An Investigation of the Optical Analysis in White Light-Emitting Diodes With Conformal and Remote Phosphor Structure

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***Abstract*—An effective emission model of phosphor film is proposed by using bidirectional scattering distribution function system (BSDF), and the model is verified by white light-emitting diodes (LEDs) with conformal and remote phosphor structure. The emission model is built to clarify the optical characteristics by analyzing the angular-dependent distribution of emission and excitation behaviors in phosphor film. The white LEDs with conformal and remote phosphor structure are also fabricated for experimental comparison. The uniformity of angular correlated color temperature (CCT) in white LEDs can be determined by the angular distribution of blue and yellow light, which is in turns decided by the refractive index variation between chip a©nd phosphor layers. Finally, the experimental results are found to have good agreement with the simulation results performing by the Monte Carlo method.**

***Index Terms*—GaN, light-emitting diodes (LEDs), optical simulation, phosphor.**

I. INTRODUCTION

RECENTLY, white light-emitting diodes (LEDs) have been regarded as the next-generation light source due to the small size, environmental friendly process as well as high luminous efficiency [1]–[3]. In general, combining the blue LED chip with the yellow luminary such as $Y_3Al_5O_{12}$ phosphor is the most promising method to generate the white light [4], [5]. For the significant progress in phosphor-converted white LEDs had been strongly motivated by the advances in III-Nitride LEDs [6]–[14] serving as pump excitation sources. The availability of high performance nitride LEDs enables the practical implementation of phosphor-based LEDs. The advances in III-Nitride LEDs had been attributed to the new approaches for reducing the charge separation issues in active region [6]–[8], methods for suppression of efficiency-droop [9], [10], and growth methods to suppress the dislocation density in materials [10]–[14]. Furthermore, for the fields of phosphors, there are also some novel materials developed to use in the solid-state lighting such as oxyfluoride [15], nitride [16], boride [17] and phosphide [18] hosts. As the results, in order to meet the practical need in the solid state lighting, high luminous efficiency and uniformity of angular-dependent correlated color temperature (CCT) become two major challenges to overcome in white LEDs [19].

For the high luminous efficiency, remote phosphor packages which separate the phosphor layer away from the chip could effectively reduce the backscattering and exhibit higher conversion efficiency, and many examples were demonstrated before such as the scattered photon extraction package and the ring-remote structure [20]–[23]. However, the disadvantages of remote phosphor structure such as concave surface and non-uniform angular CCT still exist. Therefore, the patterned structure of remote phosphor structure was proposed to improve the uniformity of CCT [24]. Conversely, for the highly uniform color distribution, conformal phosphor structure is found to be a more suitable way to improve the distribution of angular CCT [25], [26]. In this structure, the scattering and reflection characteristics of the phosphor particles are considered as the key parameters because it was shown that nearly 60% re-emitted light are reflected backward [27]. Therefore, large amount of light is reflected back and forth and eventually lost inside the package, resulting in the lower light output in the conformal phosphor structure.

The backscattering and reflection of light caused by phosphor could be minimized by optimizing the size of the phosphor particles [28]. Furthermore, Yamada *et al.* defined the transmitted and reflected flux of the blue and yellow light to build the phosphor film model [29] and Zhu *et al.* used the fiber-guided source to illuminate the characteristic of the phosphor slide [30]. Moreover, some research has simulated the relationship between particle size of phosphor and efficiency in different packages [31]. In general, the emission distribution of phosphor particle is usually regarded to be ideally isotropic to simplify the calculation in phosphor model. However, the scattering distribution in the phosphor layer usually disagrees with this assumption. Therefore, the bidirectional scattering distribution function system (BSDF) system is employed to measure the scattering phenomenon and provide the better understanding, which could be de-

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fined as the ratio of the scattering light radiance to the incident light irradiance, and defined as [32], [33]

$$\mathrm{BSDF}(\theta_i, \phi_i, \theta_s, \phi_s) = \frac{dL(\theta_s, \phi_s)}{dE(\theta_i, \phi_i)}$$

where the terms $(\theta_i, \phi_i), (\theta_s, \phi_s)$ are the incident and scattering direction angles with respect to the surface normal. It is used to describe the distribution of scattering light in the space with the angular and wavelength variable.

In this study, the emission model of phosphor film is investigated using BSDF system. Besides, the emission distribution of phosphor film and the analysis of emission distribution in remote and conformal phosphor are demonstrated. Then, the corresponding white LEDs with remote and conformal phosphor structure are both experimentally and numerically investigated. Finally, the refractive index at the air/phosphor layers interface is verified as a key factor leading to the intensity distribution of blue and yellow light in remote and conformal phosphor structures.

II. Experiment

The pulsed spray coating (PSC) method is adopted in the experiment to form a thin, uniform phosphor layer on the surface of the sample [34], [35]. First, the polyethylene terephthalate (PET) with transmittance of 90% is used as the substrate. Phosphor powder, silicone binder, and an alkyl-based solvent are blended together to form phosphor suspension slurry and sprayed onto the surface of PET. The thickness and weight-percentage of phosphor slurry was about 100 μm and 50 wt. %, respectively. The emission distribution of the PET with phosphor sample is measured by BSDF system. The PET films were applied for BSDF measurement due to the low cost, easy-to-cut sizes, and high transparency across the visible band. The glass material, which can provide a higher stability in thermal treatment and wider transparency, can also be considered for the measurement [36]. Once the BSDF measurement is finished, the final package is made of phosphor-doped silicone without any PET films to match the standard process. Furthermore, the diagrams of conformal and remote phosphor LEDs are shown in Fig. 1. For the both structures, the blue LED chips have peak emission wavelength at about 450 nm and are placed in the commercial plastic lead-frame package. For conformal structure, the phosphor slurry is sprayed in the lead-frame, then filling the silicone glue and baked at 150 °C for two hours. In remote phosphor structure, the silicone encapsulant is filled in the lead-frame and the PSC method is employed to perform phosphor coating on the top of the samples. These samples are driven at the 120 mA to measure the color temperature. The luminous efficiency of the conformal and remote phosphor structure was about 100 lm/W and 105 lm/W, respectively. When the luminous efficiencies of devices are put together for comparison, the remote phosphor structure is about 5% higher than the conformal phosphor structure at the same CCT.

III. Simulation

In the simulation, OpticsWorks software was used and based on Monte Carlo method incorporated with Mie scattering, which is common in the LED simulation [37], [38]. Fig. 3 shows the simulated structure of remote and conformal phosphor structure. The particle size distribution and the extinction coefficients of the phosphor and were considered as the important condition in the software. The particle sizes of phosphor are set as average diameter of 12 μm and a standard deviation of 0.5. The blue emission of LED chip and yellow emission of phosphor are set as 460 nm and 560 nm.

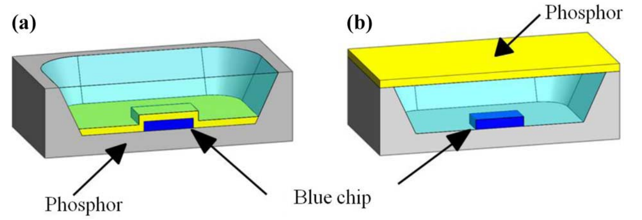

Fig. 1. Schematic diagrams of (a) conformal and (b) remote phosphor structure.

TABLE I
PARAMETERS OF STIMULATED LED CHIP

Item	Thickness (μm)	Refractive Index
Encapsulant (Silicone)	---	1.6
p-GaN	0.2	2.45
n-GaN	4	2.42
MQW	2.5	2.5
Phosphor	---	1.8

The simulated LED structures were composed of 4-μm-thick n-type GaN layer,multiple-quantum wells (MQWs) with 2.5-nm-thick wells and 200-nm-thick p-type GaN layer. The blue LED chips dimension is $0.61 \times 0.61\ \mathrm{mm}^2$ and the refractive indexes of n-GaN, p-GaN, and MQW are 2.42, 2.45, 2.54, respectively, as shown in Table I [39]. The reflectance of the surface in the leadframe was 90% [40]. The emission spectra of blue LED chip and the phosphor are centered at 455 and 560 nm, which are the same as the experiment. Moreover, for the phosphor model, the phosphor layer was simulated and calculated the scattering effect of photons through medium with particles. Furthermore, the distribution of emission obtained by experiments could input in the software to verify the results.

IV. Result and Discussion

In this study, BSDF system is employed to measure the distribution with different incident angle. First, the emission distributions of the blue chip and blue chip with and without silicone glue are measured and input into the simulation, as shown in Fig. 2(a). As a matter of fact, the angular intensity of the blue light from the LED chip can be directly measured, but the intensity of blue light emitting into the phosphor layer still could not be measured directly. Therefore, the intensity of blue light in the phosphor layer is simulated according to the previous information in Fig. 2(b). Meanwhile, the angular distribution of the blue light emitting into phosphor layer is narrow and this could be attributed to the different refractive index between interfaces.

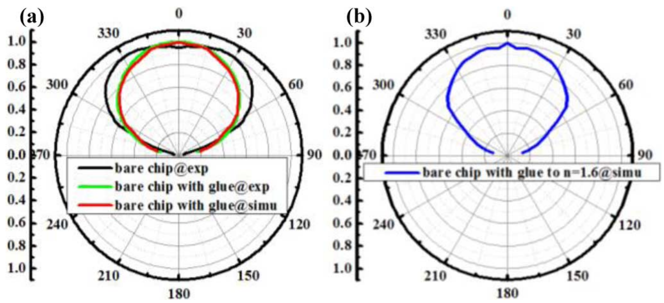

Fig. 2. Blue light intensity distribution of emitting into (a) glue (b) phosphor layer.

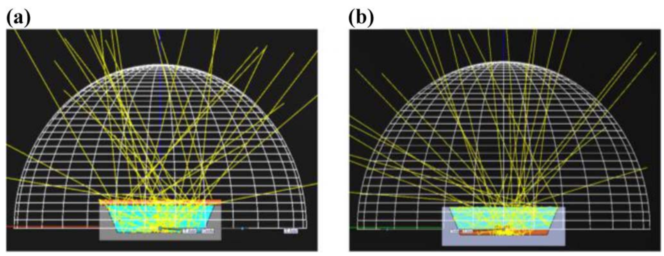

Fig. 3. Simulated structure of (a) remote (b) conformal phosphor structure.

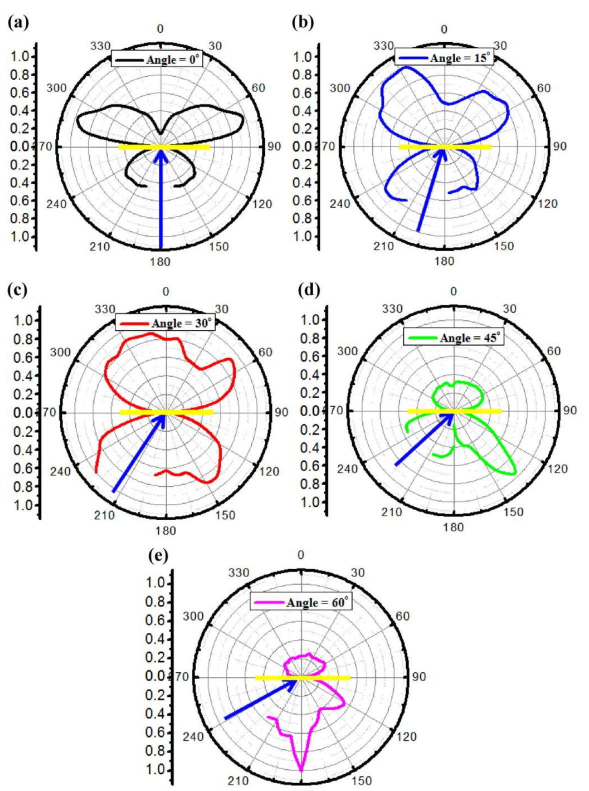

Fig. 4. Distribution of emission at different incident from 15° to 60°.

After identifying the distribution of blue light versus different interfaces including air, silicone glue and phosphor layer, the emission distribution of phosphor film is measured by using the collimated light source whose emission wavelength is about 450 nm. The emission distribution patterns from the phosphor film at different incident angles from 0° to 60° with interval of 15° are shown in Fig. 4.

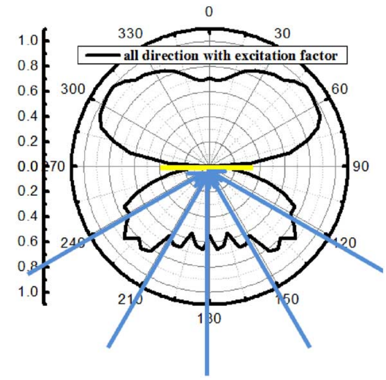

Fig. 5. Distribution of emission at all direction with the mixed of blue and yellow light.

The phosphor film could be rotated to measure the emission distribution at different incident angles and the angle between incident light and phosphor film is about 90-θ degree. For the normal incident light, the emission distribution demonstrates that the intensity at large angle is higher than that at small angle. Furthermore, with the larger incident angle, emission distribution is unsymmetrical due to the incident angle at the different angle.

We can further combine the data in Fig. 4 to obtain the graph in Fig. 5, which can be interpreted as possible outcome of a real chip. The excitation from different angles can simulate the all direction excitation of phosphors in a blue chip. Therefore, it is found that there is nearly 50% of light emit backward, which is similar to the results in [9]. This result could explain the emission behavior of the phosphor layer which is excited by a blue LED. Moreover, to verify this model, conformal and remote phosphor structure is demonstrated both numerically and experimentally as following in Fig. 6. The simulation results show good agreement with experiment both in the yellow and blue light.

Our statement on CCT can be also examined in previous publication that remote phosphor has the higher intensity than conformal phosphor structure, but the CCT distribution of conformal phosphor is much better than remote phosphor [39], [40]. As can be seen in Fig. 7, for conformal phosphor structure, the intensity of blue light is higher than remote phosphor structure at the large angle. However, the intensity of yellow light shows almost the same phenomenon in both remote and conformal phosphor structure. When putting their structure difference into consideration, we could see that the different distribution of material leading to different refractive index could be the key. Therefore, it might be reasonable to cast some calculation to verify it.

Moreover, the calculation of the refractive index (RI) in the different phosphor concentration, the RI of the phosphor layer with silicone is given by [43], [44]

$$RI = V_1 RI_1 + V_2 RI_2$$

where V_1 and V_2 are concentration of the materials. Here, the RI of silicone glue is 1.4 and the phosphor is 1.8. To verify the assumption in conformal and remote phosphor structures, the

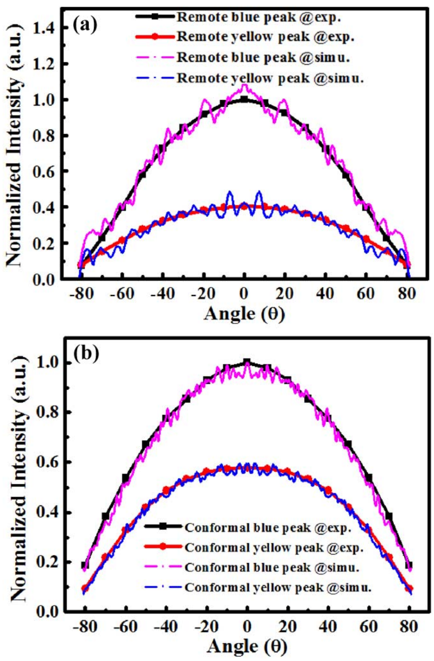

Fig. 6. Yellow and blue light intensity of (a) remote (b) conformal phosphor structure in simulation and experiment.

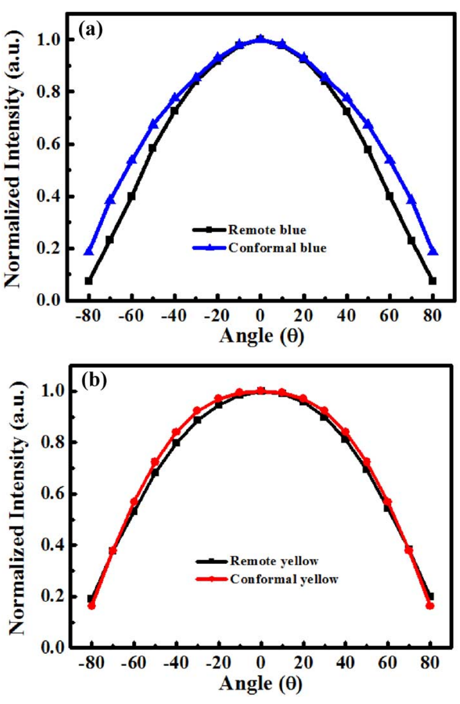

Fig. 7. (a) Normalized blue light intensity and (b) normalized yellow light intensity of remote and conformal phosphor.

different concentrations of phosphor layer for 20% and 85% in remote phosphor are fabricated.

The RI of the different phosphor concentration at 20% and 85% is about 1.74 and 1.48, respectively. It is obvious that the normalized intensity of blue light for the concentration of 20% is larger than 85% in the large divergent angle, as shown in Fig. 8(a). However, the yellow light still remain the same at the

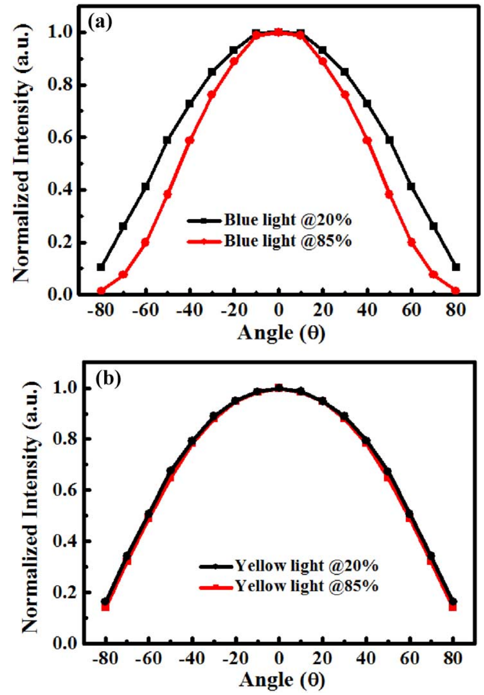

Fig. 8. Normalized intensity of different concentration: (a) blue light and (b) yellow.

both concentration in Fig. 8(b). According to Snell's law, the blue light, emitted into the air from the package, would cause a different divergence angle when passing through the different refractive index. Therefore, the smaller divergence angle could be attributed to the large discrepancy of the refractive index in the interface and the refractive index is the main reason to dominate the blue light intensity at large angle.

V. Conclusion

In conclusion, the emission model of phosphor film with BSDF system is investigated and verified both in conformal and remote phosphor structure. Accordingly, the simulation results agree well to experimental results in conformal and remote phosphor structure. Furthermore, the blue and yellow light are treated separately to discuss the optical characteristic in simulation and experiment. Finally, we think the refractive index between air and phosphor layers is the main reason for the different distribution of the intensity in the blue and yellow light, which could influence the uniformity of angular CCT in white LEDs. Such phosphor model could provide the information to understand the influence of phosphor, and is important in discussing about the optical characteristic in white LEDs.

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