# Enhancing Angular Color Uniformity of Phosphor-Converted White Light-Emitting Diodes by Phosphor Dip-Transfer Coating

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***Abstract*—High angular color uniformity (ACU) is strongly required in many illumination applications. In this study, we presented the phosphor dip-transfer coating method to realize high ACU for phosphor-converted white LEDs. The phosphor mixture was coated on top surfaces of LED chips and formed thin and convex phosphor layers by the dip-transfer coating. The optical simulations and experiments were conducted for performance verifications. Both numerical and experimental results show that the present method can obtain very high ACU. The angular correlated color temperature (CCT) deviation reaches 378 K when the average CCT of white LEDs is around 6200 K and it reduces to 63 K at the average CCT of about 4000 K.**

***Index Terms*—Angular color uniformity, LEDs, optical simulations, phosphor coating.**

## I. INTRODUCTION

DUE to advantages over traditional light sources in terms of efficiency, life time, chromatic performance, reliability and environmental protection, white light-emitting diodes (LEDs) have widely penetrated into many illumination applications, such as large size flat backlighting, street lighting, vehicle forward lamp, museum illumination and residential illumination [1]–[3]. Currently, white light qualities such as the color render index (CRI) and angular color uniformity (ACU) have become concerns for broadening further applications in the illumination area [4], [5]. One of the most popular methods to generate white LEDs is the combination of blue light chips and yellow light phosphor [6], [7]. Bad ACU often occurs in these phosphor-converted white LEDs. It discomforts the customers' eyes and blocks some illumination applications of white LEDs [8], [9].

It is well known that the phosphor coating method strongly influences the ACU performance of white LEDs. Great efforts have been devoted to enhancing the ACU through the researches of the phosphor coating methods [10]–[15]. The phosphor conformal coating method was usually thought as an attractive phosphor coating method to obtain high ACU of white LEDs, in which the phosphor layer with uniform thickness replicates the LED chip surfaces. However, due to the high requirement for the fabrication, most of current phosphor conformal coating processes including electrophoresis [16], slurry, settling [17], spin coating [18], and pulsed spray [19] are complicated and high-cost. In addition, the recent studies show that the ACU of white LEDs by phosphor conformal coating is not high enough and can't compete with traditional light sources [20], [21]. Thus, several improvement methods have been proposed [20]–[23]. Sommer *et al.* gained the ideal ACU by tailoring the phosphor layer geometry and adjusting the phosphor concentration distribution on the basis of simulations [21], [22]. Liu *et al.* proved that the multilayer phosphor arrangement with pyramidal shape and inversed concentration distribution can present higher ACU than the conventional phosphor conformal coating by simulations [20]. Although these improvement methods were confirmed to achieve high ACU in theory, they also brought large fabrication difficulties for the mass production. Therefore, it is necessary to find a phosphor coating method which not only realizes high ACU but also is with low cost and simple fabrication.

In this paper, a kind of phosphor coating method, i.e., phosphor dip-transfer coating method, was demonstrated to enhance the ACU of white LEDs significantly. We carried out both optical simulations and experiments and found that this method can achieve very uniform angular CCT distributions when the average CCT of white LEDs ranges from about 4000 K to 6200 K.

## II. PHOSPHOR DIP-TRANSFER COATING PROCESS

The low-cost dispensing coating is widely used in the LED packaging. However, it has some limitations in coating liquid with very small volume, because it can not accurately control the liquid behavior at the larger driving pressure. Dip coating is a common method and extensively applied in some industries because of its simplicity and high throughput [24]. But this coating method has never been used in the LED phosphor coating so far. One of advantages of the dip coating technology is well handling very little volume liquid by depositing it on plane and cylindrical surface. Therefore, it can be expected to obtain the high coating quality by the dip coating. Here, we tried to use the dip coating to transfer very little volume phosphor mixture on

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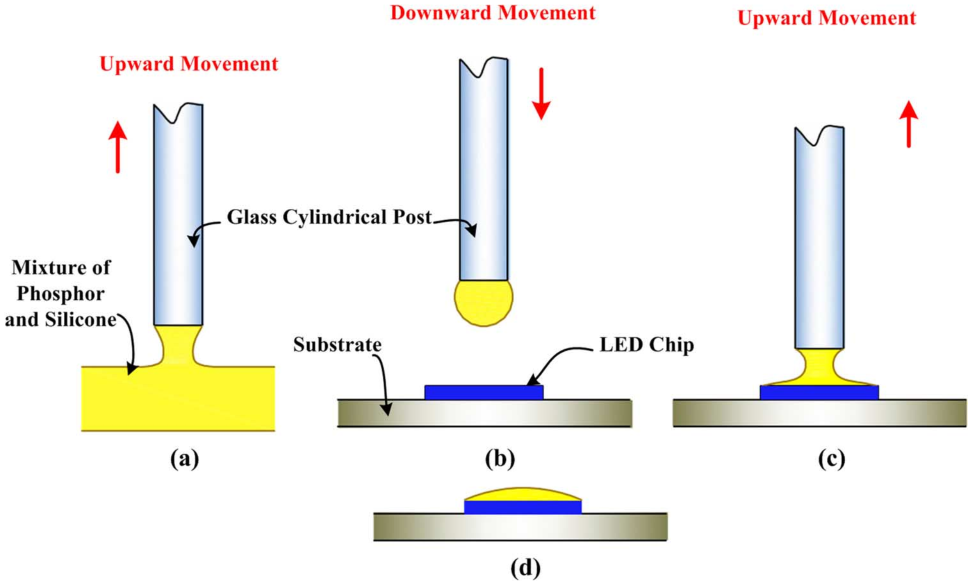

Fig. 1. Schematics of phosphor dip-transfer coating. (a) Transferring mixture of phosphor and silicone to end of cylindrical post by dip coating. (b) and (c) Coating phosphor on top surface of LED chip through contacting cylindrical post. (d) LED module after phosphor dip-transfer coating.

top surfaces of LED chips to realize the ideal phosphor geometries for high ACU. We call this phosphor coating method as the phosphor dip-transfer coating.

The detailed phosphor dip-transfer coating processes are shown in Fig. 1. Firstly, as shown in Fig. 1(a), the phosphor mixture is transferred from the container to the end surface of the glass cylindrical post. Then the phosphor mixture with very little volume is attached on the end surface of the cylindrical post and move onto the top surface of the LED chip, as shown in Fig. 1(b). After that, the glass cylindrical post with phosphor mixture contacts the top surface of the LED chip and the phosphor mixture spreads on this surface. When the post removes from the chip, the phosphor mixture stays on the top surface of the LED chip, as shown in Fig. 1(c). Because of very small volume, the phosphor mixture is confined to the top surface of the LED chip due to the pinning effect of the step edges of LED chips [11]. After completing the phosphor dip-transfer coating, a thin phosphor layer forms on the top surface, which is shown in Fig. 1(d). The thickness of final phosphor layer reduces gradually from the center to the edge due to the effect of the surface tension.

## III. OPTICAL AND PHOSPHOR LAYER MORPHOLOGY SIMULATIONS

Optical simulations were conducted by the Monte Carlo ray-tracing method. To evaluate the ACU performance of phosphor dip-transfer coating, phosphor conformal coating was brought into the comparison. Fig. 2 shows two optical models of LED modules which are packaged by the phosphor dip-transfer coating and the phosphor conformal coating, respectively. The LED models comprise the blue vertical LED chip, the phosphor layer, the silicone lens and the substrate. The size of the chip is 1.2 mm × 1.2 mm and the P-N junction area is 1.05 mm × 1.05 mm. The thicknesses of N-GaN, MQW, P-GaN and metal alloy substrate are 4 $\mu$m, 0.1 $\mu$m, 0.3 $\mu$m and 140 $\mu$m, respectively. Their absorption coefficients and refractive indexes are listed in the Table I [20]. The diffused reflection and absorption coefficients of metal alloy substrate are 89% and 11%, respectively. The hemispherical silicone lens is with the radius of 3 mm and its refractive index is 1.53. In order to simplify optical simulations, the substrate with the radius of 5 mm is set as a flat and circle shape. The specular

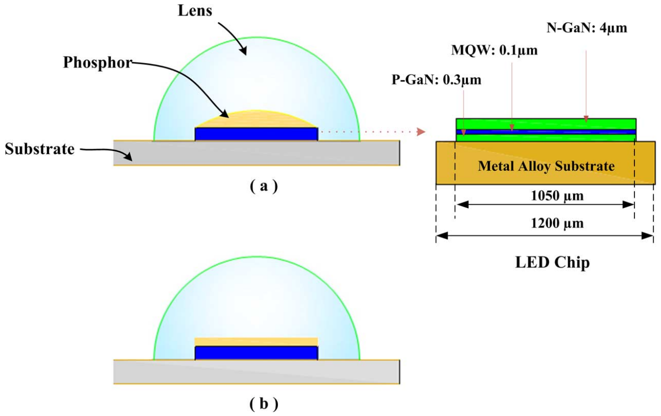

Fig. 2. Schematic illustration of the white LED optical models. (a) LED module with phosphor dip-transfer coating. (b) LED module with phosphor conformal coating.

TABLE I
OPTICAL PROPERTIES OF BLUE LED CHIP

| Symbol | Wavelength | 454 nm | 571nm |
|---|---|---|---|
| N-GaN | Refractive index | 2.43 | 2.36 |
| | Absorption efficient | 2 $\text{mm}^{-1}$ | 1.5 $\text{mm}^{-1}$ |
| P-GaN | Refractive index | 2.43 | 2.36 |
| | Absorption efficient | 2 $\text{mm}^{-1}$ | 1.5 $\text{mm}^{-1}$ |
| MQW | Refractive index | 2.51 | 2.39 |
| | Absorption efficient | 120 $\text{mm}^{-1}$ | 8 $\text{mm}^{-1}$ |

and diffused reflection coefficients of the top surface of the substrate are assumed to be 78% and 9%, respectively.

The optical properties of the phosphor layer are calculated by the Mie theory. The phosphor particle size was approximated as a Gaussian distribution with a mean diameter of 8 $\mu$m and a standard deviation of 3.2 $\mu$m. For the calculation convenience, 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 the MQW with isotropic pattern. The yellow light is remitted from the phosphor layer. After ray-tracing, the escaped rays were collected by a detector.

In the optical simulations, the phosphor concentration in the mixture was set to the 1.5 g/cm$^3$. The phosphor particles were assumed to be uniformly distributed in the phosphor layer. The volume of coating phosphor mixture was adjusted to gain the different CCTs.

The precise phosphor geometry model is the key point to the final optical simulation accuracy. The equilibrium shape of the phosphor layer is the geometry with minimal free energy. Here, the free open software Surface Evolver was introduced to simulate phosphor layer equilibrium morphologies. The total free energy E associated with the liquid drop consists of both surface free energy and gravitational energy. It is described by the following equation

$$E = \gamma_{LG}A_{LG} + (\gamma_{SL} - \gamma_{SG})A_{SL} + \iiint_V (\rho g z)dV \qquad (1)$$

where $\gamma_{LG}$ represents the surface tension of liquid drop. $V$ is the liquid drop volume. $\gamma_{SL}$ and $\gamma_{SG}$ are the interfacial tensions of solid-liquid and solid-gas, respectively. $A_{LG}$ and $A_{SL}$ are the liquid-gas and solid-liquid interfacial areas, respectively. Through the Young's equation, $\cos\theta = (\gamma_{SG} - \gamma_{SL})/\gamma_{LG}$, (1) can be transformed to

$$E = \gamma_{LG}(A_{LG} - cos\theta A_{SL}) + \iiint_V (\rho g z)dV. \qquad (2)$$

In the software Surface Evolver, the minimization of the interfacial free energies is carried out by a gradient descent method under the volume and other boundary constrains. The liquid interface is discretized and replaced by a mesh of triangles. During the minimization procedure, the surface tension exerts forces on each vertex of the triangulation and drives the mesh to a minimal configuration [25], [26].

In the geometry model by Surface Evolver, to get the precise phosphor shape, the phosphor mixture fluid properties and constraints are needed. We measured the fluid properties, such as surface tension, density and contact angle. The surface tension and the density of the phosphor mixture are 27 dyn/cm and 2160 kg/m$^3$, respectively. The contact angle of the mixture on the chip top surface is 10°. However, the contact angle at the chip edge is not the constant and it could increase from 10° to several times larger than 10° due to the step edge pinning effect [11]. In order to present this physics phenomenon, the contact line of the mixture and the chip top surface is limited within the top surface by the constraint. Gravity has also been taken in consideration. The phosphor mixture volume was adjusted in simulations. During simulations, a cube phosphor layer shape is initially set on the top surface of the LED chip. By Surface Evolver program, the discretized triangle meshes move to a minimal configuration and form the final phosphor geometry in dip-transfer coating. Discretized data of phosphor layer geometries can be gained based on this method. With sufficient data, the precise phosphor layer geometries can be built for optical simulations.

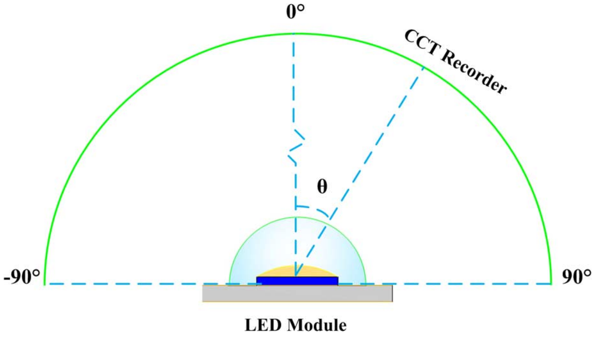

Fig. 3. Schematic of angular CCT distribution measurement.

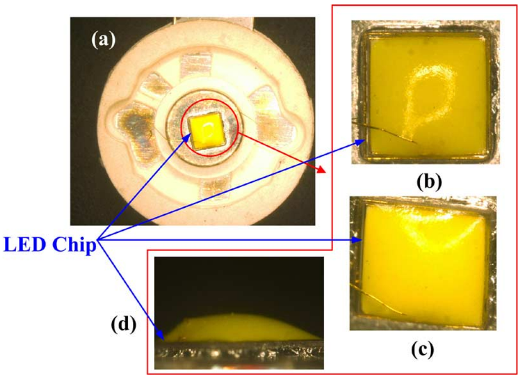

Fig. 4. Pictures of LED module after phosphor dip-transfer coating. (a) LED module. (b) Top view of phosphor layer. (c) Angle view of phosphor layer. (d) Side view of phosphor layer.

## IV. EXPERIMENTS

In experiments, the detailed information of vertical LED chips is the same as that in optical simulations. The peak wavelength of LED chips is $454 \pm 1.5$ nm. LED chips were bonded on a kind of commercial lead-frame LED packaging substrates. The YAG-based yellow phosphor was sufficiently blended with the silicone. The phosphor concentration in the mixture was 1.5 g/cm$^3$. The phosphor dip-transfer coating process is the same as described in Fig. 1. The glass cylindrical post with the radius of 250 $\mu$m was chosen as the phosphor transfer tool. The transferred phosphor volume could be adjusted by the withdrawal velocities [27]. The velocities ranged from 1 mm/s to 3 mm/s to meet phosphor volume requirement for different average CCTs. After phosphor coating, LED modules were transferred into 150°C oven for curing. Then, the lens was fixed on the LED substrate. The gap between the lens and the substrate was filled with the silicone. Then, the whole LED packaging modules were transferred into 120°C oven for curing again.

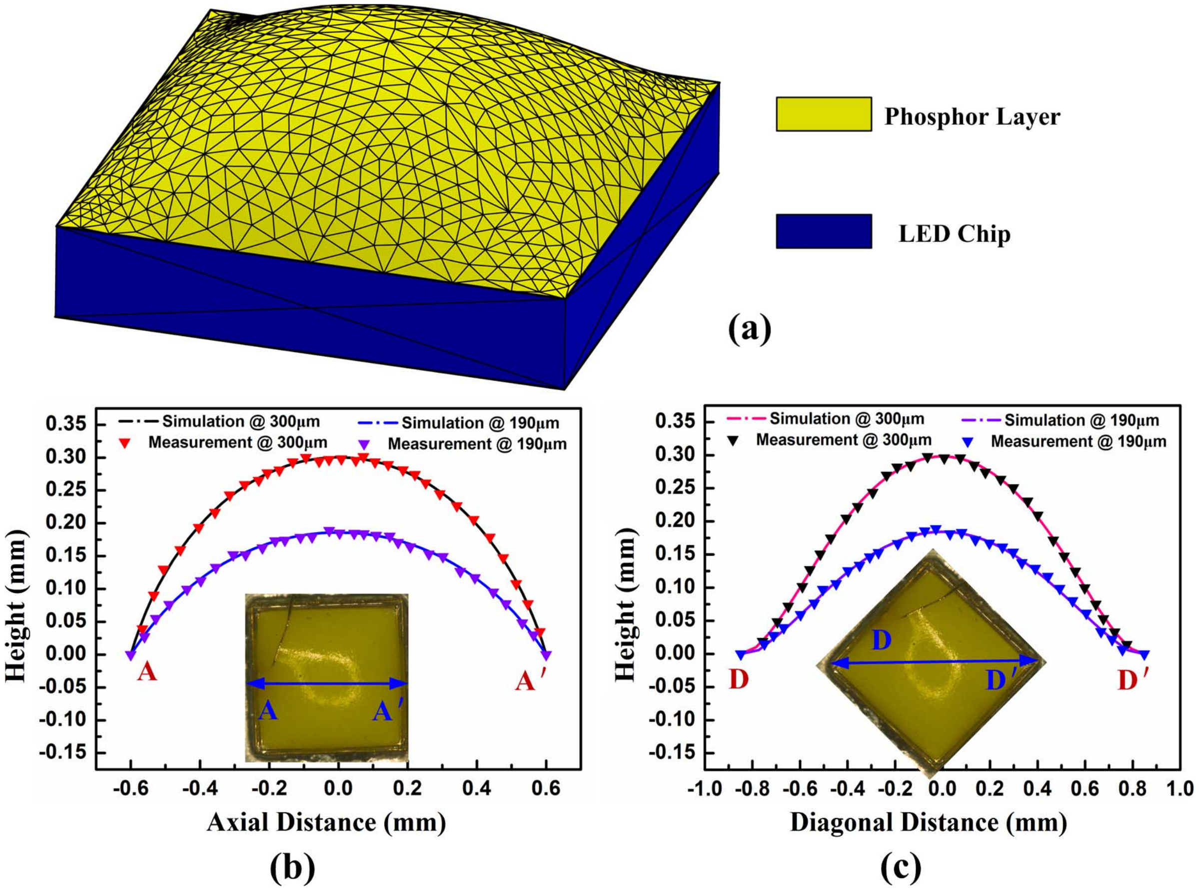

Fig. 5. Phosphor layer profile comparison between simulations and experiments. (a) Three dimensional mesh. (b) Profile along axial direction. (c) Profile along diagonal direction.

The profiles of phosphor layers were measured by the 3D measuring laser microscope. The average CCT of each LED packaging module was measured by the integrating sphere. The angular color distribution of the LED packaging module was recorded as the method shown in Fig. 3. The CCT of the LED packaging module was recorded every 5 degrees by changing the viewing angle from $-90^\circ$ to $+90^\circ$. Besides the above packaging LED modules, a kind of famous commercial LED module with the phosphor conformal coating was measured for the comparison. Their average CCT ranges are the same with our samples'.

## V. RESULTS AND DISCUSSION

Fig. 4 shows LED modules after completing the phosphor dip-transfer coating process. It is clearly seen that the phosphor mixture is limited within the LED chip top surface and forms a thin and convex phosphor layer. The simulation and experimental results are shown in Fig. 5. They present phosphor layer profiles with heights about 300 $\mu$m and 190 $\mu$m. The average CCTs of LED modules with thin and thick phosphor layer profiles are about 4000 K and 6200 K, respectively. It can be found that simulation results agree well with experimental ones.

In the simulations, the average CCTs ranging from 4000 K to 6000 K were obtained by varying the phosphor layer volume. Angular color distributions of the modules packaged by two coating methods are shown in Fig. 6. It can be seen that the CCT deviation becomes larger with the increasing of average CCT. However, the phosphor dip-transfer coating presents better ACU than the conformal coating in all average CCTs. When the average CCT is about 6000 K, the CCT deviation by the present method is reduced by 57% compared with that by the conformal coating.

The ACU measurement results were presented in Figs. 7 and 8. Fig. 7 shows the angular color distribution comparison between the two coating methods. It shows that when the average CCT is about 6200 K, the CCT deviation is only 378 K for phosphor dip-transfer coating, while the CCT deviation reaches 1416 K in the conformal coating. Fig. 8 shows the angular color distributions by the phosphor dip-transfer coating, when the average CCT ranges from about 3500 K to 6200 K. Their CCT deviations are 175 K, 63 K, 79 K, 109 K, 286 K and 378 K. All deviations in the whole measurement CCT range reach very low levels. In Fig. 8(b), it is also found that the angular CCT deviation reduces from 6000 K to 4000 K, but increases from 4000 K to 3000 K. The reason can be explained as following. When the average CCT decreases from 6000 K to 3000 K, it needs to increase phosphor mixture volume. So the shape of the phosphor layer becomes sharp. From 6000 K to 4000 K, the increasing height difference of phosphor layer between the center and the edge can lower the CCT at the central view angle and enhance

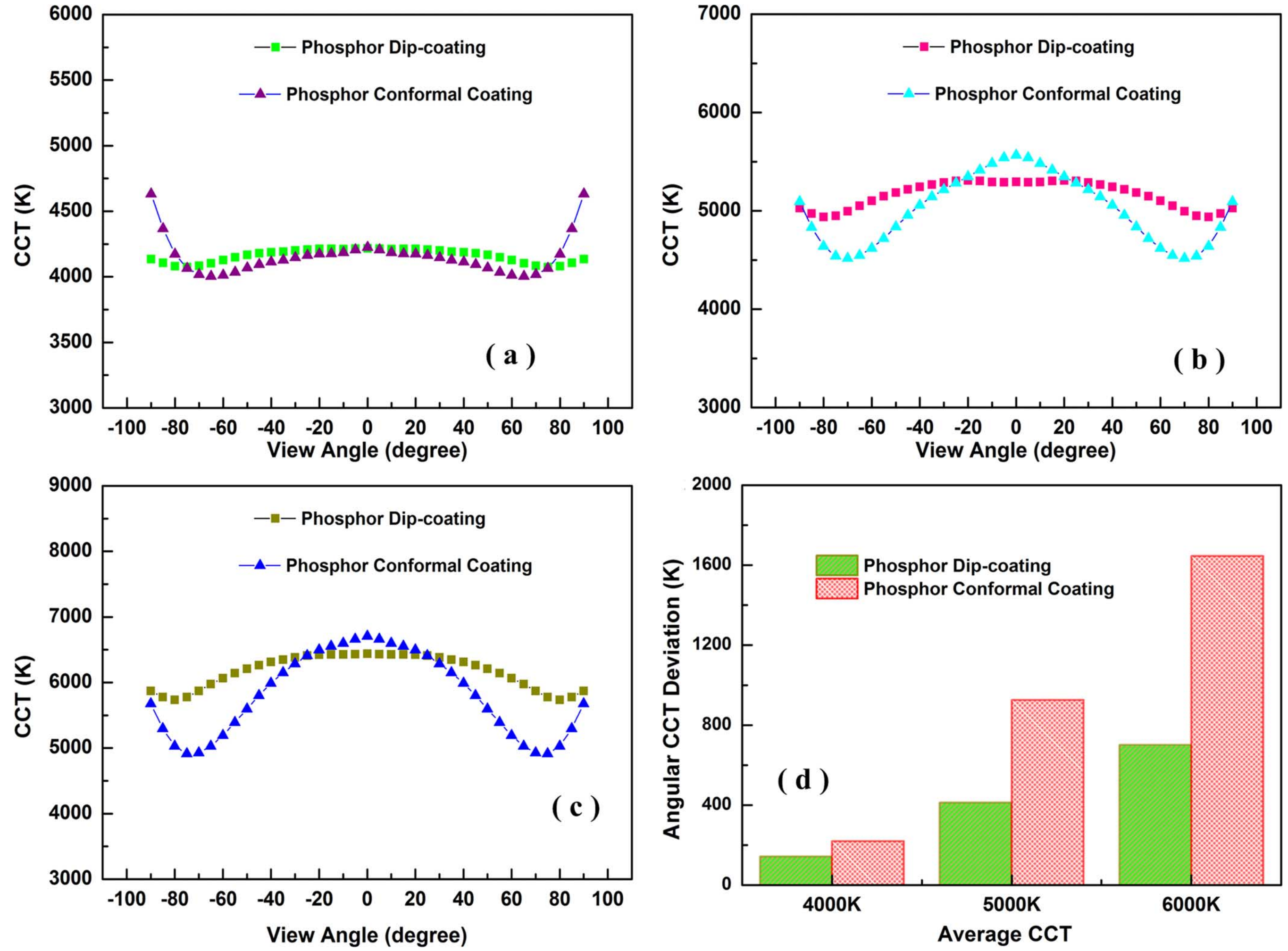

Fig. 6. Simulation angular CCT distribution comparison between phosphor conformal coating and phosphor dip-coating at different average CCTs. (a) About 4000 K. (b) About 5000 K. (c) About 6000 K. (d) CCT deviation in view angle ranging from $-80^\circ$ to $80^\circ$ at different average CCTs.

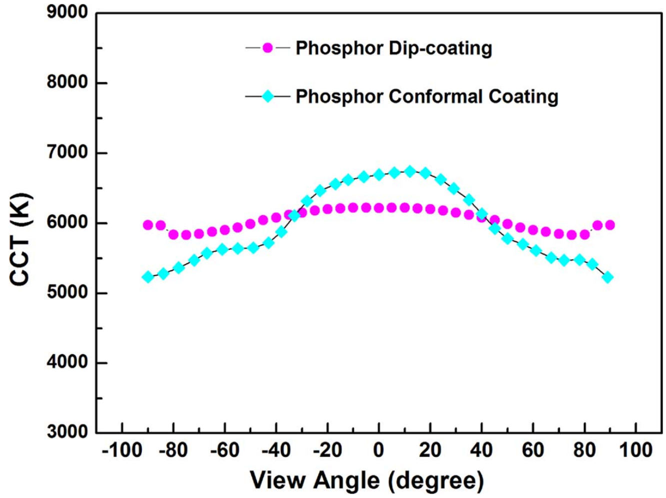

Fig. 7. Angular color distribution comparison between phosphor dip-transfer coating and phosphor conformal coating where average CCT is about 6200 K.

the ACU. However, from 4000 K to 3000 K, with the height further increasing, the CCT at the central view angle is lower than that at the edge. Thus, the angular CCT deviation gets large.

All experimental results prove that the phosphor dip-transfer coating method can well enhance ACU. The ACU improvement by phosphor dip-coating mainly results from the desirable phosphor geometry. The phosphor geometry on the top surface of the LED chip is convex shape in phosphor dip-coating because of the surface tension. Its thickness reduces gradually from the center to the edge. This phosphor geometry can benefits the blue light escaping at the edge due to the very small phosphor thickness and weakening the blue light escaping at the center owing to the thicker phosphor layer [21], [24]. Meanwhile, this geometry exhibits the opposite effect for the yellow light. More is emitted at the center compared with that in conformal coating. Therefore, the comprehensive effect is that the ratio of the yellow light to the blue light (YBR) increases at the center but weakens at the edge. It also means the CCT reduces at the small viewing angle and increases at the edge.

From Figs. 6 to 8, both simulation and experimental results demonstrate that the dip transfer coating can effectively enhance the ACU. However, we also found that the angular CCT deviations in simulations are a little larger than the measurement values. This difference could come from the simulation error,

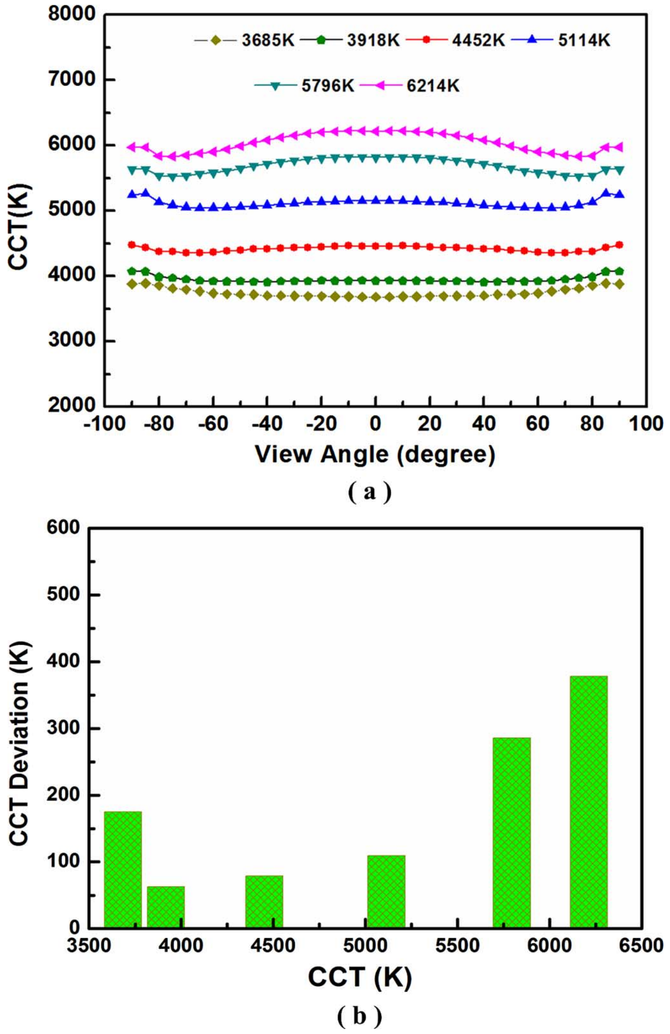

Fig. 8. Experimental angular color distribution of LED modules by phosphor dip-transfer coating. (a) CCT distribution at different average CCTs. (b) CCT deviation.

such as the single wavelength calculation for LED chip and phosphor, the accuracy of optical properties [28].

## VI. CONCLUSION

In this paper, we introduced the phosphor dip-transfer coating into LED packaging to enhance ACU. In this method, the phosphor mixture is only coated on the top surface of the LED chip so as to form a thin and ideal phosphor geometry for the high ACU. The numerical simulations and experiments were conducted. Both results prove that the phosphor dip-transfer coating performs higher ACU than conformal coating for vertical LED chips. The extreme small CCT deviation of 63 K is gained when the average CCT is 3918 K.

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