Effect Study of Chip Offset on the Optical Performance of Light-Emitting Diode Packaging

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***Abstract*— In this letter, we studied the effect of chip offset on the optical performance of bare chip and white light-emitting diode (LED) package through a series of comparative experiments. LED modules with different chip offset distances were packaged and measured. The results show that chip position offset has a great influence on white LED's performance. When the offset distance reaches 1 mm, the luminous efficiency decreases by 22.9% and the angular color distribution is deteriorated. Two methods are recommended to avoid this effect.**

***Index Terms*— Light-emitting diode (LED), chip offset, luminous efficiency, angular color distribution (ACD).**

I. INTRODUCTION

WHITE light-emitting diode (LED) has been widely used in our daily lives due to its extraordinary characteristics of high luminous efficiency, low power consumption, long lifetime and environment protection [1]–[4]. So far, the most common approach to get white light is using the phosphor-converting scheme on blue LED chips. The phosphor particles absorb part of the blue light emitted from the LED chip, then down-convert part of the blue light into yellow emission. The mixture of the transmitted blue light and yellow light gives a white visual sense.

In the LED packaging process, the LED chip is mounted onto the heat slug before solder reflowing. Usually, the equipment used for surface mounting is the lead-free reflow welding machine. This machine often uses hot wind heating method. In this case, when the solder temperature reaches its melting point, the LED chip becomes readily movable under hot wind blowing, so the chip's location is very likely to be off-centered. Besides, the improper operation of front-line workers can also lead to the off-centered situation.

Fig. 1(a) plots the model of the common LED module and Fig. 1(b) plots the sketch of an off-centered LED chip. For the off-centered module, the displacement offset can be denoted by the distance δ.

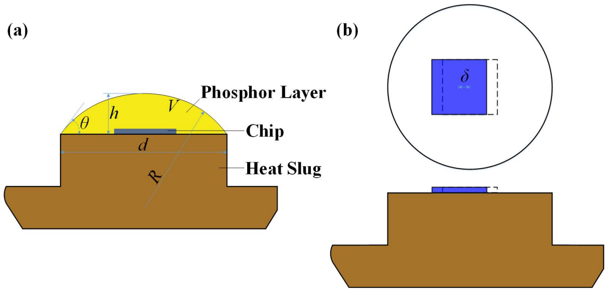

Fig. 1. (a) Schematic of the LED module and (b) Sketch of an off-centered LED bare die.

Intuitively, the chip offset would have an effect on the LED's optical performance. However, few research works were dedicated to this. Liu *et al* [5] numerically studied the impact of the different relative position of LED chip and phosphor layer on LED's optical performance. They found that in some certain package structures, the position difference can have a great influence on the luminous efficiency and correlated color temperature (CCT). Braune *et al* [6] discussed the impact of lateral chip displacement on LED's optical performance. If the chip is not in the center of the reflector, the average path length of the blue light differs across the LED, which would result in an asymmetrical distribution of both blue light and converted light and might lead to a different effective color of the LED. Sun *et al* [7] analyzed the far-field region dependence of LEDs on chip displacement in transverse direction by numerical simulations. It was found that the maximum far-field and quasi far-field distances remain almost constant despite the lateral chip displacement. Despite those researches, the experimental exploration of the chip offset effect on LED's optical performance still remains unclear.

In this letter, we studied the effect of chip offset on the LED's optical performance through a series of comparative experiments. Three groups of LED modules with different chip offset distances were packaged. Their luminous efficiencies and angular color distributions (ACDs) were measured and compared to evaluate the offset's effect.

II. EXPERIMENT

In the sample preparation, we packaged a series of white LEDs and the processes were shown in Fig. 2. For better sample consistency, all the samples were packaged by using the volume-control method, in which the coating volume of phosphor gel is kept the same. From Fig. 1(a), the phosphor gel volume can be calculated as the volume of a spherical crown, i.e.

$$V = \frac{1}{3}\pi h^2(3R - h) - a^2 b \tag{1}$$

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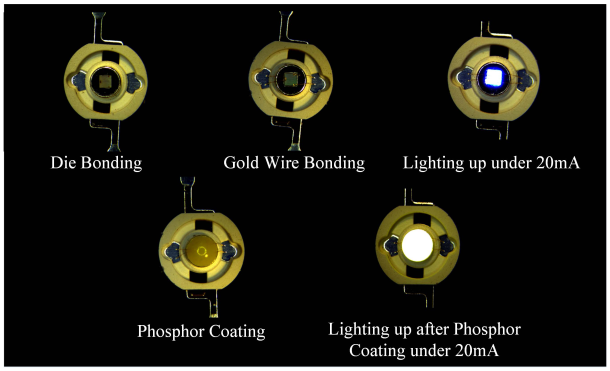


Fig. 2. Images of an LED module during packaging process.

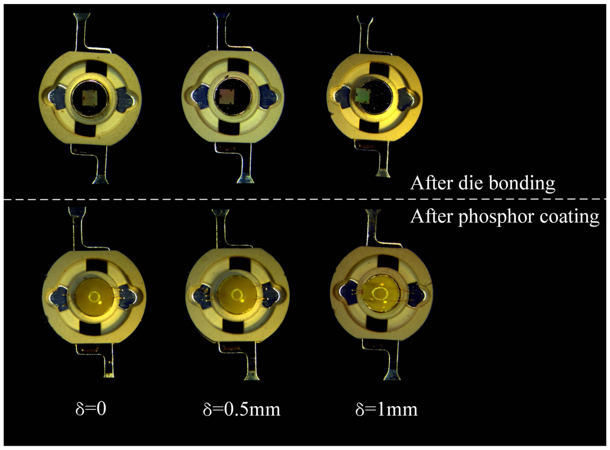


Fig. 3. Images of the three kinds of LED modules after die bonding and phosphor coating.

where h denotes the height of the phosphor layer, a, b denote the length and thickness of the chip respectively, R is the radius of the phosphor spherical shape that can be calculated by

$$R = \sqrt{\frac{1}{8h}(d^2 + 4h^2)} \tag{2}$$

where d is the diameter of the top surface of the heat slug. From Eqs. (1) and (2), it is inferred that we can control the volume V by controlling the height h. A high-speed camera was utilized to monitor and measure the height of the phosphor shape during the phosphor dispensing process in our experiments. Other parameters are respectively $a = 1$ mm, $b = 0.1$ mm, $d = 3$ mm, $h = 0.7352$ mm. According to Eq. (1), the phosphor gel volume is calculated as $V = 1.8232\text{mm}^3$.

In our experiments, 27 LED samples were packaged and sorted into three categories with various chip offset distances of $\delta = 0$mm, $\delta = 0.5$mm, and $\delta = 1$mm. The three categories were denoted as Set A, Set B, and Set C, respectively. Fig. 3 displays the images of the three categories of LED modules after die bonding and phosphor coating.

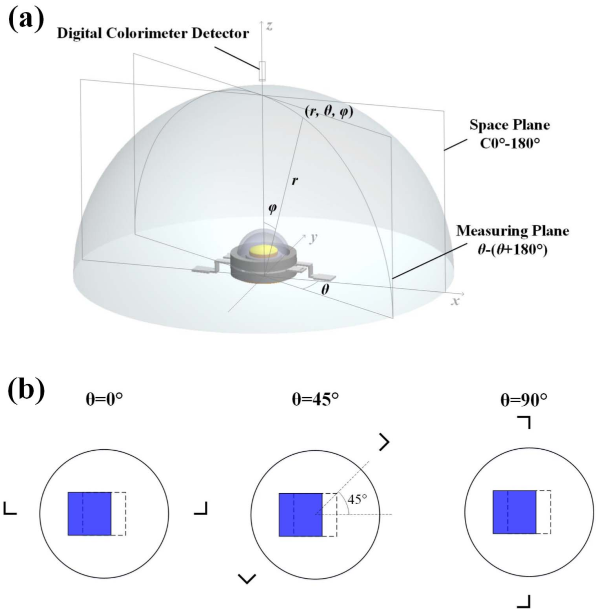


Fig. 4. Schematic of LED's angular color distribution measurement. (a) Measuring device diagram; (b) top view of different spatial measuring planes.

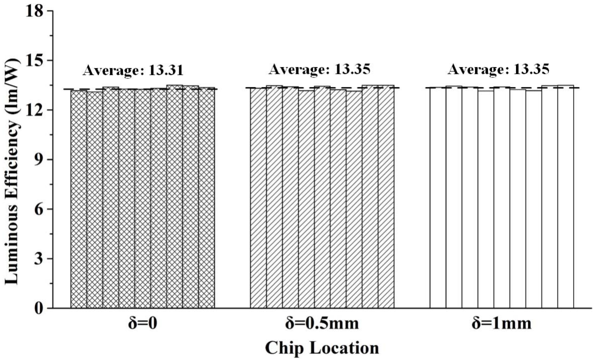


Fig. 5. The luminous efficiencies of bare dies with various chip position offset.

An integrating sphere was used to measure the optical parameters of the modules. A colorimeter coupled with goniometer was used for the ACD measurement. Fig. 4 shows the schematic of the ACD measurement. In order to get a complete understanding of the chip offset effect on LED's ACD, the measurement was performed under three selected spatial angles (0°, 45° and 90°). The relationship between the relative positions of measuring plane and chip location after displacement is shown in Fig. 4(b).

III. RESULTS AND DISCUSSION

Fig. 5 displays the luminous efficiencies of bare dies from the three sample sets. The average luminous efficiency of the three sample sets are 13.31lm/W, 13.35lm/W and 13.35 lm/W with standard deviation controlled within 2% respectively. The small deviation means good bare die consistency of each sample set and could ensure that the optical deviation after phosphor coating comes from the chip offset alone. Fig. 6 shows the optical parameters of all the specimens in Set A. The average luminous efficiency of the LED modules after phosphor coating is 103.75 lm/W with deviation controlled within 4%. The average CCT is 4366K, and the maximum CCT difference is within 100K. This means that the

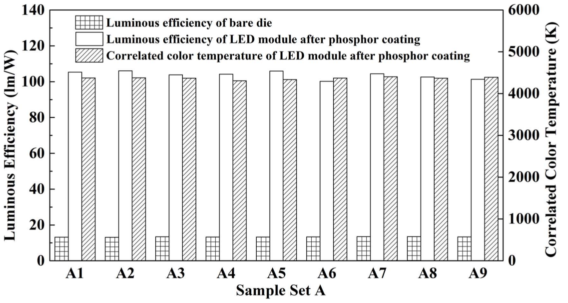


Fig. 6. Optical parameters of LED modules in Sample Set A.

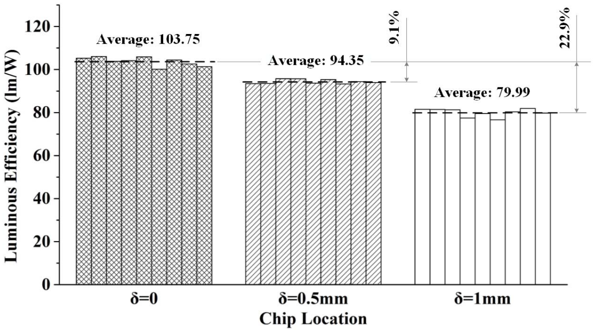


Fig. 7. The luminous efficiencies of packaged LED modules with various chip position offset.

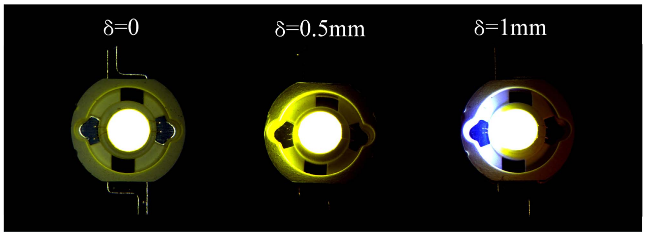


Fig. 8. Packaged LED modules with various chip offset distances under a current of 20mA.

aforementioned packaging method is good enough to ensure the consistency in each sample set.

The luminous efficiencies of LED modules with different offset distances after phosphor coating are shown in Fig. 7. Compared with the centered modules, when the offset distance is 0.5mm, the luminous efficiency decreases from 103.75 lm/W to 94.35 lm/W by 9.1%. When the offset distance is 1mm, the luminous efficiency drop reaches as high as 22.9%. The luminous efficiency drop can be explained as follows. LED's luminous efficiency highly depends on the amount of conversion of blue light into yellow one. The phosphor distribution in the silicone matrix is fixed once the phosphor gel is cured. When the chip offsets to the left, the path length of the blue light beaming to the left side becomes short and this part of blue light has less opportunity being converted. Therefore the down-conversion is reduced and the luminous efficiency is decreased.

Fig. 8 shows the electroluminance profile of packaged LED modules with various chip offset distances. It is obvious that the off-centered position will result in different spectra from different viewing directions. When the offset distance reaches 1mm, the output light on the left side of the module is mainly blue. So the color rendering index (CRI) and the angular color distribution in different detecting planes of these white LED modules are also analyzed.

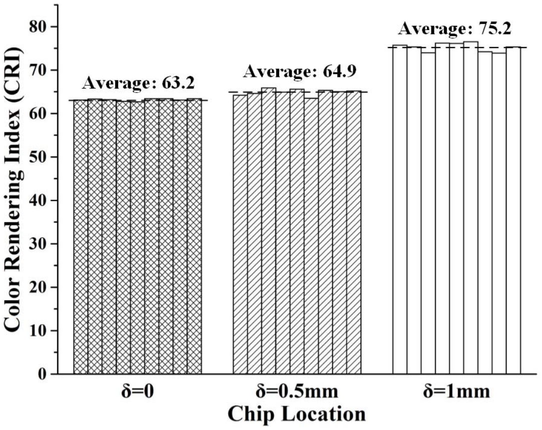
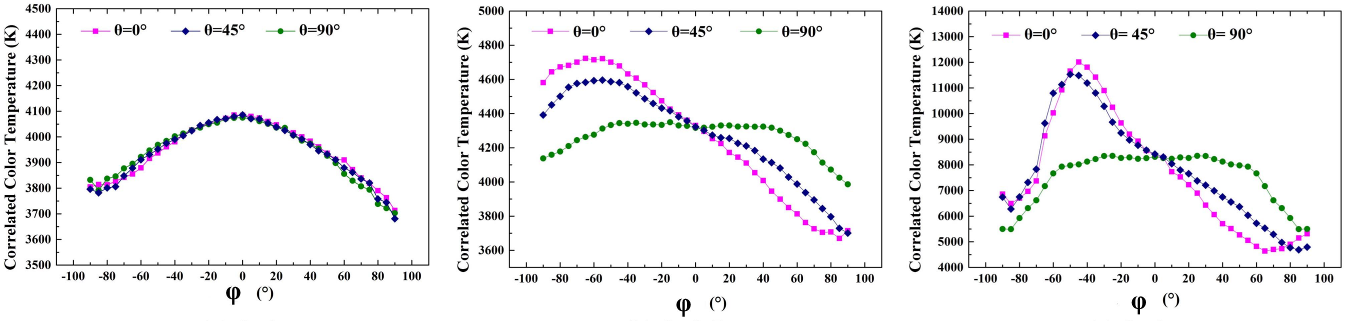


Fig. 9. Color rendering index (CRI) change of the LED modules under different chip locations.

Fig. 9 plots the CRI values change according to the chip locations. The CRI value increases as chip offset occurs. The reason behind the phenomenon is that when the chip offset occurs, the percentage of blue light in the spectrum increases. However, this enhancement of CRI is at the expense of luminous efficiency and angular color uniformity. As a whole, chip offset is bad for the performance of LED package.

Fig. 10 displays the ACD curves of different packaged LED modules with various offset chip positions. For the centered LED modules, due to the same emission of LED chip in all directions, the ACDs measured under different spatial angles are almost the same, as shown in Fig. 10(a). The specific shape of the ACD, which is known as the "yellow ring" phenomenon, is caused by the CCT decrease at the outer edge. However, when chip position offset occurs, things are different. As shown in Fig. 10(b), given the offset distance $\delta = 0.5$mm, when the spatial angle $\theta = 0°$, the peak of the CCT curve moves to the left. This is because that when the chip offsets to the left, the amount of phosphor particles over it becomes less, so the amount of converted yellow light decreases and the amount of transmitted blue light increases. Thus, the CCT on the left becomes higher. When the spatial angle $\theta = 90°$, the LED module with chip displacement can be regarded as symmetrical in the measuring plane. And the result shows that the ACD is symmetrical. Besides, owing to the displacement and chip's Lambertian emission [8], [9], the CCT curve measured under around $\varphi = 0°$ is almost flat. As for the result under spatial angle $\theta = 45°$, the results fall in between those under $\theta = 0°$ and $\theta = 90°$, just as shown in Fig. 10(b). Apart from above, the three CCT curves meet in one point at $\varphi = 0°$ where the three measuring planes meet. And the CCT measured under $\varphi = 0°$ increases as the chip offset distance increases. Based on the results, it is clear that the LED's ACD is deteriorated. Fig. 10(c) plots the ACD curves when chip offset distance reaches $\delta = 1$mm. Compared with



(a) δ=0 (b) δ=0.5mm (c) δ=1mm

Fig. 10. Angular color distribution measured under various spatial angles with chip offset distances of (a) $\delta = 0$, (b) $\delta = 0.5$mm and (c) $\delta = 1$mm.

those when $\delta = 0.5$mm, the patterns are the same, but the peak shift of CCT curve is more obvious and ACD deterioration is more serious. In a word, chip offset can influence the LED's angular color distribution greatly. To avoid the chip offset effect, two methods are recommended. One is that when using the reflow welding machine with hot wind blowing, the hot air outlet should be adjusted not to aim at the chip. The other is using LED substrate with a locating slot in the center of heat slug instead of common substrate for better operation tolerance.

IV. CONCLUSION

In this letter, we conducted a series of comparative experiments to study the effect of chip offset on the LED's optical performance. Three groups of LED modules with different chip offset distances were packaged and measured. The results show that as the chip offset occurs, the luminous efficiency of the LED decreases and the ACD deteriorates. Specifically, when the offset distance reaches 1mm, the luminous efficiency decreases from 103.75lm/W to 79.99lm/W by 22.9% and the ACD deterioration would ruin the secondary optical design of lens. It is concluded that the chip offset can have great influence on the LED's optical performance and proper measures must be adopted to avoid the offset.

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