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Improvement in optical performance and color uniformity by optimizing the remote phosphor caps geometry for chip-on-board light emitting diodes

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ABSTRACT

The remote phosphor caps (RPCs) have been studied theoretically and experimentally based on chip-on-board (COB) devices. We have investigated the effect of RPCs on the blue light and the yellow light emission distributions by ray-tracing. Moreover, the geometry of RPCs have been optimized to simultaneously achieve an excellent optical performance and color uniformity. Corresponding to simulation results, both the optimized (conical shape without straight side) and the reference (semi-spherical shape with straight side) RPCs have been manufactured by the compression molding method. These RPCs were assembled to the same blue COB source and then the COB devices have been measured. Compared with the reference RPC, the optimized RPC is able to significantly increase the radiant power and the luminous flux by 15.9% and 17.0% at a driving current of 350 mA, respectively, and it can also decrease the standard deviation of the correlated color temperature (CCT) by 48.9% for a total CCT about 4800 K. Hence, the proposed RPCs can provide a superior improvement in optical performance and color uniformity to COB devices.

1. Introduction

With the phase-out of the traditional light source with low luminous efficiency and high energy consumption, white light-emitting diodes (WLEDs) has been widely used to the lighting applications given their advantages such as long life and low environmental impact [1]. To satisfy the demands on various lighting applications, it's significantly necessary to improve the optical performance [2] and color quality [3] of WLEDs. At the present, it's one of the most important technique to generate white light by stimulating the phosphor layer (PL) through blue LED chips, and the PL is generally consisted with phosphor powders and silicone. Since the PL has strong scattering and absorption effect, its structure has great influence on WLEDs optical performance and color quality, especially in terms of the luminous flux (LF) and the color uniformity (CU). Generally, the conformal structure of the PL helps to achieve a high CU as the blue light emitted from LED chips can be uniformly and entirely scattered by the PL [4–6]; however, it's difficult to achieve a high LF simultaneously because of the serious backward scattering effect in the PL [7,8]. To reduce the probability that the back scattered light is absorbed by LED chips, the remote structure of the PL introduces an isolated layer to discrete the PL and LED chips, which is one of the most promising method to improve the performance of WLEDs [9,10], especially the LF [11–14] and the thermal stability [15,16]. In order to achieve a higher LF and CU simultaneously, the remote structure of the PL has been widely studied. On one hand, the remote hybrid structure of the PL is put forward, which combines the remote PL with special optical elements such as the micro-patterned film [17], the ZrO_2 nanoparticles coating [18] and the light-recycling filter [19]. But it's not convenient to manufacture WLEDs with these additional optical elements by the traditional packaging technique. On the other hand, it has been more common to investigate the geometry of remote PLs [20–23], which is effective to improve the *LF* and the *CU* of WLEDs.

These studies on the PL mentioned above are all based on the discrete components which is commonly comprised of a single LED chip, lead frame and ensapsulant. Practically, the multiple discrete components are demanded to achieve sufficient LF by surface-mounting assemble, which simultaneously forms the

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multi-shadow pattern [24] and decrease the lighting quality. Contrarily, chip-on-board (COB) devices [25] can obtain a sufficiently high LF by utilizing only one source, avoiding complex assemble processes and the multi-shadow pattern in illumination areas. There are also some studies focusing towards the PL of COB devices in order to further improve its optical performance. Huang [26] has formed the PL on a plastic substrate with micro line lenticular arrays, greatly improving the LF and the CU of lighting systems with COB devices. Kuo [27] has improve the CU of COB devices by coating a micro-cone patterned PDMS film on the PL. Chen [28] has designed a microscale-roughness-controlled-surface module to simultaneously achieve high optical and chromatic uniformity of lighting modules with COB devices. Similar to the discrete components, it's somehow difficult to obtain these optical elements, which potentially increase the manufacture cost of COB devices. Generally, it's more common to manufacture COB devices improved by the optimized PL geometry instead of special optical elements on the basic of the traditional packaging technique. Though there have been lots of studies focusing on the PL geometry according to discrete components [20–23], studies focusing on the PL geometry based on COB devices are barely found, especially for remote PLs. This has extremely limited the improvement in the optical performance and color quality of COB devices. Recently, Wang [15] has found that COB devices with remote PLs is able to achieve a much higher LE, CU and thermal stability compared with the multiple discrete components, which foreshadows a possible improvement in the optical performance and color quality of COB devices by investigating their remote PLs. In this paper, the remote phosphor caps (RPCs) have been studied theoretically and experimentally based on COB devices. We have investigated the effect of the phosphor concentration and the thickness of RPCs on the optical performance of COB devices by ray-tracing, mechanisms of the emission light affected by RPCs are discussed. Furthermore, we have optimized the straight side height and the radius of RPCs in order to gain a high LF and CU. Finally, the optimized and the reference RPCs have been manufactured by the compression molding method, COB devices with these RPCs were measured and discussed.

2. Experiment and simulation setups

RPCs were manufactured by the compression molding method, as shown in Fig. 1(a). Both the terrace die and concave die were pre-adhered with less surface energy coating (LSEC) in order to release conveniently, then the phosphor slurry consisted with YAG:Ce phosphor [29] and silicone was uniformly injected upon the concave die preheated to 80 °C. Meanwhile, the terrace die was pressed to close the cavity between two dies with a constant force 55 kN. After that, the phosphor slurry was immediately cured at a temperature of 130 °C for 400 s in order to preform RPCs and minimize the effect of the phosphor settling [30]. It should be noticed that the vacuum of the cavity between two dies was kept by vacuum pumps during preheating and curing processes, avoiding the formation of air bubble inside RPCs. Finally, dies were released and RPCs were transferred to be entirely cured at the oven at a temperature of 150 °C for 3 h. On the basic of this method, RPCs with various geometry can be conveniently manufactured through reasonable designs of dies, as shown in Fig. 1(b). Moreover, RPCs were assembled to the same COB source that was packaged by the silicone and with 42 square-shaped and horizontal blue LED chips. COB devices with these RPCs, which were mounted to a heat sink in order to minimize the effect of the increased junction temperature, were then spectrally measured with an integrating sphere from Instrument System. The drive current was provided by a Keithley adjustable DC source. The radiant power, luminous flux, typical spectrum at a drive current of 350 mA, and the CCT as well as its angular distributions were measured.

To study the effect of RPCs on the radiant efficiency *RE* (the ratio of radiant power to electrical power) and color uniformity *CU* of COB devices, the commercial software Tracepro was adopted to conduct optical simulations, the model of COB devices is shown in Fig. 2. The RPC was mixed with silicone (refractive index (RI) 1.54) and YAG phosphor (RI 1.78, mean particles size 16 μm, a single peak emission wavelength 565 nm), its scattering, absorption cross-sections, and scattering phase function were achieve by the finite difference time domain (FDTD) method [31]. The COB was packaged by the silicone and it has a circular light-emitting surface which was produced by horizontal blue LED chips (size 0.76 × 0.56 mm, a single peak emission wavelength 455 nm) distributed in a 6 × 7 array. What's more, the horizontal blue LED chip was simplified to be consisted with p-GaN (RI 2.43), MQW (RI 2.37), n-GaN (RI 2.43), sapphire substrate (RI 1.8) and reflection layer (reflection 95%); the MQW layer has an absorption coefficient of 0.8 mm^{-1} [32]. The output radiant power from the MQW layer of each LED chip is 1 W in our model (totally 42 W for a COB source). Besides, the reflection of the base mounting surface was assumed to be 80% and a spherical detector was 500 mm far from the center of the COB device. Subsequently, this model was used to study the

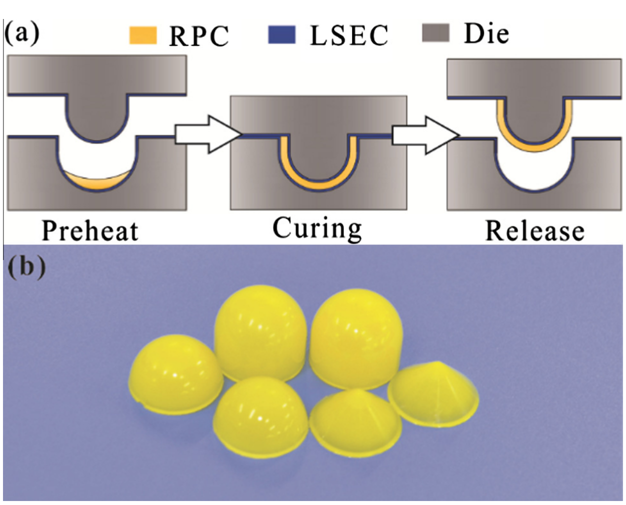

Fig. 1. (a) The compression molding process of remote phosphor caps (RPCs) and (b) the RPCs manufactured by compression molding.

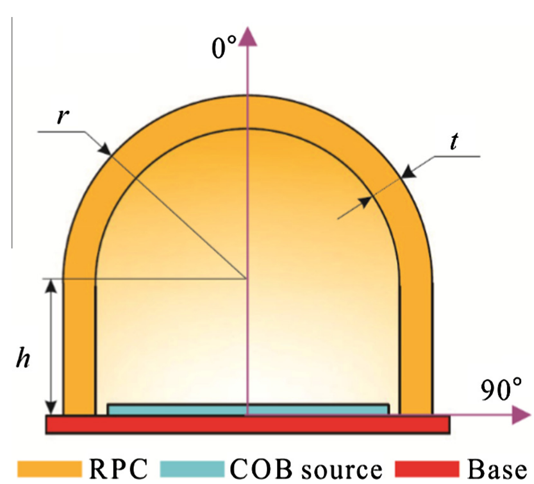

Fig. 2. Model of the COB device with a remote phosphor cap (RPC).