# Patterned structure of REMOTE PHOSPHOR for phosphor-converted white LEDs

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**Abstract:** High efficiency white light-emitting diodes with superior color-mixing have been investigated. It is suggested that the patterned remote phosphor structure could improve the uniformity of angular-dependent correlated color temperature (CCT) and achieve high chromatic stability in wider operating current range, as compared to the conventional remote phosphor coating structure. In this experiment, we employed a pulse spray coating method to place the patterned phosphor on the package and to leave a window region. The window area, a clear space without coating of the phosphor not only increases the extraction efficiency of blue rays at large angle, but also improves the stability of angular-dependent CCT. Moreover, the CCT deviation could be reduced from 1320 K to 266 K by this patterned remote phosphor method, and the stray blue/yellow light within the package can be effectively reduced and controlled. The design was verified both experimentally and theoretically.

**OCIS codes:** (230.3670) Light-emitting diodes; (230.2090) Electro-optical devices

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## 1. Introduction

Solid-state lighting (SSL) for highly efficient white light-emitting diodes (LEDs) has been vigorously developed to replace traditional lighting sources [1]. Generally, white LEDs are fabricated by three methods: 1) individual color-mixing: using LEDs of different colors to generate broad visible spectrum, such as blue (B) + green (G) + red (R) LEDs, or B + G + R + yellow (Y) LEDs [2]; 2) ultraviolet (UV) LEDs with different colors of phosphor: a short-wavelength LED providing activation energy that excites different phosphors for wavelength conversion to create a perceived white spectrum [3] ; and 3) blue-LEDs with yellow phosphors, also known as phosphor-converted white light-emitting diodes (pc-WLEDs). Among these three technologies, the first one bears high manufacturing costs and difficulties in stable color mixing, which are not favorable for mass-production. The second one suffers poor conversion efficiencies for all different phosphors. In addition, high power devices are difficult to achieve. The third method can offer not only high conversion efficiency but also easy manufacturability and thus provides one of the most important sources for the future application.

For the pc-WLEDs, blue or UV InGaN LED chip can excite YAG:Ce$^{3+}$ phosphor and generate the broadband emission spectrum of visible lights. In generic pc-WLED configurations, the yellow-emitting phosphor powders were mixed with transparent encapsulated resin and then dispersed in a cup reflector or directly coated on the LED chip surface. Even though the latter direct dispensing method is the most common approach in mass production; however, in some types of phosphors, an increase in LED device temperature could shift the excitation wavelength and affect the downconversion process. The conversion efficiency of this type of package then suffers from propagation energy losses and thermal effect caused by the LED chip. It has been shown that nearly 60% re-emitted yellow rays are backscattered to the LED chip, which seriously decreases the luminous flux [4]. To alleviate this problem, an efficient extraction of back-transferred and chip-emitting lights are very important. Hence, an inverted cone lens encapsulant and a surrounding ring remote phosphor layer were developed. This so-called "ring remote" phosphor structure could reduce the probability of the backward light from the phosphor layer to the absorptive LED chip [5,6]. In order to solve the low output power under high-current operation condition caused by the thermal problem, a phosphor with thermal-isolated package has been demonstrated [7]. This thermal-isolated encapsulant material can effectively reduce heat transfer from the LED chip to the phosphor coating layer; therefore, the phosphor with the cooling method can be an effective way to improve luminous efficiency and to decrease the color variation. In addition, a scattered photon extraction (SPE) package which was developed by Narendran, et al. could enhance the extraction efficiency by 61% over that of conventional phosphor-converted white LEDs [8]. Kim et al [9] also demonstrated that a package with highly diffused cup can increase the light extraction efficiency and reduce the re-absorption issues in the remote phosphor scheme.

Previous approaches to achieve remote phosphor structures utilize two-step method. The first step is to dispense the transparent encapsulant filled up to certain portion of the package and then bake in a chamber to harden the encapsulant. The second step is to dispense the phosphor slurry on the hardened encapsulant, so that the phosphor particles were kept in a certain distance from the blue LED chip. However, during the process, the encapsulant surface is generally a concave surface because of the capillary phenomena, which would cause the inhomogeneous phosphor thickness in the package. The longer excitation optical paths in larger angle cause more downconversion yellow rays, thus extra yellow light in the perimeter of the LED [10,11]. In addition to the yellow ring effect, since the phosphor fully covers the surface of package, numerous blue and/or downconversion yellow photons are

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trapped in the package. While the packages could use extra lens for mixing the inhomogeneous angular-dependent CCT, it would increase the cost and decrease the lumen flux.

In this study, we proposed a patterned remote phosphor structure based on a remote phosphor concept. The most obvious difference between the conventional and patterned remote phosphor structure is that the phosphor in the latter structure keeps a clear region in the perimeter area without coating phosphor on the surface surrounding. This clear region is designed not only to improve extraction of blue rays at large angle, but also to reduce the angular-dependent CCT deviation.

## 2. Experiment

In this investigation, the conventional and patterned remote phosphor structures were prepared by pulsed spray coating. The purpose of method is to press on the process convenience without chemical pollution and the suitability to fabricate the large-area and planar illumination system, as demonstrated previously [12]. Because the pulse spray coating can uniformly spray the phosphor slurry layer by layer, the CCT can easily be controlled. First of all, the $YAG:Ce^{3+}$ phosphor powders were sufficiently blended with silicone binder and alkyl-based solvent in the ratio 1:1:2.5 to form phosphor suspension slurry. The sprinkle-nozzle sprayed out the blended phosphor by compressed air, and the curl wind in the chamber was designed to achieve high uniformity. The LED lead-frame size is 5 mm by 7 mm, and the chip size is 24 mil square chips with a thickness of 220 μm. The blue LED chips were bonded on silver glue with gold wire to bond pad and then the radiant flux was measured. The radiant fluxes of all packages with bare blue LED chips were selected to be 123 mW at 150 mA to ensure the same initial condition for all remote phosphor structures. The conventional remote phosphor structures was directly sprayed with the $YAG:Ce^{3+}$ phosphor seven times onto the package with transparent hardened encapsulant resin. The patterned remote phosphor structure was formed by spraying the phosphor-contained solvent onto a hardened encapsulant resin surface with a circular shape mask. Thus, the surrounding area of package surface was left, and looked clear and transparent. Because the phosphor-covering ratio of the two structures was different, the same thickness of the sprayed phosphor could not achieve the same CCT.

To better compare these two structures, we controlled the color chromaticity coordinate located at (0.33 ± 0.003, 0.34 ± 0.003) based on CIE 1931 RGB color system at 150 mA injection current. Because the luminous flux of LED package is not only affected by color temperature but also the color chromaticity coordinates. Too large discrepancy of color chromaticity coordinates should not be regarded as representative samples for comparison, even located at the same CCT.

## 3. Measurement and analysis

The phosphor distribution of the two samples discussed in this work was observed by X-ray perspectives. Figure 1(a) shows the conventional remote phosphor structure; having a phosphor layer sprayed on top of the encapsulant resin surface. Because the phosphor was located away from the blue LED chip, it is suggested that the thermal quenching effect of the phosphor can be mitigated. However, there are many back-scattered yellow rays that can be reabsorbed by either blue LED chip or phosphor itself and will eventually be lost after a few times of reflection inside the pc-WLED package. In addition to the ray-trapping inside the pc-WLED package, the optical path difference of excitation blue rays in larger divergent angle could cause unstable angular-dependent CCT. The patterned remote phosphor structure, shown in Fig. 1 (b), was proposed to mitigate the unstable angular-dependent CCT and to minimize the light rays reabsorbed, simultaneously. We designed to leave a window region to extract the large angle of blue rays and mix with yellow rays to eliminate the angular-dependent CCT.

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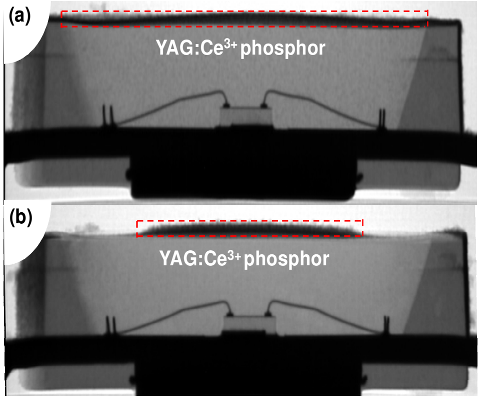

Fig. 1. X-ray perspectives of two phosphor distribution models: (a) conventional remote phosphor structure, showing phosphor on top of the encapsulant surface (b) patterned remote phosphor structure, leaving a window region without spraying phosphor.

Due to the engineering technical limitation, even when we utilized a pulsed spray approach to achieve remote phosphor structure, maintaining thickness uniformity of phosphor in large area was still difficult to achieve. The realistic conventional remote phosphor distribution on top of surface is shown in Fig. 1 (a); seem to have the phosphor in the center thicker than surrounding area. The non-uniform phosphor is suggested to cause yellow ring after turn on the pc-WLED. Even though the yellow ring could be solved by secondary optical mixing such as fog the lens or Fresnel lens, it would cost extra expense and energy loss in those modifications. The patterned remote phosphor structure is proposed to deal with the stability of angular-dependent CCT. In Fig. 2, if we consider the angular-dependent CCT from −80 to 80 degrees, the CCT deviations of the conventional remote phosphor and patterned remote phosphor structures were 1302 K, 266 K, respectively. It was obvious that the angular-dependent CCT of patterned remote phosphor structure was more uniform in larger angle distribution from the measurement data. When the blue rays travel too far into the resin, which happens to large angle diffraction of photons, the portion of down-converted yellow light will rise due to longer light path and higher absorption of phosphor. If the yellow photons take higher percentages, a lower CCT light will show up around the outer perimeter of the package, which is usually called the “yellow ring”. In our patterned mask design, most of large angle of blue rays and backscattering yellow rays exit the package via the window region, which was not completely covered by the patterned phosphor layer. Thus, we could keep the intensity ratio of yellow to blue rays ($I_{yellow}/I_{blue}$) with good constancy as compared to the conventional remote structure in larger divergent angle. Consequently, the yellow ring phenomenon can be solved via patterned remote phosphor structure.

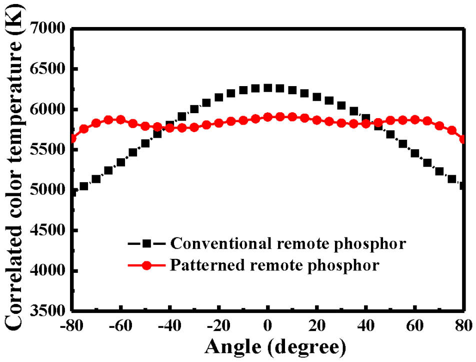

Fig. 2. The angular-dependent correlated color temperature of two phosphor distribution structures.

In order to further understand optical characteristic for both remote phosphor structures. We measured the current-dependent luminous flux and calculated the luminous efficacy. In Fig. 3, it is clear that luminous flux and luminous efficacy of patterned remote phosphor slightly decrease by 1.38% and 1.12% at driving current of 150 mA, compared to the conventional remote phosphor structures. To achieve the same color chromaticity to compare with both samples, the patterned remote phosphor structure has thicker phosphor layer than the conventional phosphor layer, as shown in Fig. 1. Because the patterned phosphor layer did not cover all over the surface of the package, the extra phosphor silicone deposition due to mask during the spray is possible and thicker phosphor layer can be seen near the center of package (as shown in Fig. 1(b)). When blue rays pass through thick phosphor layer, most of down-converted yellow rays could be trapped and re-absorbed, which could cause slightly lower total luminous flux and luminous efficacy. In the future work, the patterned remote phosphor structure could be further optimized for the shape and thickness of phosphor layer and reduced concentration of phosphor to improve total luminous flux.

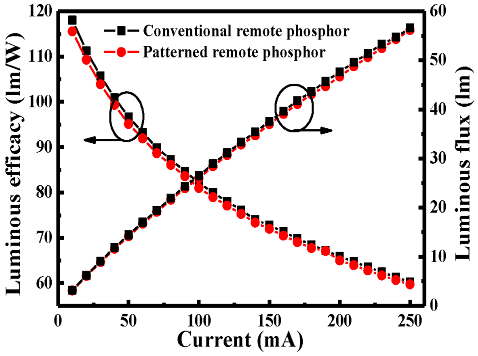

Fig. 3. The current-dependent luminous efficacy and luminous flux of the pc-WLEDs with conventional remote phosphor and patterned remote phosphor structures.

We also examine the color chromaticity coordinate deviations with increasing LED driving current. As observed in Fig. 4, both the conventional and patterned remote phosphor structures show some color chromaticity coordinate shift from 0 to 250 mA. Since both structures belong to remote phosphor model, there should be less thermal quench issue caused by phosphor [13]. We attribute the current-dependent chromaticity coordinate shift to the different phosphor coating thickness. The patterned remote phosphor structure with thicker phosphor shows a smaller color shift, which indicates this structure is more stable at high blue light excitation. This insensitivity of CIE coordinates against driving current can be reasoned as follows. The amount of down-converted yellow photons changes the CCT at various currents, and since we have a patterned phosphor distribution, most of large angled blue rays are not converted at all current levels. These constant blue photons can help to neutralize the variation brought by the centered converted light. Therefore, the conventional remote phosphor structure with thin phosphor coating has worse color mixing structure, although the luminous flux and luminous efficacy of conventional structure are slightly higher than those of the patterned remote phosphor structure. Nowadays, the lighting applications require not only the lumen output (lumen per Watt), but the light quality such as angular-dependent CCT. Therefore, it is important to keep the uniformity of CCT over the entire LED device area.

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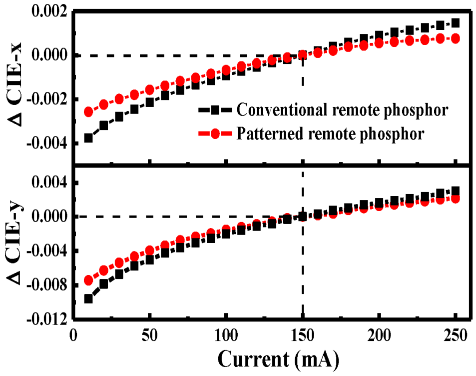

Fig. 4. The color chromaticity deviations of the LED with conventional remote phosphor and patterned remote phosphor structures with different LED injection current.

## 4. Simulation

We use SPEOS software based on Monte Carlo method to simulate both of conventional remote phosphor and patterned remote phosphor structures. In ray tracing simulation, we assume the parameters $n_{\text{phosphor}} = 1.82$, $n_{\text{silicone}} = 1.54$, $n_{\text{free space}} = 1.0$ (above package) and silver reflectance $R_{\text{Ag reflector}} = 95\%$, $n_{\text{blue chip}} = 2.4$, LED chip thickness of 220 µm, area of 24 mil square. For the patterned remote phosphor structure shown in Fig. 5 (b), we could see blue rays emit directly in large divergent angle and part of backscattering yellow rays escaped through the clear surface surrounding. In contrast, for the conventional remote phosphor structure with thinner coating phosphor, blue rays concentrate in normal direction and pass through without converting to yellow rays. We also calculate the angular-dependent the intensity ratio of yellow to blue rays ($I_{\text{yellow}}/I_{\text{blue}}$) as shown in Fig. 6, the conventional remote phosphor structure has non-uniform ratio deviation. However, the patterned remote phosphor structure keeps high ratio consistency from zero to 70 degrees. These results correspond well to what we observed in the experiment, and the conventional structure has worse geometric color mixing effect compared to the patterned remote phosphor structure.

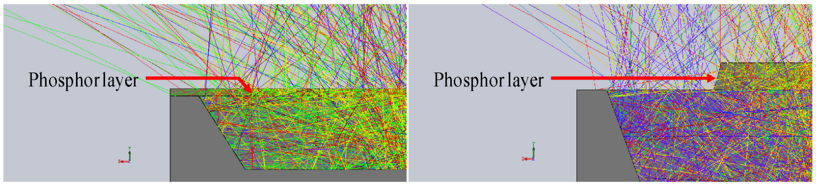

Fig. 5. The ray tracing simulation results: (a) The left is conventional remote phosphor structure (with thin phosphor coating on package entire surface) and (b) the right is patterned remote phosphor structure (with thicker phosphor coating only in the center region).

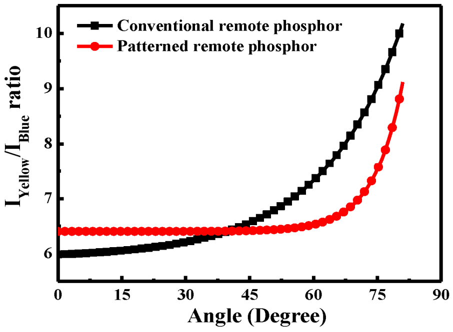

Fig. 6. The angular-dependent intensity ratio of yellow to blue rays. The conventional remote phosphor structure has serious ratio deviation. However, the patterned remote phosphor structure keeps high consistency even at the divergent angle close to 70 degrees.

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## 5. Conclusion

In this study, we effectively reduced the angular-dependent variation of CCT by patterned remote phosphor coating technique. We believe that the larger angle CCT deviation could be modified by reflected and/or directly transmitted blue rays from the surface, and the clear window region on the top can serve this important function. Even though the luminous flux and lumen per Watt were slightly lower than those of the conventional design, it is still within the range of tolerance. On the other hand, the uniformity of angular-dependent CCT is greatly improved, which is very important to achieve for high quality of lighting. Through the implementation of this novel design and also the improvement of the bare chip performance, we believe good solid-state lighting sources can be realized in near future.

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