

# Dip-transfer phosphor coating on designed substrate structure for high angular color uniformity of white light emitting diodes with conventional chips

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**Abstract:** Angular color uniformity (ACU) is one of the most important optical parameters of white lighting emitting diodes (LEDs). In this paper, we proposed a kind of phosphor coating method to enhance ACU of phosphor-converted white LEDs with conventional chips by the combination of substrate structure design and phosphor dip-transfer coating. Through this method, compact and optimal phosphor layer arrangements for high ACU can be realized. Optical simulations and experiments were conducted to examine its ACU performance. Compared with conventional phosphor dispensing coating, the present method shows very high ACU performance. Extremely small angular correlated color temperature (CCT) deviations were obtained, which are less than 200K at average CCTs ranging from 4000K to 6000K.

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OCIS codes: (230.0230) Optical devices; (230.3670) Light-emitting diodes.

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## 1. Introduction

Due to their high efficiency, good chromatic performance, high reliability and environmental protection, white light emitted diodes (LEDs) present very bright prospect to become customized light sources. In recent years, they have widely penetrated into many illumination situations, such as large size flat backlighting, street lighting, vehicle forward lamp, museum and residential illumination [1–4]. However, for white LEDs completely replacing conventional light sources, there are still several technical challenges to be overcome. They include further improvements in luminous efficiency, enhancement of reliability and delivering superb color quality [1]. In terms of superb color quality, desirable angular color uniformity (ACU) realization is one of major goals in LED packaging since bad ACU obviously discomforts customers' eyes and significantly blocks applications of white LEDs [5–7].

Phosphor coating has been thought as a main factor which influences the ACU performance in LED packaging. Thus, good quality phosphor coating is very necessary for high ACU realization. Currently, there exist two common phosphor coating methods, phosphor dispensing coating and conformal phosphor coating. Owing to its low cost and simplicity, the conventional phosphor dispensing coating has been broadly applied at present. However, in this coating method, yellow ring phenomenon usually occurs in the radiation pattern and results in bad ACU. Compared with the dispensing coating, the conformal phosphor coating shows strong attraction due to its high ACU performance in theory [8–13]. This method demands that a phosphor layer with uniform thickness replicates the LED chip shape. But common coating processes usually form curving phosphor layer morphologies with the effect of surface tension of phosphor gel. So, in order to get the conformal phosphor coating, it need apply complex and high-cost coating processes [14] such as electrophoresis [15], slurry, settling [16], spin coating [17], and pulsed spray [18]. Besides disadvantages in fabrication and cost, most of present conformal coating processes show limitations to realize conformal coating for conventional LED chips. In general, they can only fabricate flat and thin phosphor layer on the top surface of the chip, but can't effectively realize uniform phosphor layer at side surfaces. But, for conventional LED chips, high-quality phosphor coating at sides is strongly required [19]. In fact, due to their low cost, conventional LED chips are widely used in white LED products. Therefore, there is a large mismatch between high-quality phosphor coating technologies and the strong application requirements for conventional LED chips.

In this paper, we conducted exploration of optimal phosphor geometry for high ACU by optical analysis in the first part. Then a phosphor coating method was presented to realize the optimal phosphor geometry by combining the substrate structure design and phosphor dip-transfer coating. Optical simulations and experiments had been conducted to verify its superior in ACU for conventional chips.

## 2. Dip-transfer coating on a novel substrate structure

Schematics of conformal and dispensing coating are shown in Figs. 1(a)-1(b), respectively. As shown in Fig. 1(a), a uniform phosphor film is coated on top and side surfaces of LED chip. At such a structure, blue light emitted from the conventional LED chip transmits almost the same optical path length in the phosphor layer at both front and side directions. In Fig. 1(b), the phosphor layer structure in conventional phosphor dispensing coating presents the convex shape. In addition, because of the small contact angle between phosphor mixture and substrates [20], the height  $h$  of the phosphor layer is usually far smaller than its width  $r$ . Thus, the optical path length of blue light propagation at the center is much shorter than that at the side. As we know, the ratio of yellow light power to the blue light power (YBR) is proportional to the blue light optical path length [3]. And, the correlated color temperature (CCT) of white LEDs is decided by the YBR. Consequently, conformal phosphor coating could result in a uniform CCT distribution in radiation pattern, while the conventional dispensing coating leads to yellow ring phenomenon.

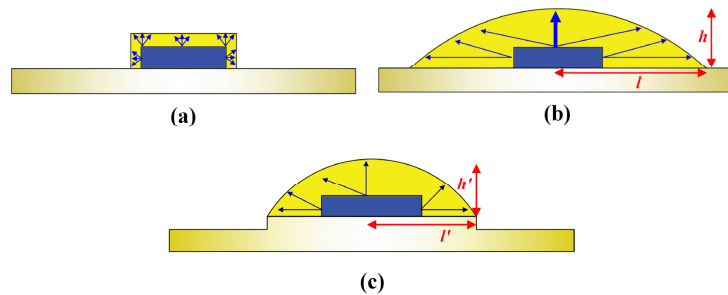


Fig. 1. Three kinds of phosphor coating structures. (a) Conformal phosphor coating. (b) Conventional phosphor dispensing coating. (c) Designed phosphor structure to enhance ACU.

The key point for high ACU is keeping the same optical path of blue light in the phosphor layer at all viewing angles. Here, we proposed another phosphor structure for high ACU, which is shown in Fig. 1(c). This phosphor geometry also shows a curving shape. But compared to the phosphor dispensing coating structure, its phosphor thickness at sides of the LED chip is reduced significantly. Thus, more blue light can escape and less yellow light is re-emitted at large view angles. Both of them make the same contribution to the yellow ring phenomenon elimination. Therefore, this phosphor structure can be expected to benefit ACU enhancement for conventional chips.

To realize the phosphor geometry shown in Fig. 1(c), we proposed a phosphor coating method based on dip-transfer coating method. Dip coating was proposed several years ago. At present, it has been extensively applied in some industries because of its simplicity and high throughput [21]. We firstly introduced dip coating method for phosphor coating in LED packaging [20, 22]. The phosphor dip coating present the ability to well control phosphor layer morphology. But in our previous works, we solved problems for vertical LED chip. The method to enhance ACU performance for conventional LED chips was not studied [22]. Here, we designed a kind of new substrate structure in phosphor dip-transfer coating. In the substrate structure, there is a small cuboid bump structure at the center of substrate. Due to the pinning effect of step edges on fluid [9], the cuboid bump can be used to limit phosphor mixture within its top surface. Thus, the side phosphor thickness can be easily controlled through adjusting the cuboid structure size. The detailed phosphor coating process is shown in Fig. 2. The process mainly includes two steps. The first step is that the phosphor mixture is

transferred from the container to the end surface of glass cylindrical post. The second step is the phosphor mixture is coated on the top surface of the cuboid structure. Finally, a compact and convex phosphor layer can be obtained as shown in Fig. 2(d).

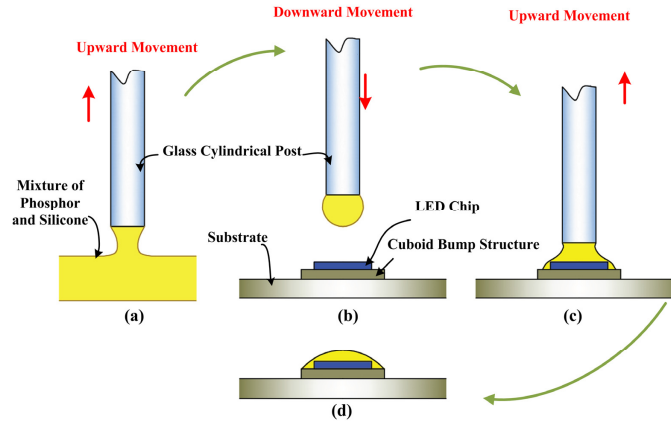


Fig. 2. Schematics of phosphor dip-transfer coating on a cuboid bump structure. (a) Transferring mixture of phosphor and silicone to the end of cylindrical post by dip-transfer coating. (b) and (c) Coating phosphor on top surface of cuboid bump structure. (d) LED module after phosphor dip-transfer coating

### 3. Optical simulation verification

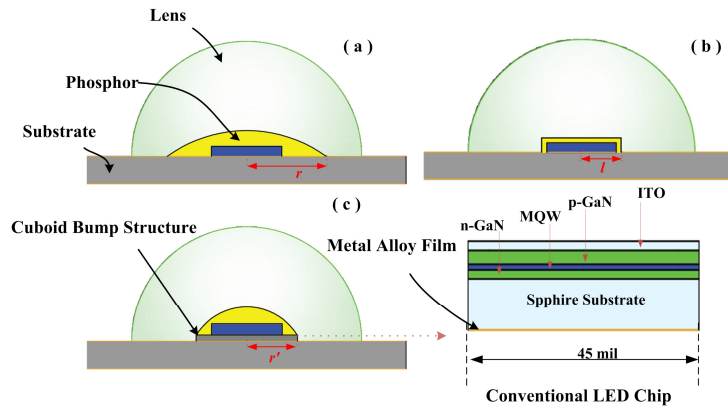


Fig. 3. Schematic illustration of white LED optical models. (a) LED module with conventional phosphor dispensing coating. (b) LED module with conformal phosphor coating. (c) LED module with present phosphor coating and cuboid bump structure.

Optical simulations were conducted by the Monte Carlo ray-tracing method. We carried out ACU performance comparison. Figure 3 presents three LED models which are packaged by dispensing coating, conformal coating and the present coating method, respectively. A kind of commercial conventional LED chip with the size of 45mil was used in LED models. The chip comprises several layers, indium tin oxide layer (ITO), P-GaN, multiple quantum well (MQW), N-GaN, transparent sapphire substrate, and metal alloy film. Their thicknesses are 0.1 $\mu\text{m}$ , 0.3  $\mu\text{m}$ , 0.1 $\mu\text{m}$ , 4  $\mu\text{m}$ , 100  $\mu\text{m}$  and 0.1 $\mu\text{m}$ , respectively. Their optical properties are the same as the description in [23]. The specular and diffused reflection coefficients of top surfaces of substrates are assumed to be 78% and 9%, respectively. Optical properties of the phosphor layer are calculated by the Mie theory [10]. The phosphor concentration was chosen as 1.2 g/cm<sup>3</sup>. The lens radius is 5mm and its refractive index is 1.53. In order to simplify the calculation, specific wavelengths of 454 and 571 nm were used to represent blue and yellow

light, respectively. The blue light is assumed to be emitted from MQW isotropic pattern. The yellow light is remitted from the phosphor layer. After ray-tracing, escaped rays are collected by a detector.

In optical simulations, precise phosphor geometry models are critical to the final accuracy. In phosphor dispensing coating structure, a spherical cap shape was defined as the phosphor geometry. The radius  $r$  of contact area between phosphor layers and substrates was set as 1.5mm which is a common size in current LED packaging structure. The half-width of phosphor layer  $l$  varies according to the required average CCT. The half-width  $r'$  of the cuboid bump structure was 0.8mm. Because the phosphor layer geometry is irregular, the free and open software Surface Evolver was applied to simulate the phosphor layer equilibrium morphologies [20, 22]. In [23], its simulation accuracy has been proved. In order to gain LED modules with different average CCTs, coating phosphor volume has been adjusted in simulations.

Figure 4 presents simulation results of angular color distribution at view angles from  $-90^\circ$  to  $90^\circ$ . Average CCTs in Figs. 4(a)-4(b) are about 4500K and 6000K, respectively. It can be seen that compared with the conventional phosphor coating method, CCTs at large view angles increase effectively by the present phosphor coating method. This will result in significant ACU improvement. The changing trending of angular color distribution in simulation is consistent with predictions in the above optical analysis. When the average CCT is at 4500K, the CCT deviation reduces from 977K to 349K. When the average CCT reaches about 6000K, the CCT deviation is also improved by 50%. These figures also indicate that the present phosphor coating method has the same ACU performance with conformal phosphor coating.

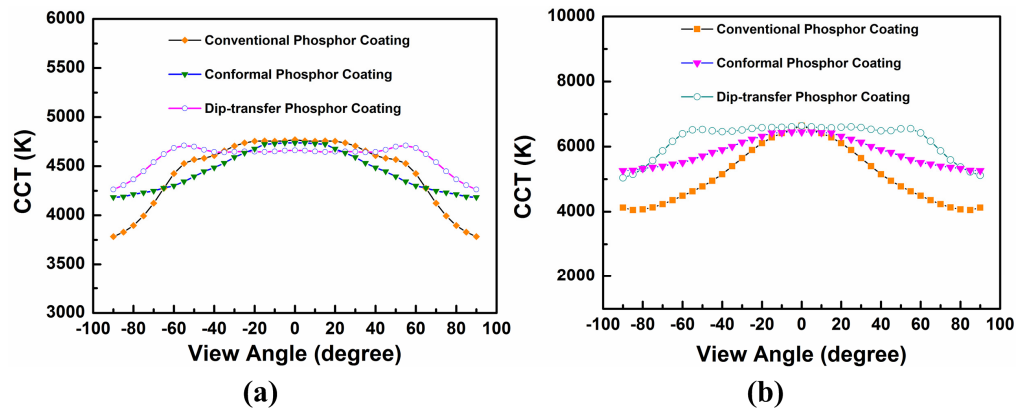


Fig. 4. Angular CCT distribution comparison between present phosphor coating method, conformal coating and convention coating method at different average CCTs by simulations. (a) About 4500K. (b) About 6000K.

#### 4. Experiments

Figure 5 shows fabricated lead-frame LED packaging substrates with designed substructures. Three groups of substrates had been made and their widths of the cuboid structure  $w$  are 1.5mm, 1.6mm and 1.7mm, respectively. The peak wavelength of the LED chips is  $454 \pm 1.5$ nm which fits the optical simulation parameter. LED chips were bonded at the center of the top surfaces of the cuboid bump structures. YAG-based phosphor powder was sufficiently blended with the silicone and its concentration is  $1.2 \text{ g/cm}^3$ . The viscosity and specific gravity of silicone are  $4.0 \text{ Pa}\cdot\text{s}$  and  $1.14 \text{ g/cm}^3$ , respectively. The phosphor coating process is the same as that in Fig. 2. The coated phosphor mixture volume was changed to meet different average CCT by adjusting upward and downward velocities of the glass cylindrical post from 1 to 3mm/s [21]. After phosphor coating, LED packaging modules were transferred into  $150^\circ\text{C}$  oven for 2 hours for phosphor mixture curing. Then lenses were fixed on the LED

substrate. The gap between the lens and the substrate was filled by silicone. Then the whole LED packaging modules were transferred into 120°C oven for 1 hour for silicone curing again. LED modules were also packaged by the conventional phosphor dispensing coating method for comparison. All LED modules by the two coating methods used the same LED chips and phosphor material.

The average CCT, color rendering index (CRI) and luminous efficiency of each LED packaging module were measured at driving current of 350 mA by the integrating sphere (HAAS-2000, Everfine, China). The angular color distribution of the LED packaging module was recorded as shown in Fig. 6. To measure the color distribution accurately, the distance between the CCT recorder (XYI-III, Xinye, China) and the LED packaging module is 2m far. The CCT of the LED packaging module was recorded every 5 degrees for the viewing angle changing from  $-90^{\circ}$  to  $+90^{\circ}$ .

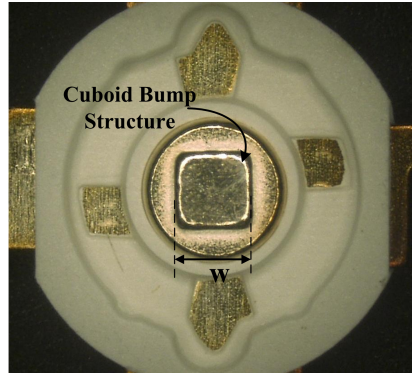


Fig. 5. Picture of designed lead-frame LED packaging substrate

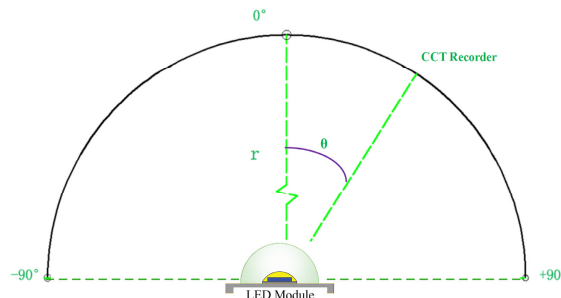


Fig. 6. Schematic of angular CCT measurement method.



## 5. Results and discussion

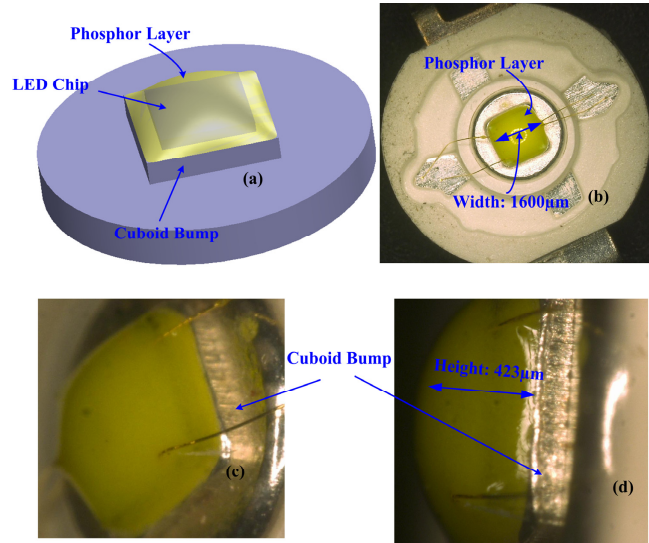


Fig. 7. LED modules after completing phosphor dip-transfer coating. (a) Phosphor layer geometry built by Surface Evolver simulation. (b), (c) and (d) Pictures of phosphor layer in top view, angle view and side view, respectively.

Figure 7 presents LED modules by applying the present phosphor coating process on a cuboid bump substrate. In this figure, a convex phosphor layer is located on the top surface of the cuboid bump. The phosphor layer height is about 423 μm and its width is 1.6mm, which is the same as the cuboid bump width. Figure 8 shows the angular color distribution comparison between the present phosphor coating and conventional phosphor dispensing coating. It can be seen that at the average CCT of about 4500K, the CCT deviation is 161K by the present phosphor coating. Compared with the CCT deviation of 1110K by phosphor dispensing coating, it presents the large superiority. Figure 9 shows the angular color distribution with cuboid bump width of 1.6mm. Here the average CCTs are 4126K, 5218K and 6012K, the CCT deviations are about 314K, 189K and 449K correspondingly. It must be mentioned that at each of three average CCT zones, several LED modules were measured. And for LED modules with the same average CCT, the difference between their CCT deviations is less 40K. So it can be conclude that high ACU performance of the present phosphor coating method has good reproducibility.

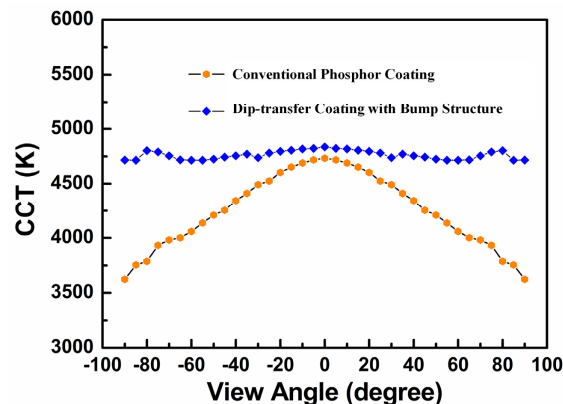


Fig. 8. Angular color distribution comparison between present phosphor coating and phosphor dispensing coating at average CCT of 4500K.

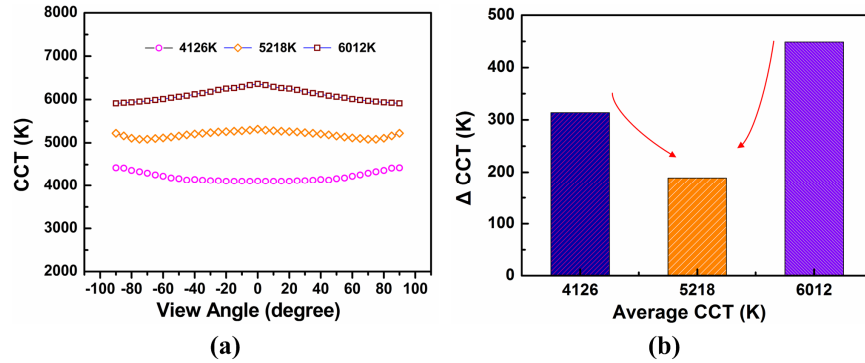


Fig. 9. Angular color distribution of LED modules by present phosphor coating in experiments. (a) CCT distribution at different average CCTs. (b) CCT deviations.

In general, the CCT variation reduces with the average CCT decreasing [20]. However, from Fig. 9, we can see that the minimum CCT variation occurs at the average CCT of 5000K. Furthermore, the angular CCT distribution curves at 4000K and 6000K average CCTs are concave and convex, respectively. The reason for such a phenomenon is the ratio variation of the phosphor layer height to its width (HWR) at different average CCTs. When the average CCT changes from 6000K to 4000K, more phosphor mixture was coated on the cuboid bump. Because their heights are the same, its height increases. The comprehensive result is that HWR get larger with average CCT reducing. Owing to the longer central blue light transmitting path, large HWR reduces the CCT at the center. Consequently, CCT at the center varies from the maximum value to the minimum value when average CCT reduces.

In order to further enhance the ACU of LED modules with average CCTs of 4000K and 6000K, we changed the bump size to adjust the HWR of phosphor layer. The detailed results are shown in Fig. 10. Here, when the average CCT is 4000K, the cuboid width increases from 1.6mm to 1.7mm and this will reduce HWR. In Fig. 10(a), the CCT becomes flat at all view angle because the HWR change will prevent blue light escaping in large viewing angles. While at 6000K CCT case shown in Fig. 10(b), by the same method, we improve the CCT distribution at different view angles. The CCT deviation is reduced by about 50% for both average CCTs at 4000K and 6000K.

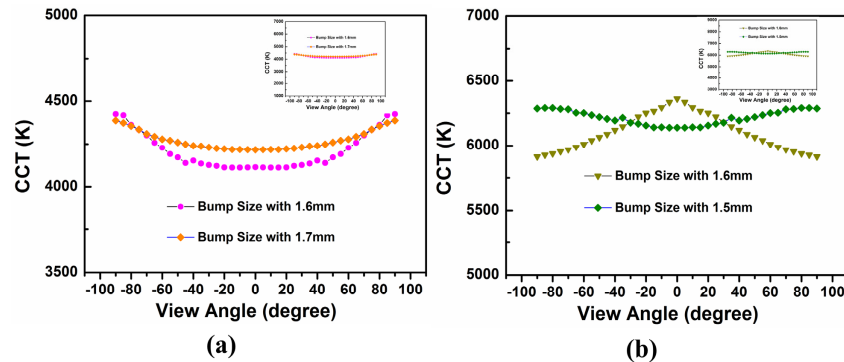


Fig. 10. Angular color distribution by optimizing cuboid bump structure. (a) Average CCT of about 4200K. (b) Average CCT of about 6000K.

Luminous efficiency and CRI of LED modules with the present phosphor coating method and conventional phosphor coating method are shown in Fig. 11. From this figure, we can see that the average luminous efficiency of the present phosphor coating method is about 97lm/W and that of conventional phosphor coating is 98lm/w. It indicates that these two phosphor coating methods show the same efficiency performance. CRIs of two phosphor coating methods are both about 70.



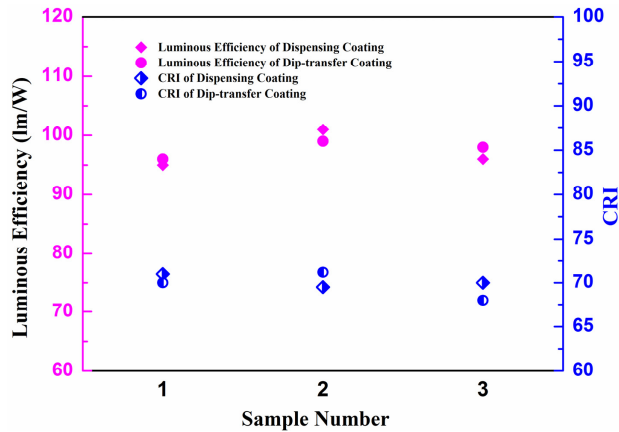


Fig. 11. Luminous efficiency and CRI comparison between present phosphor coating and phosphor dispensing coating at average CCT of 4500K and driving current of 350mA.

## 6. Conclusions

In this paper, a phosphor coating method coupled with a substrate structure design was presented to improve ACU of phosphor-converted white LEDs with conventional chips. For this method, the optimal phosphor layer geometry can be well realized. Optical simulation and experimental results have verified its high ACU performance. We also confirmed its feasibility to optimize phosphor arrangement at different desired CCTs. By adjusting the width of the cuboid bump on the substrate, the CCT deviation of 200K was obtained for the whole average CCT ranging from 4000K to 6000K.

## Acknowledgments

Authors would like to acknowledge the financial support in part from National Science Foundation of China (51376070), in part by 973 Project of The Ministry of Science and Technology of China (2011CB013105) and in part by the Huazhong University of Science and Technology Graduate Innovation Fund (No. HF-11-01-2013). Authors also want to thank Bin Cao, Shuiming Li and Fei Wang for their aid in experiments.