# Conformal phosphor coating using capillary microchannel for controlling color deviation of phosphor-converted white light-emitting diodes

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**Abstract:** We demonstrated a conformal phosphor coating method for phosphor-converted white light-emitting diodes (LEDs) using capillary microchannel formed by a fixture. The mixture of the phosphor particles and the silicone spontaneously flows in capillary microchannel and was pinned at the edge of the fixture due to the surface tension effect. The present coating method was applied to different packaging types with both the conventional chip and the vertical injection chip. Experimental results show this method can efficiently improve the angular color uniformity (ACU). Compared with those samples packaged by conventional dispensing coating, angular color correlated temperature (CCT) deviation of the test samples by the present method can reduce from 1500K to 200K for the average CCT 5200K from −90°to +90 view angles, and reduce from 5000K to 1000K for the average CCT 9150K. Additionally, this method can prevent the packaging non-consistency that the average CCT varies from package to package due to the deviation of phosphor-silicone mixture volume. In the experiments, even when the phosphor-silicone mixture volume varies from 0.3µl to 0.5µl, the deviation of the average CCT is less than 80K.



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

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## 1. Introduction

White LEDs have been regarded as the most important and promising solid-state light source for the next generation lighting due to many advantages over the incandescent and the fluorescent in efficiency, life time, chromatic performance, reliability and environmental protection [1–3]. In recent years, white LEDs have developed rapidly and penetrated into many illumination areas such as large size flat backlighting, street lighting, vehicle forward lamp, museum illumination and residential illumination [4–6]. To broaden the application of white LEDs in illumination, the quality of white light in terms of CCT, ACU and color rendering index (CRI) is the other major challenge besides the efficiency [4].

So far, one of the most common methods for generating white light is the combination of blue light emitted from LED chip with yellow light re-emitted from YAG:$Ce^{3+}$ phosphor, which is known as phosphor-converted white LEDs (pc-WLEDs) [3]. In LED packaging, the mixture of phosphor particles with transparent encapsulant resin is coated on LED chip to form a phosphor layer. The complex optical phenomenon which consists of the absorption of blue light, yellow light re-emitting, and the light scattering happens in the phosphor layer. Therefore, the LED optical performances in terms of the efficiency and the quality of white light are critically decided by the shape, the concentration, the thickness and arrangement of the phosphor layer [7, 8].

The phosphor coating technology is vital for gaining the high efficiency and white light quality of the LED device because it controls the shape and arrangement of the phosphor layer. A phosphor coating technology is known as the dispensing coating in which the phosphor mixture is directly dispensed on the LED chip surface. Due to its simple operation and low cost, this method is widely adopted in industry. However, its phosphor geometry is usually a spherical cap shape in result of the surface tension of the mixture. Such a geometry results in yellow rings in the radiation pattern, which reduces ACU [9]. In addition, due to the inconsistency of mixture volume in the dispensing coating process, the average CCT may vary from package to package [10]. It would result in low yield and increase the cost of the LED production.

To overcome the poor ACU of the dispensing coating, the conformal phosphor coating was proposed [4, 11]. This coating means that the phosphor layer replicates the LED chip surface. To realize the conformal phosphor coating in LED packaging, many methods were developed and they include electrophoresis [12], slurry, settling [13], spin coating [14], and pulsed spray [15]. However, electrophoresis would cause Cr ion pollution in coating processes and is unfriendly to environment [15]. Slurry settling approach is a chemical reaction and requires a flip-chip LED with a flat surface for phosphor coating [15]. Spin coating centrifugally separates phosphor from slurry [15]. Pulsed spray can form uniform phosphor layer on the LED chip top surface, but it can't easily control the phosphor layer on LED chip

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side. Because the blue light emits from not only the top but also the sidewalls of the LED conventional chip and flip chip [16], this may propose a challenge to realize the optimal conformal phosphor coating shape for the conventional LED chip and flip chip by pulsed spray.

In this study, a novel conformal phosphor coating method based on capillary microchannel was proposed. Experiments were conducted for LED conventional chips and vertical chips. The results show that this method is able to gain better ACU compared with the conventional dispensing coating at different CCT ranges. It also exhibits high stability for keeping the average CCT consistency under wide deviation of the phosphor-silicone mixture volume.

## 2. Principle of the present phosphor coating method

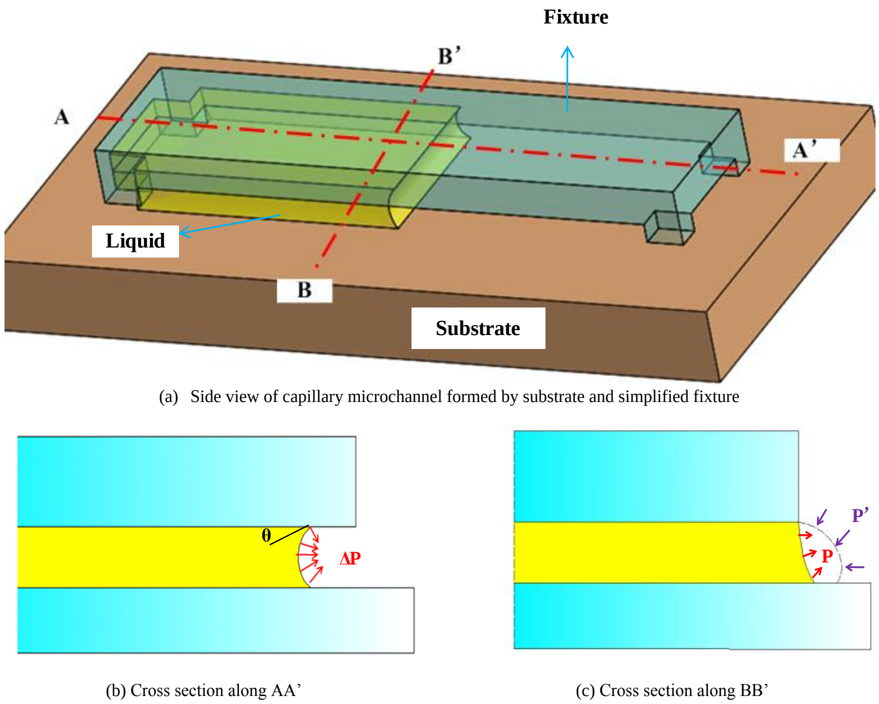


Fig. 1. (a) Flow schematic of phosphor particles and silicone mixture in capillary microchannel. (b) Pressure difference inducing the liquid spontaneous imbibition and (c) liquid pinned at step edge of the fixture.

The phosphor coating method using capillary micrichannel is based on the effect of the spontaneous imbibition of the liquid in capillary microchannel and liquid-air surface pinned at step edge [17, 18]. Figure 1(a) shows a simplified capillary microchannel model, in which the fixture is a cubic shape for description convenience. Figure 1(b) is a cross-section of capillary microchannel along the liquid flow direction. While the liquid flows into the channel, there is a pressure difference between the liquid and the air. The pressure difference between the liquid and the air can be determined by Young–Laplace equation

$$\Delta P=\gamma_{LG}\left(\frac{1}{R_1}+\frac{1}{R_2}\right) \tag{1}$$

where $\Delta P$ is the pressure difference between the liquid and the air, $\gamma_{LG}$ is the surface tension, $R_1$ and $R_2$ are the principal radius of the meniscus curvature in the width and height directions, respectively. Because the dimension in width direction is large enough, Eq. (1) is reduced to

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$$\Delta P = \gamma_{LG}\frac{1}{R_2}. \tag{2}$$

The $R_2$ can be expressed as

$$R_2 = \frac{h}{2\cos(180-\theta)} \tag{3}$$

where h is the height of capillary microchannel, θis the contact angle. If Eq. (3) is substituted into Eq. (2), the pressure difference between the liquid and the air can be expressed by the height of the capillary microchannel and the contact angle as following,

$$\Delta P = \gamma_{LG}\frac{2\cos(180-\theta)}{h} \tag{4}$$

The contact angle of the phosphor mixture is about 30°, so the pressure difference $\Delta P$ is negative. The liquid would spontaneously flow along the capillary microchannel.

Figure 1(c) shows that the liquid is pinned at the step edge of the microchannel (the side edge of the fixture). It can be seen that the liquid must overcome an addition pressure P', when it flows out the microchannel. However, the pressure difference $\Delta P$ between the liquid and the air mentioned above is negative. Thus, the liquid-air surface is pinned at the step edge and the mixture of the phosphor particles and encapsulant resin could copy the fixture shape after cured. This means that we can use proper fixtures to get desirous coating shapes.

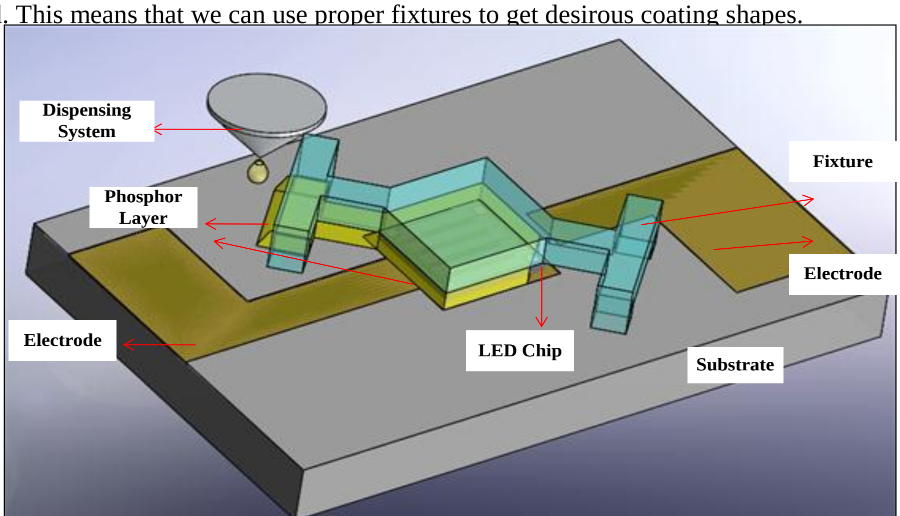


Fig. 2. Schematic of conformal phosphor coating using capillary microchannel.

Fixtures were designed for conformal coating and the process was shown in Fig. 2. Here, the microchannel is the gap between the fixture and the substrate. The main part of the fixture is the cubic shape, which is applied to form the conformal phosphor coating. The LED chip is bonded on the top surface of the substrate and aligned as the cubic shape along the center. The mixture of phosphor particles and the encapsulant resin is dispensed on an end of the fixture and spontaneously imbibed into the microchannel. The flow of the mixture stops when all the liquid enters into the microchannel. The mixture is confined in the zone under the fixture. After the mixture is cure, the fixture is removed from the substrate and a cubic shape phosphor layer is fabricated.

## 3. Experiments

To prove the above idea and get conformal coating, experiments were conducted. The YAG:$Ce^{3+}$ phosphor particles were applied in the experiments. The phosphor particles were sufficiently blended with the silicone. The mixture of the phosphor particles and the silicone was dispensed at an end of the fixture using the conventional dispensing coating device. The mixture would spontaneously flow along the capillary microchannel and reaches equilibrium state in two minutes. The substrate and the fixture were transferred into baking oven for mixture curing. After the silicone cured, the fixture was removed from the substrate. In the experiments, the different fixture sizes and phosphor concentrations were applied to get various average CCTs. The roughness and the thickness variation of the phosphor layer were measured by optical profiling system WYKO NT1100.

The volume deviation of the mixture usually happens in the dispensing process and would result in low CCT consistency from packaging to packaging. In order to test the stability to the volume deviation, different mixture volumes with the range from 0.3ul to 0.5ul were used to test. In these experiments, the LED chips were the same and the optical performances of all LED chips were measured to assure the same optical performance. The phosphor concentration was also kept the same. The same fixture was used and the thickness of the capillary microchannel maintains the same value.

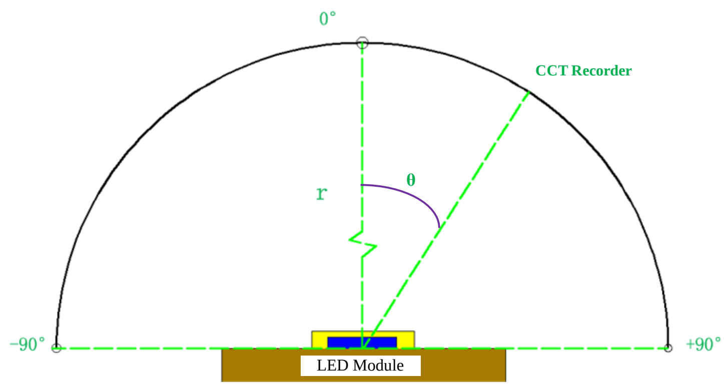


Fig. 3. Schematic of angular CCT measurement.

After phosphor coating, the optical performance of LED packaging modules was measured. The average CCT of each LED packaging module was measured by the integrating sphere. The color distribution of the LED packaging module was recorded as shown in Fig. 3. To measure the color distribution accurately, the distance between the CCT recorder and the LED packaging module is large enough. The CCT of the LED packaging module was recorded every 5 degrees for the viewing angle changes from –90°to + 90°.

## 4. Results and discussion

Figure 4 shows the phosphor geometries using capillary microchannel coating. It can be seen that the phosphor geometry could completely copy the fixture's shape. The top surface of the phosphor layer is a plane. The roughness of the top surface is about 1μm and the thickness variation of the phosphor layer is about 6μm. The roughness and thickness variation are determined by the fixture. The roughness of the top surface is roughly equal to that of the fixture's bottom surface. The thickness variation is the comprehensive effect of the fixture smoothness and gradient. In Fig. 4, it can be found that the side surface of the phosphor layer is not a plane but a curve. It is different from the traditional definition of the conformal phosphor coating. However, the experimental results prove that this phosphor geometry can improve the ACU of the LED compared with conventional dispensing coating.

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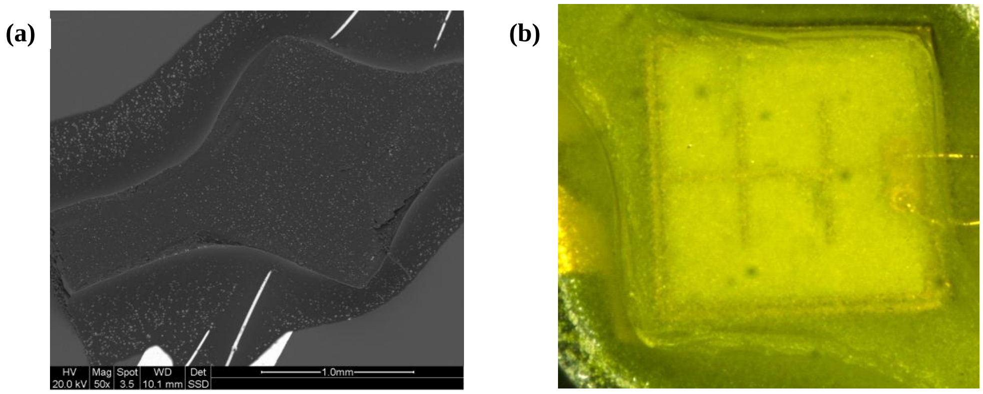


Fig. 4. Geometries of phosphor layer by present coating method.

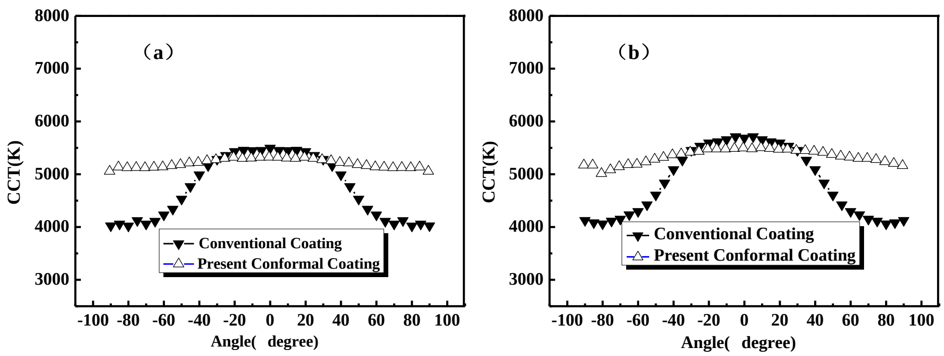


Fig. 5. Angular CCT distribution comparison between conventional coating and the present coating method at the average CCT around 5200K, (a) for the conventional chip and (b) for the vertical injection chip.

Figure 5 shows the color distributions of dispensing coating and the present conformal coating method for conventional chips and vertical injection chips from –90°to + 90°. The average CCT keeps cool white (about 5200K). It is found that the CCT deviations of the dispensing coating and the present coating using capillary microchannel are 1525K and 153K for the LED conventional chip in Fig. 5(a). For the LED vertical injection chip shown in Fig. 5(b), they are 1459K and 214K, respectively. It is obvious that the CCT distribution of the present coating method is more uniform than that of the dispensing coating for both two kinds of chips.

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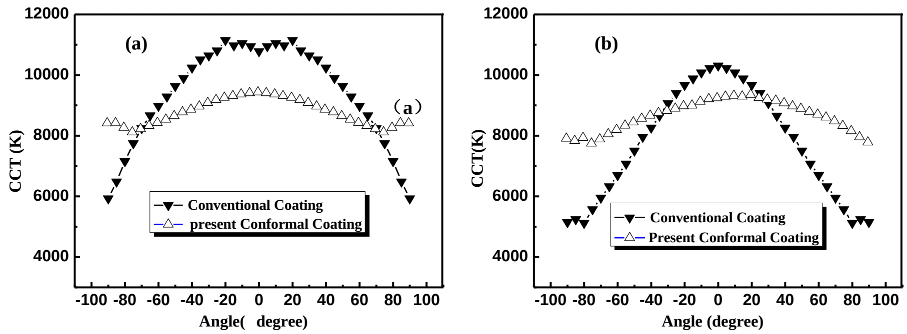


Fig. 6. Angular CCT distribution comparison between conventional coating and the present coating method at the average CCT around 9150K, (a) for the conventional chip and (b) for the vertical injection chip.

Figure 6 shows the comparison between the conventional coating and the present conformal coating method when the average CCT is about 9150K. It can be found that the color deviations of the present conformal coating is about 1000K and less than that (about 5000K) by dispensing coating for both conventional chip and vertical injection chip. Therefore, the present conformal phosphor coating using capillary microchannel can be used to improve the ACU. It is believed that better ACU can be obtained by employing the optimal coating process parameters in the present coating method.

**Table 1. Average CCT variation with different phosphor-silicone mixture volumes**

| Volume(μL) | 0.3 | 0.35 | 0.4 | 0.45 | 0.5 |
|---|---|---|---|---|---|
| CCT(K) | 4321 | 4309 | 4316 | 4351 | 4369 |

This conformal coating using capillary microchannel presents high CCT consistency to the deviation of phosphor-silicone mixture volume. Table 1 shows the average CCT variations with different dispensing volumes. It can be found that the CCT varies less than 80K when the mixture varies from 0.3ul to 0.5ul. It is because that the mixture volume staying around the chip keeps the same and the CCT is hardly affected by the volume deviation in spontaneous flow. Therefore, the average CCT is less affected by the dispensing volume deviation.

## 5. Conclusions

A novel conformal coating using capillary microchannel is presented to reduce the color deviation for the white LEDs in this paper. The experimental results show that this coating method can effectively improve the ACU for both conventional chip and vertical injection chip at different overall color temperature ranges. Additionally, the present coating method exhibits good CCT consistency to the dispensing volume deviation of the phosphor and silicone mixture, which is helpful for mass production.

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