Dynamic Phosphor Sedimentation Effect on the Optical Performance of White LEDs

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***Abstract*— In this letter, we investigated the dynamic phosphor sedimentation effect on the optical performance of phosphor-converted light-emitting diodes (pcLEDs) with dispensed phosphor layer. To analyze the phosphor sedimentation effect, we realized two packaging structures to sediment phosphor particles above/outside LED chip separately. The phosphor sedimentation effect on the luminous efficiency and correlated color temperature (CCT) were tested by experiments, followed by a quantitative exploration to the mechanism by evaluating the angular color uniformity and light intensity distribution-based Monte Carlo ray-tracing simulations. Results show that phosphor sedimentation happened above LED chip will decrease CCT by 33.19%, and happened outside LED chip will increase CCT by 269%. For the conventional packaging structure, phosphor sedimentation will lead to the decreasing CCT at first and the increasing CCT soon afterwards, and the CCT variation is 39.62%.**

***Index Terms*— Light-emitting diodes, phosphor sedimentation, packaging structure, experiment and optical simulation.**

I. INTRODUCTION

PHOSPHOR-CONVERTED light-emitting diodes (pcLEDs) are the most popular white LED products in the LED industrial due to its high efficiency, low cost, and high reliability [1]–[3]. Phosphor particles [4]–[6] absorb the short-wavelength light emitted from the LED chip and convert into long-wavelength light emission partly, and the short- and long-wavelength light mix with each other and produce while light in the end [1]. Nowadays, dispensing coating and conformal coating the most widely-applied two phosphor coating processes, in which the phosphor particles are coated onto the LED chips [1], [7], [8]. Although the conformal coating process was verified to possess better ACU performance than the dispensing coating process [9]–[11], the latter is still popular in the LED packaging industrial due to its low cost and simplicity [1]. During the dispensing coating process, phosphors are mixed with the silicone matrix to form phosphor gel and then coated onto the LED chips directly [1]. Due to the flowing characteristics and difference in density, the phosphor particles ($\rho = \sim 4800$ kg/m^3) will sediment spontaneously in the silicone matrix ($\rho =\sim 1120$ kg/m^3) [12]. As a result, the phosphor particle distribution is changed, as well as the optical performance of pcLEDs, such as the luminous efficiency (LE), correlated color temperature (CCT), angular color uniformity (ACU) and light intensity distribution (LID) [13]–[16]. Phosphor sedimentation is rather complicated problem which involves with silicone flowing and chemical curing, phosphor particle sedimentation, light absorption, scattering and conversion, etc. As a result, quite a few work in terms of phosphor sedimentation have been reported. Lee *et al.* [13] investigated the effect of phosphor sedimentation on the white LEDs with different structure chips, and a maximum luminous efficiency difference of 20% was found with the vertical structure chip. Sommer *et al.* [14] investigated the phosphor sedimentation in LEDs through simulations and found that the CCT and flux-output are highly sensitive to the variations of phosphor distribution. In our previous studies [15], [16], we investigated the phosphor concentration change in the silicone matrix during the phosphor sedimentation and established a multi-layer phosphor model to study the effect of phosphor sedimentation on the light extraction efficiency, we found that the phosphor sedimentation caused a light extraction efficiency variation of 13.04%. These works only reported the optical performance of pcLEDs under limited phosphor distribution. However, in the real LED packaging, due to the packaging condition, the phosphor distribution varies from uniform distribution to completely sedimentation as the conformal coating. Besides, the simulation models in [14]–[16] only involve with the conformal phosphor layer, while sedimentation models involving with dispensed phosphor layer are still out of study. The exploration of the sedimentation effect quantitatively will benefit the understanding, manipulating and improving the phosphor coating process for high-quality pcLEDs, which is the exact motivation behind this study.

In this study, we investigated the effect of the dynamic phosphor sedimentation on the optical performance of pcLEDs with three packaging structures experimentally and numerically. In the experiments, we applied an online testing experimental setup to record the optical performance of pcLEDs while keeping the phosphor gel uncured. By such a measurement, the luminous efficiency and CCT of pcLEDs with phosphor distribution from uniform distribution to completely sedimentation could be captured and analyzed. A multi-layer phosphor model based on Monte Carlo ray-tracing method was adopted

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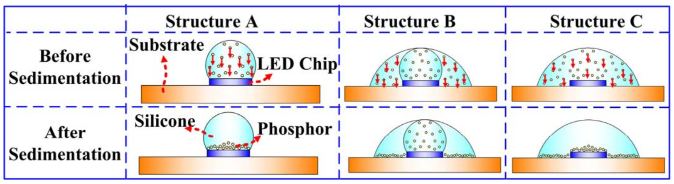

Fig. 1. Three packaging structures.

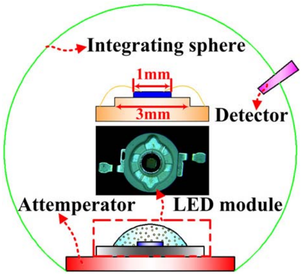

Fig. 2. Experimental setup.

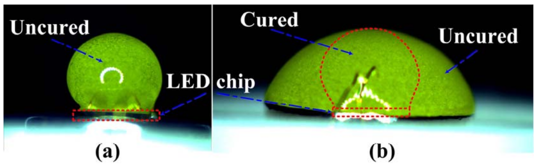

Fig. 3. Phosphor layer geometries of (a) Structure A and (b) Structure B.

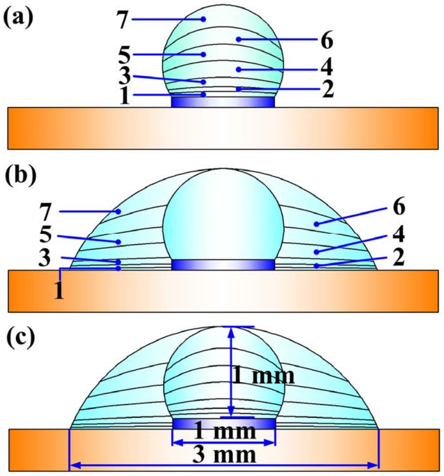

Fig. 4. Simulation models: (a) Structure A, (b) Structure B and (c) Structure C.

to further investigate the phosphor sedimentation effect on the ACU and light intensity distribution.

II. EXPERIMENTS

To study the dynamic phosphor sedimentation effect quantitatively, we proposed to realize the phosphor sedimentation above and outside LED chip and analyzed the consequence separately. Three packaging structures were adopted. Fig. 1 schematically shows the three packaging structures and the phosphor particle distribution before and after sedimentation. Structures A and B are two structures proposed in this study, and Structure C is the conventional packaging structure of pcLEDs. For Structure A, the phosphor gel is coated above the LED chip and keeps uncured, so the phosphor sedimentation only happens above the LED chip. For Structure B, the phosphor gel is firstly coated above the LED chip and immediately began to cured at 15 °C for 1 hour, then the phosphor gel is coated outside the LED chip and keeps uncured. As a result, the phosphor sedimentation only happens outside the LED chip. Structure C represents the conventional structure, in which the phosphor gel is coated on the whole LED chip and the substrate and keeps uncured, so the phosphor sedimentation happens above and outside the LED chip simultaneously.

To capture the optical performance of pcLEDs from uniform distribution to complete sedimentation, we applied an online testing experimental setup. Fig. 2 schematically shows the experimental setup, it consists of an attemperator, an LED module, an integrating sphere of 1 meter in diameter (ATA-1000) and a detector which is connect with a spectroradiometer to record the CCT and LE of LED modules. The dimensions of LED chip and the cylindrical substrate are 1×1 mm^2 and 3.0 mm in diameter. Due to the edge confinement effect, the phosphor gel is restricted within the cylindrical substrate.

Phosphor particles were sufficiently blended with transparent silicone matrix to form the phosphor gel and the phosphor concentration was controlled at .1g/ml. Phosphor particle is produced by Intematix (YAG-04) with averaging diameter of 13 μm and silicone is produced by Dow Corning (OE-6550 A/B).

In the experiments, the LED module was fixed on the attemperator at 25°C, then the phosphor gel was coated onto the LED module using the dispensing coating method. Fig. 3 shows the phosphor layer geometries of the Structures A and B. For Structure A, the coating volume above the LED chip is 1 μL; for Structure B, the coating volume above and outside the LED chip are 1 μL and 3 μL, and the cured phosphor gel geometry above the LED chip is same as Structure A. The coating volume of structure C is 4 μL and its overall phosphor geometry is same as Structure B.

After the phosphor gel reaches to its stable geometry, we started measuring the optical performance of LED sample every 30s until it remains unchanged. By such a method, the optical performance of pcLEDs under various phosphor distribution was obtained. In our measurement, we mainly tested the CCT and LE of LED samples to characterize the effect of phosphor sedimentation.

III. OPTICAL SIMULATIONS

To further explore the physical mechanism behind the experimental phenomena, we analyzed the phosphor sedimentation effect on the ACU and LID by optical simulations. Here, we adopted the successful multi-layer model based on Monte Carlo ray-tracing method established in our previous papers [15], [16]. Fig. 4 shows the multi-layer phosphor models of the three samples, including a conventional blue LED chip, substrate and phosphor layer. The structure and the parameters of the LED chip were set as same as [17]. The

TABLE I

THE PROPERTIES OF EACH LAYER

Layer	VF	Phosphor concentration for each case (g/ml)						
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
1	0.05	0.1	0.5	0.9	1.3	1.7	1.9	2
2	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0
3	0.1	0.1	0.1	0.1	0.1	0.1	0	0
4	0.2	0.1	0.1	0.1	0.1	0	0	0
5	0.2	0.1	0.1	0.1	0	0	0	0
6	0.2	0.1	0.1	0	0	0	0	0
7	0.2	0.1	0	0	0	0	0	0

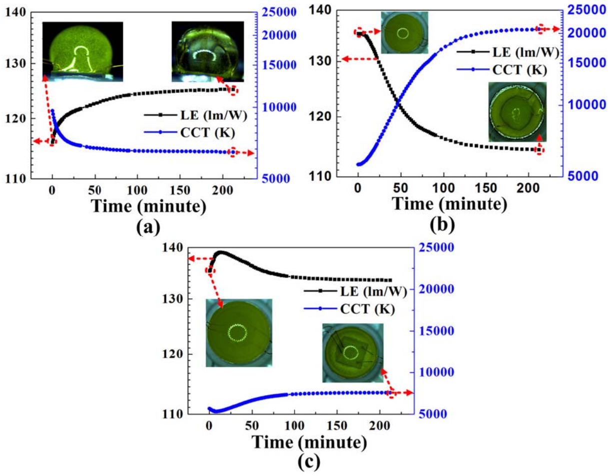

Fig. 5. Time evolution of the CCT and LE of the three packaging structures: (a) Structure A, (b) Structure B and (c) Structure C.

phosphor layer geometries of the three structures were set as the same as experiments. The previous multi-layer phosphor models are less than 3 layers [14]–[16] which is not enough for characterizing the whole sedimentation process. In this study, we further divided the phosphor layer into seven layers, and the phosphor concentration of each layer are listed in Table 1. The volume fraction (VF) of each layer is defined as the ratio of the volume of the layer to the volume that above/outside the LED chip. According to [16], the total quality of phosphors was kept as constant in each case. In each layer, the phosphors were assumed to be uniformly distributed with diameter of 13 μm.

IV. RESULTS AND DISCUSSIONS

Fig. 5 shows the time evolution of the luminous efficacy and CCT of the three packaging structures. For each structure, ten LED modules were packaged, and the average CCT and LE were calculated. The results of Structure A and Structure B show that the phosphor sedimentation happened above the LED chip decreases the CCT, while the phosphor sedimentation happened outside the LED chip increases the CCT. While in Structure C, the CCT decreases at first and increases soon afterwards. The luminous efficiency shows the opposite trend to the CCT curves. We define the CCT variation as the ratio of the deviation of the maximum CCT and minimum CCT to the initial CCT. Similarly, we also define the LE variation. For Structure A, B and C, the LE variations are 8.02%, 15.50% and 4.08%, and the CCT variations are 33.19%, 269% and 39.62%, respectively.

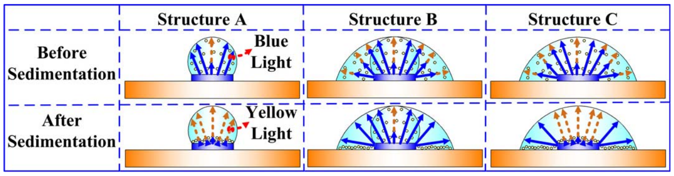

Fig. 6. Light emission of the LED modules with the three packaging structures before and after the phosphor sedimentation process.

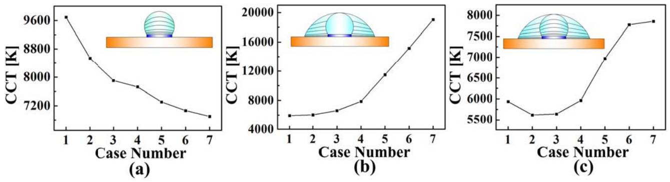

Fig. 7. Simulated CCT of the three packaging structures under each case: (a) Structure A, (b) Structure B and (c) Structure C.

Fig. 6 schematically shows the light emission of the LED modules with the three packaging structures respectively before and after the phosphor sedimentation process. For Structure A, the phosphor sediment to a thin layer on the LED chip, and almost all the blue light will propagate across the thin phosphor layer, leading to higher percentage of yellow light and lower CCT [1]. For structure B, the phosphor sedimentation happens just outside the LED chip, thus more blue light will directly emit without propagating across the phosphor layer especially for the side-emitting blue light, leading to higher CCT at large viewing angle. For structure C, it sits between Structure A and Structure B, so its CCT decreases at first and increases soon afterwards. More detailed mechanism and quantitative discussion on the trend of CCT and LE will be presented later based on the simulations.

Fig. 7 shows the simulated CCT of the three packaging structures under seven cases as shown in Table 1. Comparing the simulated and the experimental results, we can see that the multi-layer phosphor models can capture the similar trend of CCT of the three structures as those in the experiments. For Structures A, B and C, the simulated CCT variations are 28.77%, 22.86% and 37.75%, respectively, which are comparable to those in experiments.

Fig. 8 shows the blue and yellow LID of the three structures under Cases 1, 3, 5 and 7. The LID curves of Cases 2, 4, and 6 are in between and we neglect these curves only for clearer clarification. It is seen in Fig. 8(a) that as the phosphor sedimentation happens in Structure A, the blue light intensity decreases while the yellow light intensity increases, resulting in the increase of CCT. For Structure B, as shown in Fig. 8(b), the blue light intensity increases while the yellow light decreases, so leading to the decrease of CCT. Fig. 8(c) shows the LID of Structure C, and it is seen that the blue light intensity increases, while the yellow light intensity increases firstly and then decreases. As a result, the CCT decreases firstly and increases afterwards, which is consistent with Fig. 5(c) and Fig. 7(c). To analyze the ACU performance, we first define the YBR as the ratio of the yellow light intensity to the blue light intensity, and then the ACU is defined as

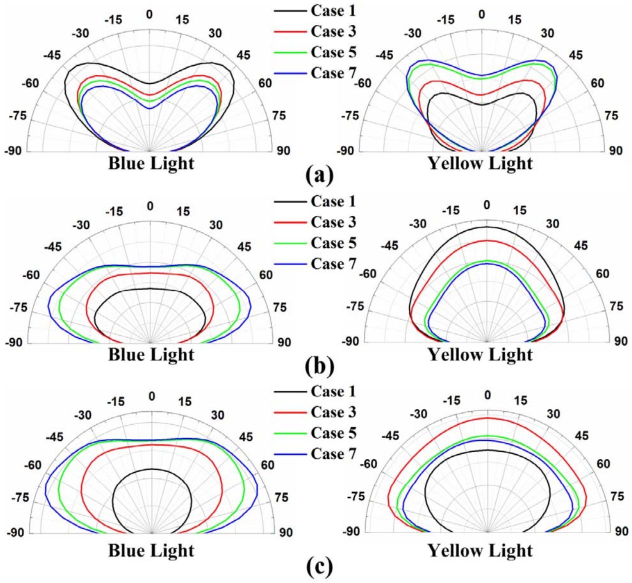

Fig. 8. Blue and yellow light intensity distribution of the three structures under Cases 1, 3, 5 and 7: (a) Structure A, (b) Structure B and (c) Structure C.

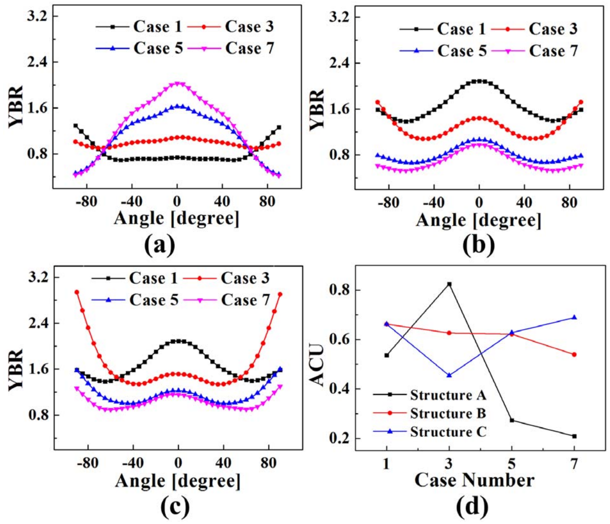

Fig. 9. YBR distribution and ACU performance of the three structures under Cases 1, 3, 5 and 7: (a) YBR of Structure A, (b) YBR of Structure B, (c) YBR of Structure C and (d) ACU performance of the three structures.

the ratio of the minimum YBR to the maximum YBR. The corresponding YBR and ACU performances of the three structures under Cases 1, 3, 5 and 7 are shown in Fig. 9. It is seen that the phosphor sedimentation happened above the LED chip enhances the ACU in the beginning of phosphor sedimentation and then deteriorate the ACU afterward, while the phosphor sedimentation happened outside the LED chip deteriorate the ACU monotonously. Besides, for the conventional packaging structure shown as structure C, as the phosphor sedimentation happens, the ACU turns worse firstly and better afterward, the ACU of Cases 1, 3, 5 and 7 were calculated as 0.66, 0.45, 0.63 and 0.69 respectively.

V. CONCLUSIONS

In this study, we investigated the dynamic phosphor sedimentation effect on the optical performance of pcLEDs with dispensed phosphor layer. Three packaging structures were taken into consideration. The results show that the phosphor sedimentation happened above the LED chip enhances the blue-yellow light converting possibility, while the phosphor sedimentation happened outside the LED chip lower the possibility. Therefore, for saving the usage of phosphor in LED packaging, the phosphor sedimentation above the LED chip should be promoted, while the phosphor sedimentation outside the LED chip should be restrained. This study provides a deeper understanding of the phosphor sedimentation effect on the optical performance of pcLEDs, it is helpful for designing pcLEDs with high optical performance.

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