Thermal Remote Phosphor Coating for Phosphor-Converted White-Light-Emitting Diodes

Xingjian Yu, Bin Xie, Qi Chen, Yupu Ma, Ruikang Wu, and Xiaobing Luo

***Abstract*— We demonstrated a thermal remote phosphor coating method for realizing high angular color uniformity (ACU) and high efficiency of phosphor-converted white-light-emitting diodes based on thermal control. The proposed phosphor-coating method can fabricate remote phosphor layer geometries through a simple package process. Experimental results show that compared with those samples packaged by conventional dispensing coating, this method can efficiently improve the ACU. Angular color-correlated temperature (CCT) deviation of the test samples by the present method can reduce from 1100 to 90 K for an average CCT of 4300 K from −90° to +90° view angles, and the CCT distributions are 150 and 250 K for average CCTs of 5300 and 6300 K, respectively. In addition, this method can improve the lumen efficiency by 4.45% for an average CCT of about 4300 K, and increased by 4.96% and 5.45% for average CCTs of 5300 and 6300 K, respectively.**

***Index Terms*— Angular color uniformity (ACU), luminous efficacy, thermal remote phosphor coating, white light-emitting diodes (wLEDs).**

I. INTRODUCTION

WITH the rapid development of Gallium Nitride (GaN)-based blue-LEDs (LEDs), high-power white LEDs (wLEDs) have achieved very wide applications from general indoor lighting to some special-application illuminations such as vehicle forward lamp and projector light source [1]–[3]. For further penetration of wLEDs into general market, besides cost reduction, efficacy enhancement, and good reliability, the improvement in the white-light quality is of essential importance. There are several methods for realizing the wLEDs, but owing to their fabrication simplicity and cost effectiveness, the combination of blue light emitted by an LED chip and yellow light excited from phosphor is the most common approach [4]. In contrast to conventional light sources, such phosphor-converted wLEDs often face a technological problem, i.e., undesirable angular color uniformity (ACU) due to the mismatch between blue light and yellow light radiation patterns [5]. And the bad ACU performance usually blocks some applications with high white-light quality requirement.

Recent studies have highlighted that the ACU performance was thought to be closely related to the phosphor coating process in LED packaging, including phosphor particle size, recipe and distribution, and phosphor layer geometry [6]. Their quantitative effects on ACU have been revealed in [5]–[10], and the phosphor layer geometry was regarded as the main factor. Thus, many theoretical studies were devoted to exploration of the optimal phosphor geometry [8]–[10].

Currently, the phosphor coating methods mainly include dispensing coating, conformal coating, and remote coating. However, for conventional coating and conformal phosphor coating, phosphor materials are applied directly on top of LED chip. As the behavior of phosphor materials highly depends on their temperature, when the phosphor materials are heated up by the LED chip during operation, the emission efficiency decreases as temperature increases and even may also introduce reliability problems at a high phosphor temperature [11], [12].

To decrease the phosphor temperature and improve the poor ACU of the dispensing coating during operation, the remote phosphor configurations have been proposed to reduce the probability of the backscattering and thereby decrease absorption loss, as well as improve phosphor conversion efficiency by solving the problem of phosphor thermal quenching by keeping particles away from the LED surface. However, conventional remote phosphor coating suffers a mismatch of the thickness profile of phosphor layer with the angular intensity distribution of blue light and leads to a bluish center, also known as yellow ring. There are several ways to improve ACU. Kuo *et al.* [13] proposed a patterned remote phosphor coating to improve the uniformity of angular-dependent color-correlated temperature (CCT). Sun *et al.* [14] proposed an optimized design of packaging structure with a silicone lens covering a phosphor dome which performed an extremely small angular CCT deviation of 105 K in the simulation and 182 K in a corresponding real sample for a wLED with CCT near 6500 K. Huang *et al.* [15] fabricated a remote phosphor plate consisting of a highly regular organization of patterned structure on sapphire and a phosphor-prayed layer for flip-chip LEDs. Zheng *et al.* [16] proposed a kind of phosphor coating method to enhance ACU of pc-wLEDs with conventional chips by the combination of substrate structure design and phosphor dip-transfer coating. So far, for meeting the optimal phosphor geometry fabrication, more work needs to be done to improve the phosphor coating process.

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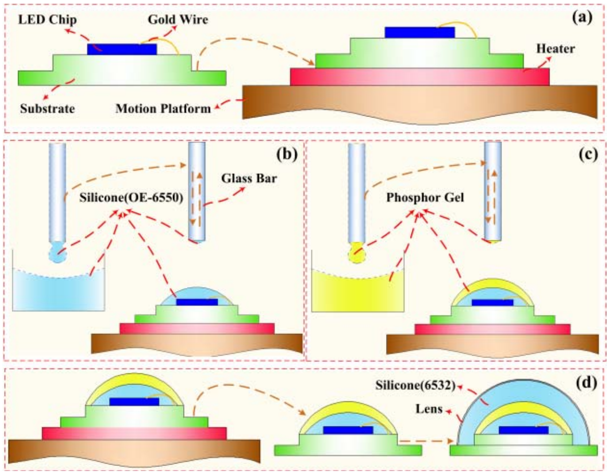

Fig. 1. Process flow schematic of thermal remote phosphor coating. (a) Putting the LED frame on the heater. (b) Coating silicone. (c) Coating phosphor gel. (d) Finishing packaging.

In this paper, the thermal remote phosphor coating is proposed to improve the ACU as well as the luminous efficacy. The detailed process theory and implementation were described. Its fabrication flexibility and processibility were proved by simulation and vast experiments. Applying this phosphor coating approach, a very small CCT deviation was obtained by the optimal phosphor layer geometry for a kind of conventional LED chip.

II. EXPERIMENT

The samples were prepared over the conventional LED chips mounted in the same leadframe through conventional dispensing phosphor coating and thermal remote phosphor coating for comparison. In our experiments, phosphor particles were sufficiently blended with transparent silicone to form the phosphor gel. Phosphor particles were produced by Intematix (YAG-04) with an averaging diameter of 13 μm and silicone is produced by Dow Corning (OE-6550 A/B). A heater with temperature controller was applied to control the substrate temperature at 150 °C. The conventional dispensing phosphor coating was formed by directly dispensing the phosphor gel on the LED surface and baked in an oven. After curing, the packages were encapsulated with a silicone lens by standard LED packaging processes.

Fig. 1 show the process flowchart of thermal remote phosphor coating, which includes the following steps.

1) Putting the LED frame on a heater and heating it to 150 °C [Fig. 1(a)].
2) Coating the silicone (OE-6550 A/B) onto the LED chip surface and circle around the LED chip and followed curing at 150 °C for 5 min. As a result, the remote configuration with a thin layer of silicone between the LED chip and the phosphor layer was obtained [Fig. 1(b)].
3) Coating the phosphor gel onto the silicone layer and curing at 150 °C for an hour, and a thin layer of phosphor gel above the silicone layer was obtained [Fig. 1(c)].
4) Taking the LED modules away from the heater and further encapsulated with silicone lens by standard LED packaging technology [Fig. 1(d)].

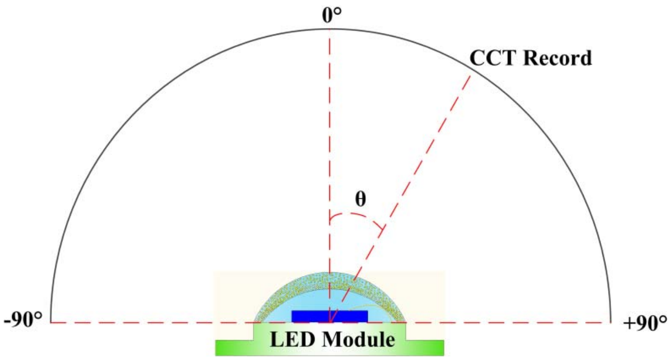

Fig. 2. Schematic of angular CCT measurement.

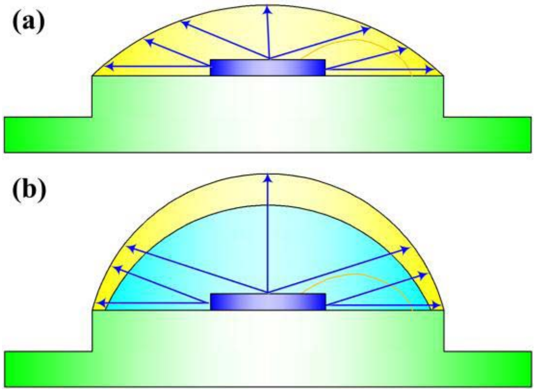

Fig. 3. Phosphor layer structure in the two phosphor coating methods. (a) Conventional dispensing phosphor coating. (b) Thermal remote phosphor coating.

Lots of LED modules were packaged using the conventional dispensing phosphor coating process and the thermal remote phosphor coating process. Fig. 2 shows the color distribution measurement of the LED packaging module which was recorded every 5° for the viewing angle changes from $-90°$ to $+90°$ with a colorimeter, and the optical performance of LED packaging modules was measured with a spectroradiometer equipped with an integrating sphere 1 m in diameter (ATA-1000). The average CCT deviation and the average luminous efficacy were used to evaluate the improvement in ACU performance and luminous efficacy.

III. OPTICAL SIMULATION

Before we conducted experiment, we studied the optical performance by simulation. The ratio of yellow light power to the blue light power (YBR) is proportional to the blue light optical path length while the CCT of wLEDs is decided by the YBR. Fig. 3 schematically indicates the phosphor layer structure for the conventional dispensing coating method and the thermal remote phosphor coating method, it shows that the optical path length in the thermal remote phosphor layer is more uniform than the conventional phosphor layer. Thus, the ACU performance of thermal remote phosphor coating

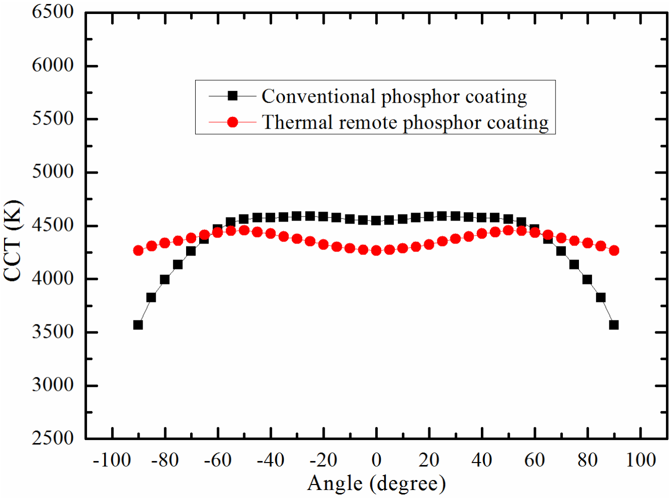

Fig. 4. Simulation angular CCT distribution comparison between conventional phosphor coating and thermal remote phosphor coating at an average CCT of 4300 K.

is expected to be better than that of conventional dispensing phosphor coating.

To verify the aforementioned assumption, optical simulations were conducted by the Monte Carlo ray-tracing method. The LED models comprise a conventional blue LED chip, a phosphor layer, a lens, and a substrate. The size of the conventional chip is 1 mm × 1 mm. The thicknesses of N-doped Gallium Nitride, Multiple Quantum Well, and P-doped Gallium Nitride are 3, 0.1, and 0.3 μm, respectively. The optical properties of the phosphor layer are calculated by the Mie theory. The phosphor particle size was approximated as a Gaussian distribution. For convenience of calculation, specific wavelengths of 454 and 570 nm were used to represent blue and yellow lights, respectively. In the optical simulations, the phosphor particles were assumed to be uniformly distributed in the phosphor layer. The concentration of coating phosphor mixture was adjusted to gain different CCTs.

Fig. 4 shows the simulation angular CCT distribution comparison between the two methods at an average CCT of 4300 K; it shows that the CCT deviations of the two methods are 150 and 1000 K, respectively. This proves that the thermal remote phosphor coating can get better ACU.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 5 shows the cutaway view of phosphor geometry packaged by the thermal remote phosphor coating method. It can be seen that the phosphor layer geometry is a curve with nonuniform thickness and away from the LED chip, and it is different from the traditional definition of the remote phosphor coating.

We confirmed its feasibility to optimize optical performance at different desired CCTs. Different CCTs can be obtained by adjusting the phosphor concentration or the coating volume of the silicone and phosphor gel. In our experiment, LED samples with CCTs of 4300, 5300, and 6300 K were packaged by adjusting the phosphor concentration while keeping the coating volume of the silicone and phosphor gel fixed. The coating volumes of silicone and phosphor gel were set as 2 and 5 μL, respectively, for CCTs of 4300, 5300, and 6300 K, and the corresponding phosphor concentrations were 0.2, 0.15, and 0.13 g/mL, respectively. Fifty LED samples were packaged for each desired CCT using the conventional dispensing coating method and the thermal remote phosphor coating method. Table I shows a detailed comparison of luminous efficacy between LED samples packaged using the two methods at each CCT. Fig. 6 shows the statistic data of the 50 samples at each CCT with the standard deviation of CCT and luminous efficacy. From Table I and Fig. 6, we can see that compared with conventional dispensing phosphor coating, a luminous efficacy improvement of 5% was obtained for the whole average CCT ranging from 4300 to 6300 K at a driving current of 350 mA.

Furthermore, to understand optical characteristics for two phosphor coating structures, the current-dependent luminous efficiency was measured with an integrating sphere (ATA-1000) for an integrating time of 1500 ms. Fig. 7 shows

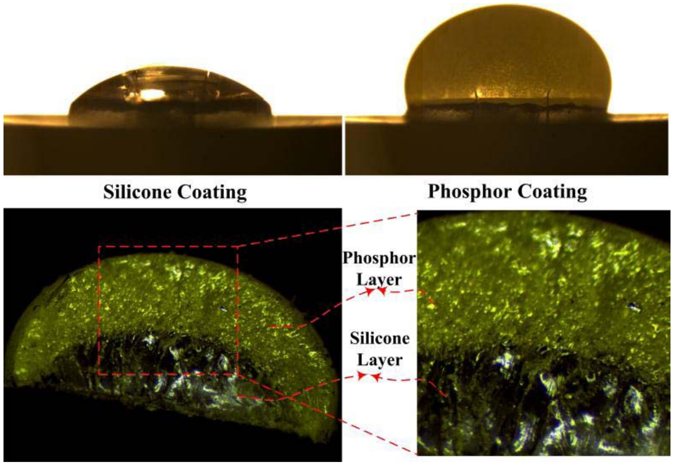

Fig. 5. Cutaway view of phosphor geometry packaged by the thermal remote phosphor coating method.

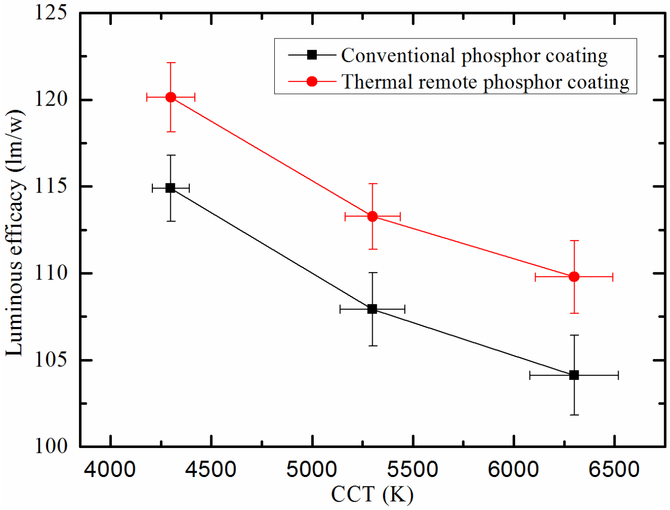

Fig. 6. Statistic data of the 50 samples at each CCT with the standard deviation of CCT and luminous efficacy.

TABLE I

EFFICIENCY MEASUREMENT RESULT

Average CCT	Sample numbers	Average luminous efficacy(lm/w)		Luminous efficacy improvement
		Conventional coating	Thermal remote coating	
4300K	50	114.90	120.14	4.45%
5300k	50	107.92	113.27	4.96 %
6300K	50	104.12	109.79	5.45%

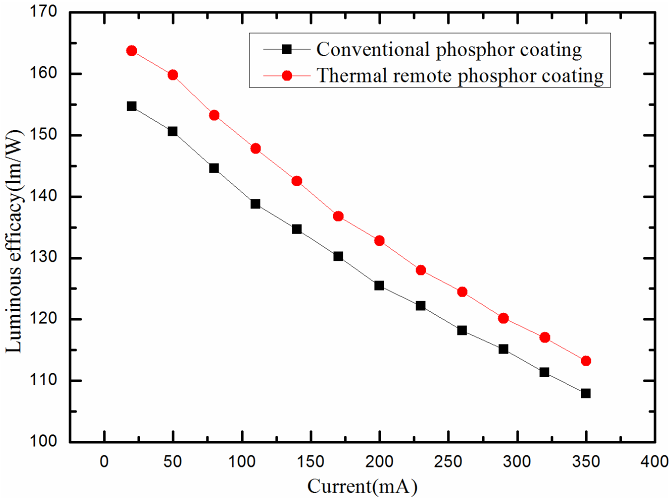

Fig. 7. Current-dependent luminous efficacy of wLEDs with two coating methods at 5300 K.

the luminous efficacy dependence on the current for the two coating methods. It shows that the luminous efficacy of thermal remote phosphor structure increases by 5.33% and 4.96% at driving currents of 350 and 20 mA, respectively, compared with the conventional dispensing phosphor structure at an average CCT of about 5300 K.

The improvement of the luminous efficacy improvement of LED samples fabricated using thermal remote phosphor coating method is ascribed to higher phosphor convention efficiency because there is less heat transfer from LED chip to phosphor layer, and also the higher extraction efficiency of blue light due to the decrease of the backscattering probability of LED emitted light by phosphor particles [12], [17], [18]. Besides, Fig. 7 shows that luminous efficacy decrease as the input current; this is caused by the decrease in the internal quantum efficacy of LED chip as the input current increases [19].

Fig. 8 shows the color distributions of conventional chips from −90° to +90° when the average CCT is about 4300 K using two coating methods. It is found that the CCT deviations of the conventional method and the present method are 1100 and 90 K, respectively. The CCT distribution of the thermal remote phosphor coating method is more uniform than that of the dispensing coating for each average CCT. Therefore, the present coating method can be used to improve the ACU.

Fig. 9 shows the color distributions from −90° to +90° when the average CCTs are about 4300, 5300, and 6300 K, respectively. When the average CCTs are about 4300, 5300, and 6300 K, the corresponding CCT distributions are 90, 150, and 250 K, respectively.

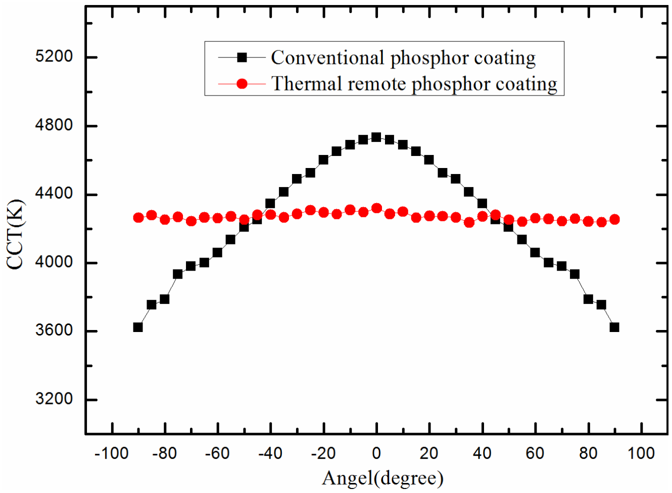

Fig. 8. Angular CCT distribution comparison between the conventional phosphor coating and thermal phosphor coating methods for an average CCT of about 4300 K.

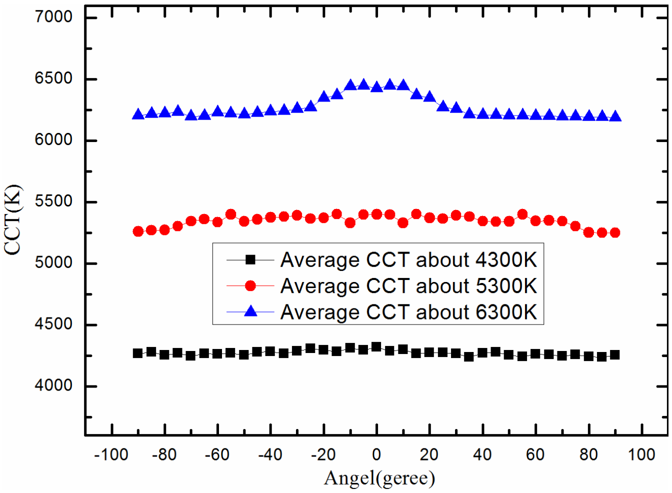

Fig. 9. Angular CCT distribution for average CCTs of about 4300, 5300, and 6300 K, respectively.

V. CONCLUSION

In this paper, thermal remote phosphor coating based on thermal control was introduced and described in detail. Its flexibility and processibility for different desired CCTs were verified through simulation and experiments by adjusting the phosphor concentration while keeping the coating volume of the silicone and phosphor gel fixed. The average CCT deviation and the average luminous efficacy were used to evaluate the improvement. The results show that compared with the conventional dispensing coating method, the present method can reduce the CCT distribution as well as improve the efficiency of LEDs. Compared with conventional dispensing phosphor coating, a luminous efficacy improvement of 5% was obtained for the whole average CCT ranging from 4300 to 6300 K, and the smallest CCT deviation of 90 K was obtained for the whole average CCT ranging from 4300 to 6300 K.

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