) refractive index of encapsulant layer $n_{\text{encap}}$, and (b) refractive index of lens array $n_{\text{lens}}$.

Figure 5 shows the relationship between the simulated normalized LEE of blue COB-LEDs and $n_{\text{encap}}$, $n_{\text{lens}}$, where the lens radius and lens curvature were set as 1 mm and 90°. When $n_{\text{encap}}$ or $n_{\text{lens}}$ was set as 1, it means that the corresponding layer is composed of air. From Fig. 5, we obtain the following conclusions.

1. For COB-LEDs with only a flat encapsulant layer, the normalized LEE of COB-LEDs decreases as the $n_{\text{encap}}$ increases, shown as the black line with square symbol in Fig. 5(a). Although increasing $n_{\text{encap}}$ can diminish the TIR at the chip-encapsulant interface, the TIR at the encapsulant-air interface plays a dominant role in determining the LEE of COB-LEDs. Moreover, an enhancement of normalized LEE was observed at $n_{\text{encap}} = n_{\text{ITO}} = 2$, where $n_{\text{ITO}}$ is the refractive index of the top layer of the conventional LED chip. As shown in Fig. 6, when $n_{\text{encap}} < 2$, the TIR at the chip-encapsulant interface becomes less serious as $n_{\text{encap}}$ increases. However, when $n_{\text{encap}} \geq 2$, no TIR happens at the chip-encapsulant

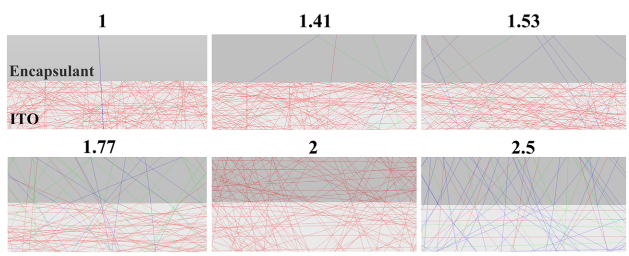


**Fig. 6.** Light propagation at chip-encapsulant interface when $n_{\text{encap}}$ varies from 1 to 2.5.

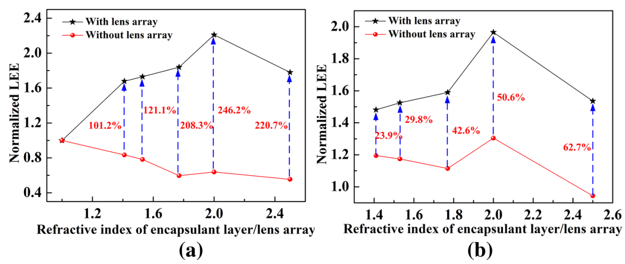


**Fig. 7.** Simulated normalized LEE of (a) blue, and (b) white COB-LEDs with and without lens array when $n_{lens} = n_{encap}$.

interface. As a result, an enhancement of LEE was observed at $n_{encap} = n_{ITO} = 2$.

2. For COB-LEDs without encapsulant layer but with lens array, the normalized LEE of COB-LEDs decreases monotonously as $n_{lens}$ increases, shown as a black line with square symbol in Fig. 5(b). This is caused by two reasons. First, part of the lens-air interface is composed of a flat interface shown as the inset figure of Fig. 5(b), and the TIR at the flat interface becomes more serious as $n_{lens}$ increases. Second, because the chip size (1 mm × 1 mm) is close to the lens radius (1 mm), TIR also happens at the curved interface shown as the inset figure of Fig. 5(b), and the TIR at the curved interface becomes more serious as $n_{lens}$ increases.
3. For COB-LEDs with both encapsulant layer and lens array, the normalized LEE of COB-LEDs decreases as the refractive index difference of encapsulant layer and lens array $|n_{lens-}n_{encap}|$ increases, and a highest normalized LEE is achieved at $n_{lens} = n_{encap}$. As shown in Fig. 7, the normalized LEE of blue and white COB-LEDs packaged with $n_{lens} = n_{encap}$ increases with $n_{encap}$ and $n_{lens}$ if $(n_{lens} = n_{encap}) < (n_{ITO} = 2)$, and decreases with $n_{encap}$ and $n_{lens}$ if $(n_{lens} = n_{encap}) > (n_{ITO} = 2)$. A maximum normalized LEE is achieved at $n_{lens} = n_{encap} = n_{ITO} = 2$ among all the simulated cases. This is attributed to two reasons. First, no TIR happens at chip-encapsulant and encapsulant-lens interfaces. Second, the lens array diminishes the TIR at the lens-air interface. Figure 8 shows the light propagation in three typical COB-LEDs with $n_{lens} = n_{encap} = n_{ITO} = 2$. For COB-LEDs without encapsulant layer and lens array shown as Fig. 8(a), TIR happens at the chip-air interface with critical TIR angle of arcsin(1/2) = 30°. For COB-LEDs with only an encapsulant layer shown as Fig. 8(b), TIR only happens at encapsulant-air with critical TIR angle of 30°. Although the critical TIR angle at the encapsulant-air interface is the same with that at chip-air interface, the LEE of COB-LEDs with encapsulant layer is much lower than that without encapsulant layer. This is because sufficient reflected light is absorbed by the LED substrate in the COB-LEDs with encapsulant layer shown as Fig. 8(b). For COB-LEDs with both encapsulant layer and lens array shown as Fig. 8(c), no TIR happens at chip-encapsulant and encapsulant-lens interface, while the TIR at the lens-air interface is greatly diminished by the curved-interface. As a result, the normalized LEE of COB-LEDs is enhanced significantly by the lens array. Compared to the COB-LEDs with only encapsulant layer, the LEEs of blue and white COB-LEDs with $n_{lens} = n_{encap} = n_{ITO} = 2$ are enhanced by 246.2% and 50.6%, respectively. The LEE enhancement of the while COB-LED is much lower than the blue COB-LEDs due to the scattering effect of the phosphors [18,21].
4. For fixed $n_{lens}$ shown as Fig. 4(a), the TIR at the lens-air interface is assumed to be unchanged, and the LEE of COB-LEDs is mainly determined by the TIR at chip-encapsulant and encapsulant-lens interfaces. For $n_{encap} < n_{lens}$, the TIR only happens at chip-encapsulant interface, so the LEE of COB-LEDs increases with $n_{encap}$ because the TIR at the chip-encapsulant interface becomes less serious as $n_{encap}$ increases. For $n_{lens} < n_{encap} < n_{ITO}$, TIR happens at both chip-encapsulant and encapsulant-lens interfaces. Although increasing $n_{encap}$ can diminish the TIR at the chip-encapsulant layer, it causes more serious TIR at the encapsulant-lens interface. As a result, the LEE of COB-LEDs decreases with $n_{encap}$. For $n_{encap} \geq n_{ITO}$, TIR only happens at encapsulant-lens interfaces, so the LEE of COB-LEDs decreases with $n_{encap}$ because the TIR at the encapsulant-lens interface becomes more serious as $n_{encap}$ increases, and a highest light efficiency is achieved at $n_{encap} = n_{lens}$. Similar to COB-LEDs without lens array, the reduction rate of LEE slows down when $n_{encap} \geq n_{ITO}$.
5. For fixed $n_{encap}$ shown as Fig. 4(b), the TIR happens at the chip-encapsulant interface is assumed to be unchanged, and the LEE of the COB-LEDs is mainly determined by the TIR at encapsulant-lens and lens-air interfaces. The TIR at the lens-air interface is inevitable because $n_{lens}$ is always larger than $n_{air}$. However, the LEE of COB-LEDs could be enhanced by reducing the difference of $n_{lens}$ and $n_{encap}$ to diminish the TIR at the encapsulant-lens interface. For $n_{lens} < n_{encap}$, TIR happens at the encapsulant-lens interface, and the LEE of COB-LEDs increases with $n_{lens}$ because the TIR at the encapsulant-lens interface becomes less serious as $n_{lens}$ increases. For $n_{lens} \geq n_{encap}$, no TIR happens at the encapsulant-lens interface, so the LEE of COB-LEDs is determined by the lens-air interface. The TIR at the lens-air interface becomes more serious as $n_{lens}$ increases. So the LEE of COB-LEDs decreases with $n_{lens}$, and the highest LEE is obtained at $n_{lens} = n_{encap}$.

Figure 9(a) shows the normalized LEE of samples 1–7 at driving current of 0.5 to 3.5 A. The normalized LEE of the samples is defined as the light output ratio of each sample (with encapsulant layer or lens array) to sample 1 (without encapsulant layer and lens array). It indicates that the normalized LEE of samples 2–7 rarely changes with the driving current. Figure 9(b) shows the comparison of normalized LEE that is obtained from simulations and experiments, and the experimental results are consistent with the simulated results with maximum deviation of 7.3%. For samples 1–3, the LEE of COB-LEDs decreases after coating flat encapsulant layer and the LEE of COB-LEDs packaged with DC-184 is higher than that packaged with OE6550. For samples 4–7, the LEE increases after introducing the lens array on the flat encapsulant layer. Besides, by comparing sample 4 with 5 and sample 6 with 7, the LEE of COB-LEDs packaged with the same material is higher than that packaged

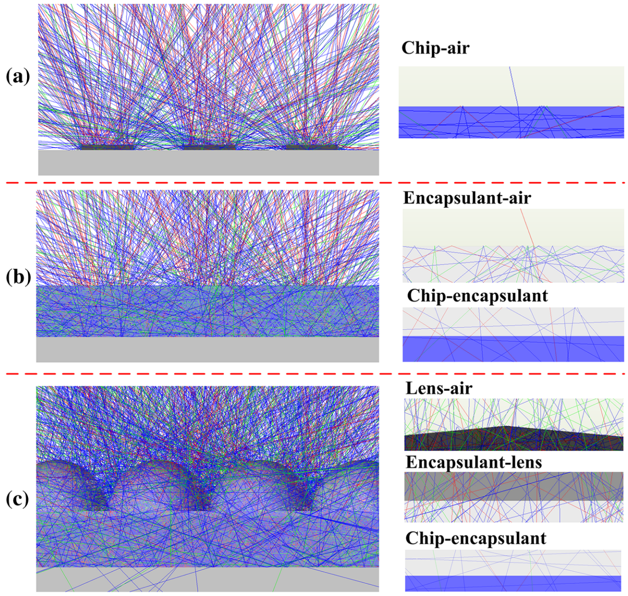


**Fig. 8.** Light propagation at COB-LEDs (a) without encapsulant layer and lens array, (b) with only encapsulant layer, and (c) with both encapsulant layer and lens array.

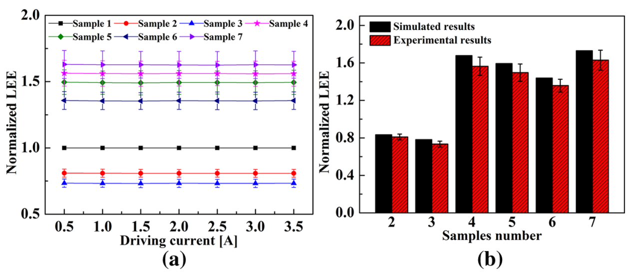


**Fig. 9.** Experimental results. (a) LEE of the seven series of samples under different driving current, and (b) comparison of normalized LEE obtained from simulations and experiments.

with different materials, and the LEE of COB-LEDs packaged with OE6550 is higher than that packaged with DC-184. Moreover, the LEE of sample 4 is 93.1% higher than that of sample 2, and the LEE of sample 7 is 122.1% higher than that of sample 3, which indicates that the lens array can enhance the LEE of COB-LEDs significantly. The LEE enhancement could be further increased by using packaging materials with refractive index closer to $n_{\mathrm{ITO}}$ to fabricate the encapsulant layer and lens array. However, limited by the current packaging technology, it is difficult to achieve such a goal because the typical transparent packaging materials with high refractive index are mostly solid. The solid materials are not suitable to fabricate the encapsulant layer because the encapsulant needs to have strong fluidity to fill the gap between LED chips at room temperature.

## 4. CONCLUSION

In this study, optical simulations were conducted to explore the effect of the refractive index of the encapsulant layer $n_{\mathrm{encap}}$ and lens array $n_{\mathrm{lens}}$ on the LEE of COB-LEDs with millilens array and analyze the TIR phenomenon at the chip-encapsulant, encapsulant-lens, and lens-air interfaces. Experiments were conducted to verify the accuracy of the optical simulations. Limited by the experimental conditions and packaging technology, only transparent resins DC-184 and OE6550 with refractive index of $\sim$1.41 and $\sim$1.53 at wavelength of 454 nm were used to fabricate the encapsulant layer and lens array, and seven series of samples with different packaging configuration were studied. The simulated results show that the LEE of COB-LEDs with only flat encapsulant layer decreases as $n_{\mathrm{encap}}$ increases. However, when the lens array is imported, the LEE of COB-LEDs can be enhanced significantly by reducing the difference of $n_{\mathrm{ITO}}$, $n_{\mathrm{encap}}$, and $n_{\mathrm{lens}}$. The LEE of COB-LEDs packaged with $n_{\mathrm{lens}} = n_{\mathrm{encap}}$ increases with $n_{\mathrm{encap}}$ and $n_{\mathrm{lens}}$ if $(n_{\mathrm{lens}} = n_{\mathrm{encap}}) < (n_{\mathrm{ITO}} = 2)$ and decreases with $n_{\mathrm{encap}}$ and $n_{\mathrm{lens}}$ if $(n_{\mathrm{lens}} = n_{\mathrm{encap}}) > (n_{\mathrm{ITO}} = 2)$. Compared to the COB-LEDs with only a flat encapsulant layer, a maximum LEE enhancement of 246.2% was obtained at $n_{\mathrm{lens}} = n_{\mathrm{encap}} = n_{\mathrm{ITO}} = 2$. The experimental results agree well with the simulated results with normalized LEE deviation within 7.3%.

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