Angular Color Uniformity Enhancement of White LEDs by Lens Wetting Phosphor Coating

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***Abstract*— In this letter, we proposed a remote phosphor coating method by lens wetting for enhancing the angular color uniformity of phosphor-converted white light-emitting diodes. Simulations based on the volume of fluid (VOF) method were applied to investigate the geometry evolution of a phosphor gel droplet after being dropped onto the lens, and the stable geometry of the phosphor gel was obtained. Monte Carlo ray tracing was used to study the optical performance of LED samples with the stable phosphor geometries. Besides, experiments were conducted to verify the fabrication flexibility of the proposed method. The VOF simulation and experimental results show that the proposed method can realize the hemispherical remote phosphor layers with uniform or non-uniform thickness by adjusting the coating volume. The optical simulations and the experimental measurements show that the LED samples with non-uniform thickness remote phosphor geometry achieves smaller correlated color temperature deviation (<200 K at 5000 K) than the uniform thickness remote phosphor geometry.**

***Index Terms*— White LEDs, remote phosphor coating, lens wetting, angular color uniformity.**

I. INTRODUCTION

HIGH power white light-emitting diodes (wLEDs) have been considered as the fourth generation of light source, with advantages of low cost, high efficacy and good reliability, they have been applied in many illumination areas such as street lighting, indoor lighting, and projector lighting [1]–[3]. To realize white LEDs, the most common way is to coat yellow-emitting phosphors onto the blue LED chip in packaging. The blue light emitted from the LED chip mix with the yellow light re-emitted from the phosphors to form white light [1], [3]. In LED packaging, dispensing phosphor coating is widely-used, in such phosphor coating process, phosphor gel which consists of phosphor powder and silicone is directly dropped on to the LED chip. However, due to the small contact angle of the phosphor gel on the substrate, the phosphor layer is thicker on the side of the chip than on its top. This phosphor shape leads to poor angular color uniformity (ACU), i.e. high CCT along the center angles and low CCT along the side angles [4], [5]. The ACU is calculated by the deviation of the correlated color temperature (CCT) in the whole viewing angle. The poor ACU discomforts our eyes and hinders the applications of pcLEDs in general lighting especially with high light quality requirement. Therefore, for further application of pcLEDs, good ACU performance should be taken into consideration.

Vast works have been done to enhance the ACU by proposing new phosphor coating methods. Conformal phosphor coating is thought to be a promising method and its effect on the ACU performance of pcLEDs has been proved by simulations and experiments [6], [7]. Besides, Sun *et al.* fabricated a large phosphor dome (with radius of 3 mm) onto a small size LED chip (0.66 mm × 0.66 mm × 0.1 mm) using a molding lens of silicone. The size difference between the LED chip and phosphor dome makes it possible to regard the LED chip as a point source and therefore achieve high ACU performance. Sun *et al.* also demonstrated that ACU performance can be further improved by extending the vertical thickness of the phosphor along the normal direction [8]. Both conformal phosphor coating and the coating method proposed by Sun *et al.* need molding which would increase the cost. The remote phosphor coating method was thought to be a simpler and cheaper method to improve ACU and thermal performance of pcLEDs [9]–[11]. Liu *et al.* demonstrated that a remote phosphor layer with hemispherical geometry and uniform thickness can enhance the ACU [12]. However, their work was based on Monte Carlo simulations and the CCT deviation is still large. One possible idea to further enhance the ACU is to fabricate a hemispherical phosphor layer with non-uniform thickness. How to realize such specific phosphor geometry remains a challenge.

In this letter, we propose a simpler phosphor coating method to achieve remote phosphor geometries based on lens wetting for pcLEDs. The detailed process, theory and implementation are described and the fabrication flexibility is validated by simulations and experiments.

II. METHODOLOGY

A. Fluid Flow Simulation

The Volume of Fluid (VOF) technique is one of the most widely used numerical methods of computational fluid dynamics (CFD) in modeling of free-surface flows [13], [14]. Here, we employed this method to simulate the geometry evolution of a phosphor gel droplet after being dropped onto the inner surface of a hemispherical lens.

Manuscript received December 30, 2015; revised April 11, 2016; accepted April 13, 2016. Date of publication April 15, 2016; date of current version May 19, 2016. This work was supported by the National Science Foundation of China under Grant 51376070 and Grant 51576078. *(Ting Cheng and Xingjian Yu contributed equally to this work.)*

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Digital Object Identifier 10.1109/LPT.2016.2554631

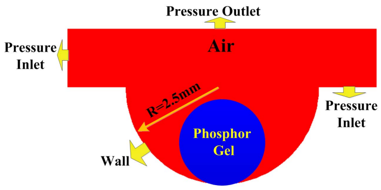

Fig. 1. Simplified two-dimensional symmetrical numerical model.

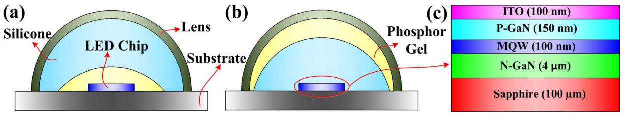

Fig. 2. The simulation models. (a) Spherical cap phosphor geometry, (b) Remote phosphor geometry, (c) Structure of the conventional chip.

Fig. 1 shows the simplified two-dimensional symmetrical numerical model, which was validated to be adequate to predict the morphology change of the liquid phase in an axisymmetric three-dimensional wetting process [15]. The numerical model consists of air, phosphor gel, wall, and pressure inlet and pressure outlet. In the simulation, the air and phosphor gel were considered as incompressible, laminar and Newtonian fluids with constant viscosity. The continuum surface force (CSF) technique was applied to model surface forces and surface adhesion [16]. The phosphor gel which consists of phosphor powders and silicone was treated as a whole, its viscosity μ of was set as 4 Pa·s according to the testing result by a viscometer (CAP2000, BROOKFIELD), its surface tension was set as 0.031N/m and its static contact angle on the wall was set as 20°. Both the surface tension and the contact angle were measured by a Drop Shape Analyzer (DSA25, KRUSS). The pressure of the outlet and inlet were set as atmospheric pressure and a relative pressure of zero was set in the simulations. The radius of the semi-circle wall is 2.5 mm which is consistent with the lens used in the experiments. In each simulation, the droplet was assumed as a sphere with a pre-defined droplet radius R when it initially contacts with the inner surface of the lens. The simulation was divided into two stages: at the first stage, the lens was downward, and the phosphor gel would automatically wet the bottom of the lens until an equilibrium state was obtained. At the second stage, the lens was put upside down and the phosphor gel would continue wetting the lens until its geometry becomes stable.

B. Optical Simulation

Before the experiments, we conducted optical simulations by the Monte Carlo ray-tracing method to examine the ACU performance of the LEDs, spherical cap phosphor geometry coated by the dispensing phosphor coating method and the stable phosphor geometries obtained from the VOF simulations were applied. Fig. 2 schematically indicates the simulation models, Fig. 2(a) shows the spherical cap phosphor geometry, and Fig. 2(b) shows the remote phosphor geometry, and Fig. 2(c) shows the structure of the conventional chip. The models consists of conventional blue LED chip, phosphor layer, silicone layer, lens, and substrate. The optical parameters, such as absorption and scattering coefficients, of the phosphor layer were calculated by the Mie theory. The phosphor particle was approximated as sphere with uniform diameter of 13 μm. For the convenience of calculation, specific wavelengths of 454 nm and 570 nm were used to represent the blue and yellow light, respectively [6]. In the optical simulations, the phosphor particles were assumed to be uniformly distributed in the phosphor layer with a concentration adjusted to gain the desired CCTs.

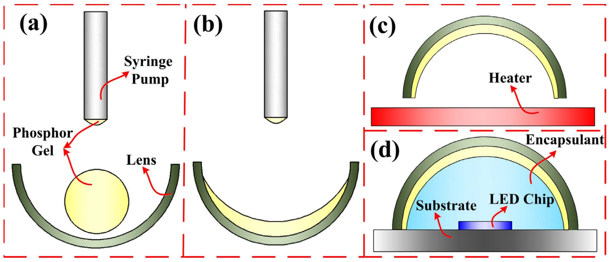

Fig. 3. Process flowchart of the lens wetting phosphor coating method. (a) Dropping the phosphor gel into lens, (b) Phosphor gel wetting the lens, (c) Curing phosphor gel, (d) Finishing packaging.

C. Experiment

To verify the proposed process, experiments were conducted to fabricate LED samples and the ACU performance of the LED samples were tested. Two kinds of samples were prepared: one with the dispensing phosphor coating and the other with the lens wetting phosphor coating. In our experiments, phosphor particles were sufficiently blended with transparent silicone to form the phosphor gel. Phosphor particle are produced by Intematix (YAG-04) with average diameter of 13 μm and silicone is from Dow Corning (OE-6550 A/B). The dispensing phosphor coating was formed by directly dispensing the phosphor gel on the LED surface and baking in an oven at 150°C for an hour. After curing, the LED modules were encapsulated with silicone encapsulation by standard LED packaging process.

Fig. 3 shows the process flowchart of the lens wetting phosphor coating method. The process includes following steps.

1) Dropping the phosphor gel onto the lens with a syringe pump (Fig. 3(a)).
2) Keeping the lens downward, the phosphor gel, driven by the surface tension, would wet the lens gradually (Fig. 3(b)).
3) Putting the lens upside down on a heater at 150 °C for an hour until the phosphor gel gets cured (Fig. 3(c)).
4) Fastening the lens on the LED module and encapsulating it with silicone (Fig. 3(d)).

100 LED modules were packaged with the two coating methods. Fig. 4 shows the angular CCT distribution measurement of the LED modules. The colorimeter (XYC-1) recorded the angular chromaticity coordinate for the viewing angle from −90° to +90°, and based on the angular chromaticity coordinate, the angular CCTs were calculated by the software.

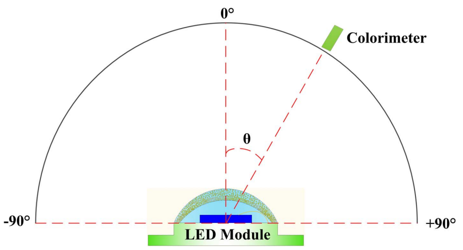

Fig. 4. Schematic of angular CCT measurement.

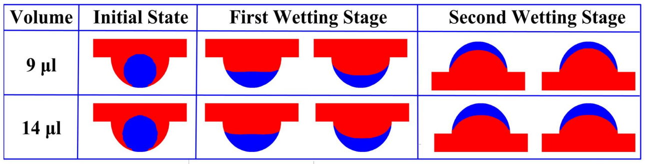

Fig. 5. Simulated geometry evolution of phosphor gel droplets with volume of 9 μl and 14 μl.

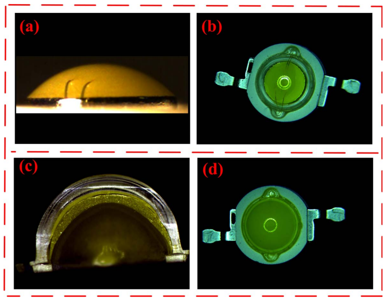

Fig. 6. Phosphor geometries and LED samples packaged by the dispensing phosphor coating and lens wetting phosphor coating method: (a) (b) dispensing phosphor coating; (c) (d) lens wetting phosphor coating.

III. RESULTS AND DISCUSSIONS

In the VOF simulations, the volume of the phosphor gel was set as 9 μl and 14 μl, respectively. Fig. 5 shows the simulated geometry evolution of phosphor gel droplets with volume of 9 μl and 14 μl after it being dropped onto the lens. It is seen that at the first wetting stage, the phosphor gel cannot wet all the lens, while at the second wetting stage, the phosphor gel would wet all the lens due to the gravity effect. Remote phosphor layer with uniform thickness was obtained for a volume of 9 μl, while the thickness is non-uniform for 14 μl.

Fig. 6(a) and Fig. 6(b) show the phosphor geometry and LED sample packaged by the dispensing coating method, and Fig. 6(c) and Fig. 6(d) show the phosphor geometry and LED sample packaged by the lens wetting coating method. From Fig. 6(a), it is seen that the phosphor layer fabricated by the dispensing phosphor coating is above the LED chip with spherical cap geometry. From Fig. 6(c), it is seen that the phosphor layer fabricated by the lens wetting method adheres to the lens and is away from the LED chip. Fig. 7 shows the comparison of phosphor geometries obtained from simulations and experiments. It indicates that deviation of the main phosphor geometric values obtained from experiments and VOF simulations is less than 5%.

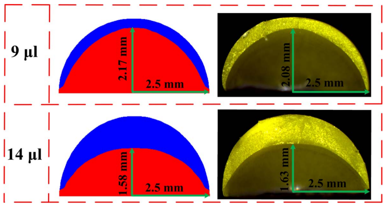

Fig. 7. Comparison of phosphor geometries obtained from simulations (left) and experiments (right).

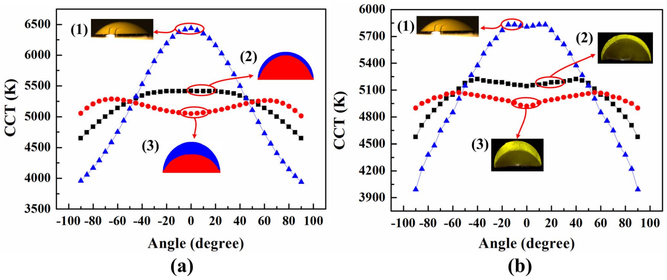

Fig. 8. Simulated and experimental CCT distribution of the phosphor geometries shown in Fig. 6(a) and Fig. 7: (a) simulated results; (b) experimental results.

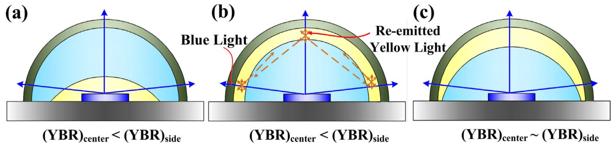

Fig. 9. Schematic of the blue light and yellow light emission of pcLEDs. (a) Shows the LED module with spherical cap phosphor geometry, (b) shows the LED module with uniform thickness remote phosphor geometry, and (c) shows the LED module with non-uniform thickness remote phosphor geometry.

Fig. 8 shows the simulated and experimental CCT distribution of the phosphor geometries shown in Fig. 6(a) and Fig. 7 at average CCT of 5000K. The phosphor geometries and the corresponding sample numbers are embedded in the figure, it indicates that the remote phosphor geometry packaged by the lens wetting method achieves better ACU performances than the spherical cap phosphor geometry, and non-uniform thickness phosphor geometry achieves better ACU performance than uniform thickness phosphor geometry. For the simulated results shown in Fig. 8(a), the CCT deviations of sample 1-3 are 2498K, 770K, and 273K, respectively. For the experimental results shown in Fig. 8(b), the CCT deviations of the Sample 1-3 are 1840K, 644K and 175K, respectively. Besides, the luminous efficiency of sample 1-3 are 116.7 lm/w, 122.5 lm/w and 121.8 lm/w, respectively, which indicates that the remote phosphor geometries fabricated by lens wetting phosphor coating method have higher lumen efficiency.

Fig. 9 shows the schematic of the blue and yellow light emission of pcLEDs with the three phosphor geometries, and it explains the mechanism behind Fig. 8. We know that the angular CCT is inverse proportional to the angular ratio of the re-emitted yellow light power to the blue light power. The radiation pattern of blue light emitted from the LED chip is similar to Lambertian, which means higher blue light intensity in the center. The radiation pattern of yellow light re-emitted from the phosphor is isotropically and the angular re-emitted yellow light intensity is proportional to the angular phosphor layer thickness. For Sample 1, as shown in Fig. 9(a), the phosphor layer in the center is thinner than in the side, for Sample 2, as shown in Fig. 9(b), the phosphor layer is of the same thickness. Therefore, the poor ACU of sample 1 and sample 2 is mainly caused by the mismatch between the angular phosphor layer thickness and the Lambertian radiation pattern of blue light, and resulting in $\mathrm{CCT}_{\mathrm{side}} < \mathrm{CCT}_{\mathrm{center}}$. However, for Sample 3, as shown in Fig. 9(c), the phosphor thickness gradually reduces from center to side and the angular phosphor layer thickness matches the Lambertian radiation pattern of blue light well, and resulting in $\mathrm{CCT}_{\mathrm{side}} \sim \mathrm{CCT}_{\mathrm{center}}$.

IV. CONCLUSIONS

In this letter, the remote phosphor coating by lens wetting was proposed and investigated through simulations and experiments. Results show that the proposed lens wetting method can achieve remote phosphor layers with thickness profile from uniform to non-uniform by adjusting the volume of phosphor gel. Optical simulations and experimental measurements show that the LED samples with remote phosphor geometry have better ACU performance than the spherical cap phosphor geometry coated by the dispensing phosphor coating method, and the LED samples with remote phosphor geometry of non-uniform thickness can achieve smaller CCT deviation (<200K @ 5000K) than the uniform phosphor geometry. The proposed method shows its superiority in simplicity and fabrication flexibility. Therefore, it would be a potential way to improve the ACU of pcLEDs.

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