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Research Article

Optical Modeling Analysis of Red, Green, and Yellow Phosphors with a Blue LED

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The luminous properties of red, green, and yellow phosphors with a blue LED are evaluated and a corresponding optical model is constructed using the optical simulation software LightTools®. According to the phosphor particle model, the desired chromaticity coordinate of the multicomponent light which is excited by a blue LED can be achieved by modifying the weight concentration of the phosphors. A comparison of the four types of LED package modules tested shows that the yellow phosphor encapsulated with a semispherical module takes up a lesser percentage of the total weight percentage of a constructed white light with a correlated color temperature of around 4000 K. The simulation and experimental results provide a cross-reference for better packaging and encapsulating designs for lumen improvement.

1. Introduction

The white light LED has become a popular choice to replace traditional lighting sources. Compared to incandescent and fluorescent lamps, white LEDs have many advantages, such as a long lifetime, high efficiency, and lower energy consumption [1]. Most white LEDs use phosphors excited by diode chips with short wavelengths (blue or violet) to reemit a broad spectrum light with a good color-rendering index [2–4]. Since the optical performance of LED lighting, including the correlated color temperature (CCT) values, is strongly dependent on the thickness, combination concentration, and geometrical distribution of the phosphors, the commercially available recipes for white LEDs usually require careful manipulation if they are to meet the CCT requirements. Any modification to the pattern of the package could change the volume, density, concentration, or uniformity of the luminescent phosphor film and cause variations in the CCT, chromaticity coordinates, and luminous efficacy.

To empirically determine the factors that dominate the optical properties of the white light LED, detailed experiments must be carried out. In terms of time savings and cost effectiveness, a proper optical model of phosphors is most beneficial in reducing the trial-and-error process. In order to establish an LED model, experiments and simulations dealing with the relationships between the encapsulants, package structures, performance of the radiation power spectrum, CCT, and chromaticity coordinates must be conducted and the results analyzed. Further, some special LED package designs with higher uniformity but using lesser phosphor can be considered as an adjunct of the proposed model [5]. Yang et al. [6] demonstrated the accuracy feedback method of chromaticity coordinates and spectra. This feedback coating method offers an easy approach towards optimized spectra. Wang and Huang [7] also reported the chromaticity coordinates and spectra of phosphor-converted LEDs are well controlled by the feedback coating method. Our phosphor particle model was designed to simulate the scattering and absorbing process of light inside the phosphors. This model was based on the Mie theory, the ray tracing method, and Monte-Carlo algorithms [8–11]. A blue light LED was used to excite the phosphors, with the samples numbered R-645 and R-626 indicating red lights, G-531 and G-529 indicating green lights, and Y-561 yellow light. The number of the samples indicates the peak value of the emission spectrum in nanometers produced by the phosphor. For example, the

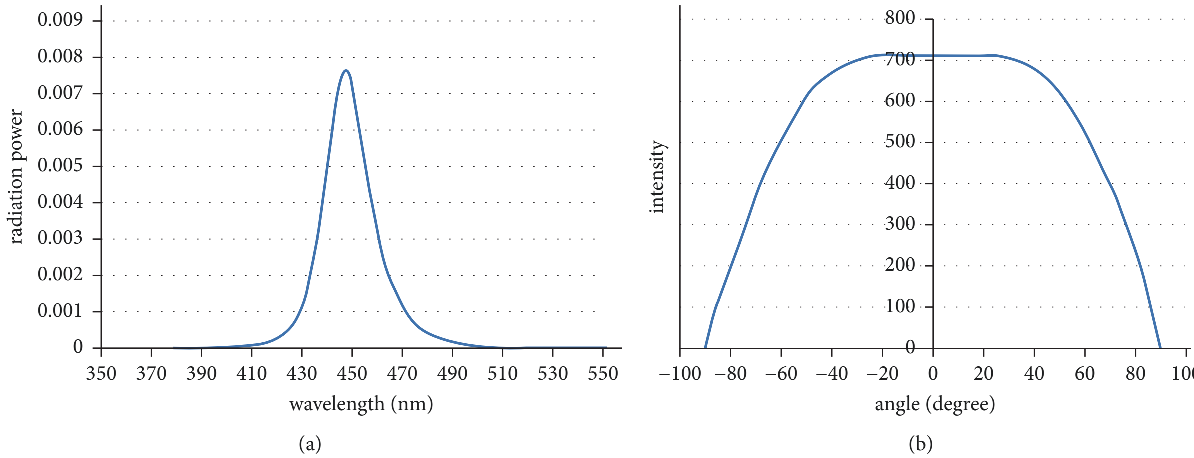

Figure 1: (a) Radiation power spectrum and (b) luminous intensity angular distribution curve of the blue LED light source.

peak value of the R-645 phosphor is 645 nm. The LED power efficiency at a CCT value of about 4000 K for the different package types was compared with this phosphor particle model. The simulation and experimental results should provide a reference to improve the luminous properties for better packaging and encapsulating designs.

2. Principle

The characteristic parameters of the blue LED, the spectra of the phosphors, and the power transform efficiency of the phosphor powders acting with blue light were established.

2.1. Blue LED Light Source. The dimensions of the blue LED chip were 0.97 mm × 0.51 mm × 0.11 mm. Figure 1(a) shows the radiation power distribution versus wavelength with a peak value of 447 nm; Figure 1(b) shows the angular distribution of the luminous intensity curve.

2.2. Blue LED Source Spectrum, Excitation, and Emission Spectra of the Phosphors. Figure 2 shows the excitation and emission spectra of the R-645, R-626, G-531, and G-529 phosphors and the spectra of the pumping source for the experimental results. The blue LED spectrum is indicated by the blue line with a peak value of 447 nm, the green lines indicate the excitation spectra of the phosphors, and the red lines show the reemission spectra of phosphors with a longer wavelength shift under the blue LED pumping.

2.3. Spectra Analysis of Different Weight Concentrations of Phosphor under the Blue LED Excitation. The radiation power and chromaticity coordinates of four monochromic phosphors, the red phosphors, R-645 and R626, and the green phosphors, G531 and G529, at different weight percentages were measured. Figure 3 shows the schematic structure of the blue LED with a uniformly distributed phosphor film used in this study. The weight concentrations of the four different phosphors are shown in Table 1.

Table 1: List of weight concentrations of the four different phosphors.

Type	Weight concentration of phosphors		
R-645	3%	5%	10%
R-626	0.83%	1.37%	2.11%
G-531	5%	10%	20%
G-529	8%	11.2%	15%

A normalized cross-correlation (NCC) formula was adopted to evaluate the fitness between the simulation and empirical data [12]. The NCC is given by

$$\mathrm{NCC} = \frac{(1/N)\sum_{\lambda=380}^{\lambda=780}\left(A_\lambda-\overline{A}\right)\left(B_\lambda-\overline{B}\right)}{\sqrt{(1/N)\sum_{\lambda=380}^{\lambda=780}\left(A_\lambda-\overline{A}\right)^2}\sqrt{(1/N)\sum_{\lambda=380}^{\lambda=780}\left(B_\lambda-\overline{B}\right)^2}}, \quad (1)$$

where A_λ and B_λ are the values of the radiation power at certain wavelengths, λ; $\overline{A}$ and $\overline{B}$ are the values of the average radiation power for the simulations and experiments, respectively; and N is the number of experiments and the number of wavelengths to be evaluated.

3. Simulation Results

The empirical and simulated data curves of the radiation power spectra of phosphors of different weight percentages under blue light excitation are discussed in Sections 3.1–3.4.

3.1. Comparison of the Radiation Power Spectra and CIE Chromaticity Locations of Phosphor R-645 with Different Weight Concentrations. Figure 4 shows the radiation power of phosphor R-645 with different weight concentrations (3%, 5%, and 10%) excited by a blue LED. The blue line indicates

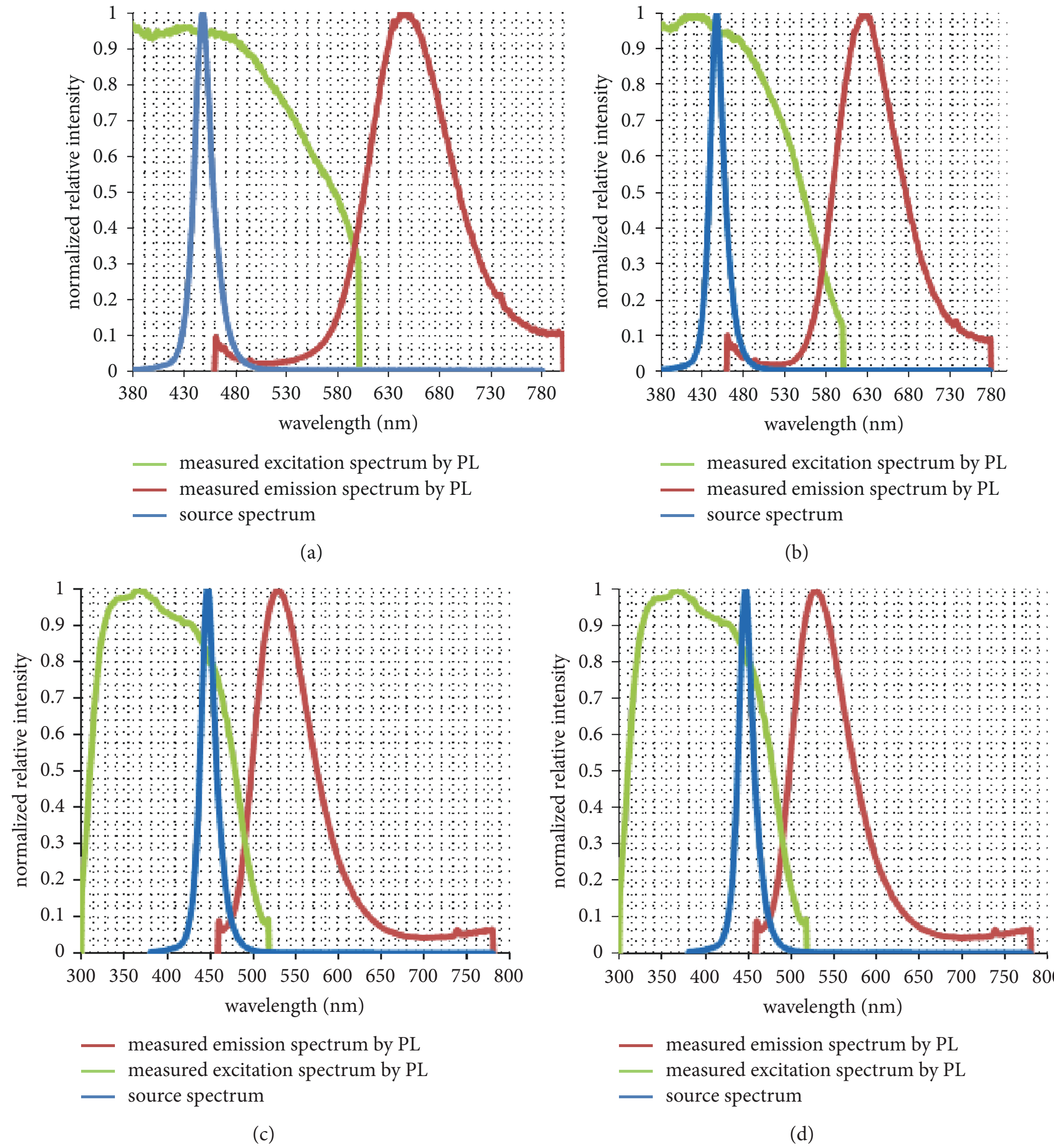

FIGURE 2: Empirical emission spectrum of the blue LED and the excitation and emission spectra corresponding to phosphors (a) R-645, (b) R-626, (c) G-531, and (d) G-529.

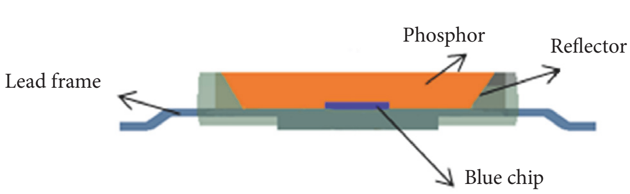

FIGURE 3: Schematic representation of the package with phosphors and a blue LED chip used in the simulation.

the empirical data measured by an integrating sphere and the red lines show the simulation data. A comparison of these curves shows that the higher the weight concentration, the higher the emission spectra intensity, although the deviations between the simulation and the empirical data were small. The CIE chromaticity coordinates of the five concentrations are listed in Table 2. The location points with values are in terms of the CIE 1931 chromaticity diagram, as shown in Figure 5. It can be seen that a weight concentration of 5% was the best choice for obtaining a magenta-colored light.

3.2. Comparison of the Blue LED Excited Radiation Power Spectrum and CIE Index for Phosphor R-626 of Different Weight Concentrations. Figure 6 shows the radiation power spectra of R-626 phosphors with weight concentrations of 0.83%, 1.37%, and 2.11%, when excited by the blue LED. The intensity of the emission spectra showed a tendency to

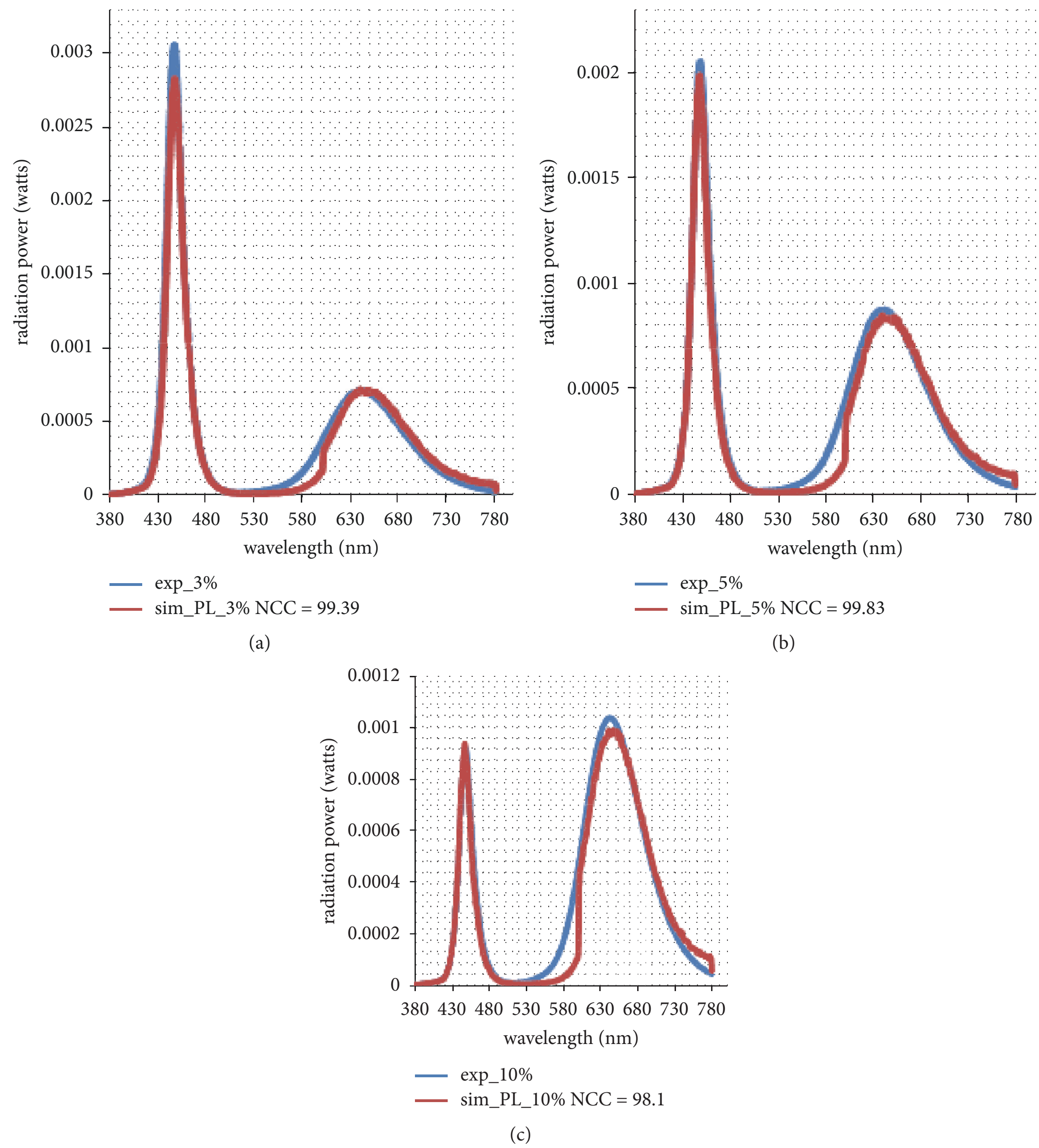

Figure 4: Radiation power of phosphor R-645 at three weight concentrations: (a) 3.0 wt%; (b) 5.0 wt%; and (c) 10.0 wt% with blue LED excitation.

Table 2: Empirical and simulated chromaticity coordinates of R-645 phosphor with three different weight concentrations with blue LED excitation.

Wt%	Exp_ CIE (x, y)	Sim_PL CIE (x, y)
3.0%	(0.2739, 0.1065)	(0.2638, 0.0884)
5.0%	(0.3309, 0.1444)	(0.3138, 0.1151)
10.0%	(0.4412, 0.2114)	(0.4247, 0.1727)

Table 3: Empirical and simulated chromaticity coordinates of R-626 phosphor with three different weight concentrations with blue LED excitation.

Wt%	Exp_ CIE (x, y)	Sim_PL CIE (x, y)
0.83%	(0.2481, 0.0946)	(0.2416, 0.0847)
1.37%	(0.2912, 0.1267)	(0.2801, 0.1111)
2.11%	(0.3305, 0.1568)	(0.3231, 0.1399)

increase as the concentration increased. The CIE coordinates are listed in Table 3. Figure 7 shows the distributions for the different concentrations as illustrated in the CIE chromatic diagram. As can be seen in this figure, if magenta light

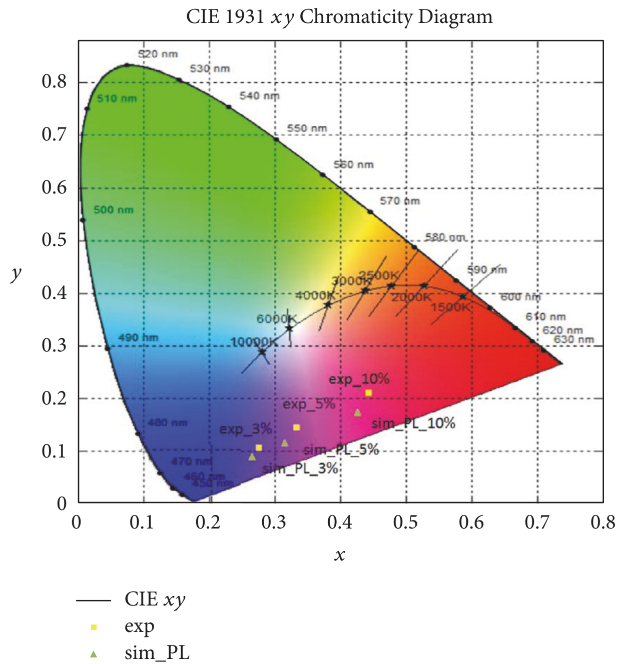

Figure 5: Location points on CIE 1931 chromaticity diagram for three different concentrations of phosphor R-645 excited by a blue LED.

Table 4: Empirical and simulated chromaticity coordinates of phosphor G-531 with three different weight concentrations under the blue LED excitation.

Wt%	Exp_ CIE (x, y)	Sim_PL CIE (x, y)
5%	(0.1988, 0.2047)	(0.2022, 0.1857)
10%	(0.2158, 0.2783)	(0.2321, 0.2792)
20%	(0.2460, 0.3957)	(0.2745, 0.4017)

Table 5: Empirical and simulated chromaticity coordinates of phosphor G-529 with three different weight concentrations under the blue LED excitation.

Wt%	Exp_ CIE (x, y)	Sim_PL CIE (x, y)
8%	(0.2669, 0.3361)	(0.2804, 0.3124)
11.2%	(0.2862, 0.3876)	(0.3101, 0.3740)
15%	(0.3013, 0.4268)	(0.3413, 0.4354)

is required, then the 2.11 wt% would be a good choice for this design. Also, as discussed in Section 3.1, if light with a magenta color (R-645 phosphor at 5 wt%) was required, only the 2.11 wt% of R-626, for a 2.89 wt% reduction, would be used.

3.3. Comparison of the Radiation Power Spectrum and CIE Index of G-531 Phosphor with Different Weight Concentrations under the Blue LED Excitation. Figure 8 shows the radiation power spectra of the G-531 phosphors with weight concentrations of 5%, 10%, and 20% under the blue LED excitation. The intensity of the emission spectra increased with the increases in the concentration. The CIE coordinates are shown in Table 4, and the distributions for the different concentrations in the CIE chromatic diagram are shown in Figure 9. As can be seen in the figure, if a design with cyanic light were demanded, then the concentration of the G-531 phosphor should be near 15%.

3.4. Comparison of the Radiation Power Spectrum and CIE Index of G-529 Phosphors with Different Weight Concentrations under the Blue LED Excitation. Figure 10 shows the radiation power spectra of G-529 phosphors under the blue LED excitation with weight concentrations of 8%, 11.2%, and 15%. The intensity of the emission spectra also increased as the concentration increased. The CIE chromaticity coordinates are listed in Table 5, and the distributions of the different concentrations in the CIE chromatic diagram are shown in Figure 11. When cyanic light is required, the concentration of G-529 phosphor should be about 8%. Compared with the results discussed in Section 3.3, where the concentration was 15%, this design reduced the weight concentration by 7% and produced mixed light located at the cyan region.

3.5. Weight Concentrations of Phosphor and Luminal Efficiency Analysis for Four Types of Packages at a Color Temperature of 4000 K. Figure 12 depicts the absorption and emission spectra of Y-561 phosphors and the source spectrum of the

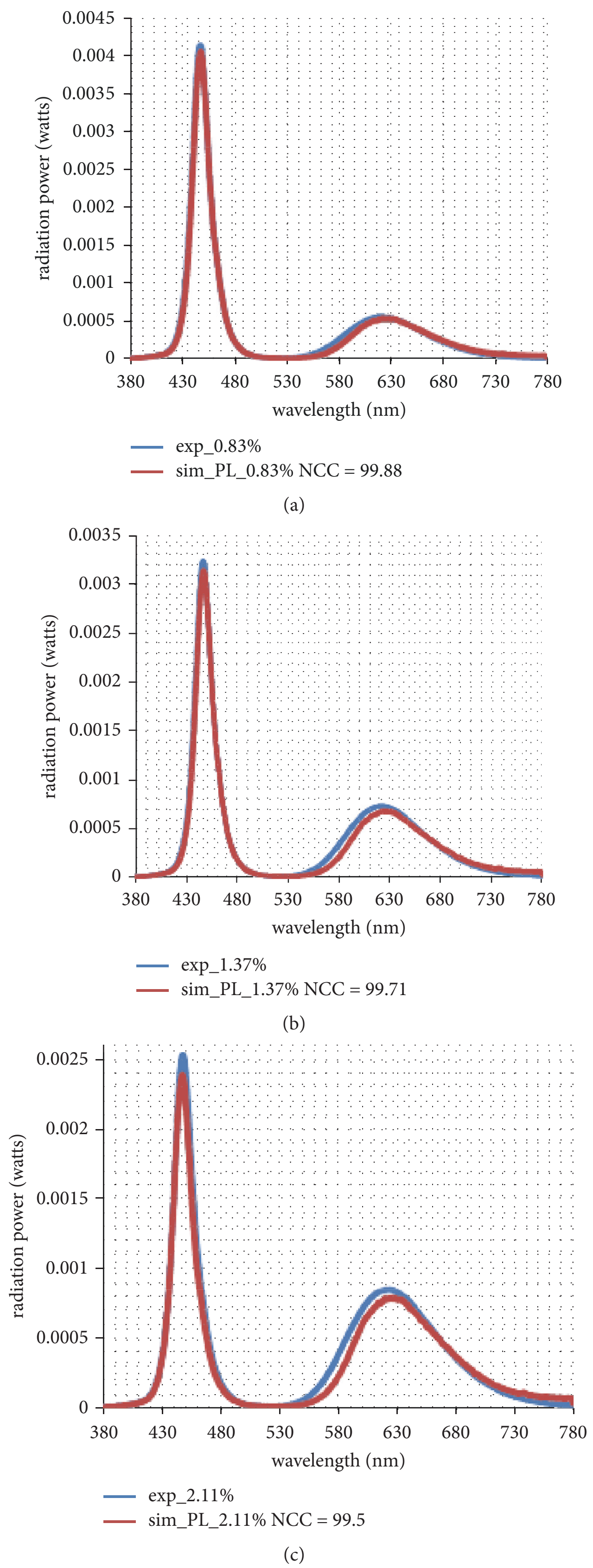

Figure 6: Radiation power of R-626 phosphor at three weight concentrations: (a) 0.83 wt%; (b) 1.37 wt%; and (c) 2.11 wt% with the blue LED excitation.

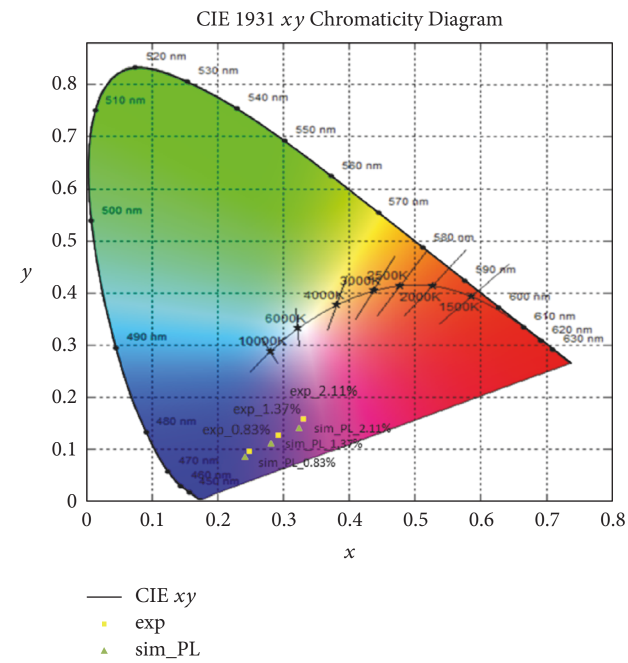

Figure 7: CIE chromaticity diagram from empirical and simulation data for R-626 phosphor (with three different weight concentrations) under blue LED excitation.

blue LED. Since white light can be obtained by mixing blue and yellow light, we combined a blue LED, with a spectrum peak value of 447 nm, and adjusted the weight percentage of the Y-561 phosphor under excitation to obtain white light of the desired color temperature.

If we want the color temperature of the mixed light to be 4000 K, we must calculate the weight concentration of Y-561 phosphor from the coordinates of the cross point of the black locus at 4000 K and a line connecting the location points of the blue LED and phosphor emission spectra on the CIE chromaticity diagram, as shown in Figure 13.

Figure 14 shows the four types of packages adapted in our simulation models. The weight percentages of the Y561 phosphor in these packages were manipulated to ensure that the chromaticity points were at the locus of blackbody radiation of 4000 K for simulation purposes; the percentages corresponding to the four types of packages, dispensing, conformal, remote, and semispherical, were 7.6%, 64.0%, 24.1%, and 24%, respectively. The weights of the epoxy encapsulants were 15.13 mg (dispensing), 0.24 mg (conformal), 6.20 mg (remote), and 0.77 mg (semispherical). Based on this data, the amount of phosphors used by the four types of packages could be calculated. The weights were 1.24 mg for the dispensing type, 0.42 mg for the conformal type, 1.97 mg for the remote type, and 0.24 mg for the semispherical type, as shown in Figure 15.

It was found that the Y-561 phosphor was excited by a blue LED with a power spectrum having a peak wavelength of 447 nm and that the semispherical type of package had a lower weight percentage than the other types for a color temperature of around 4000 K.

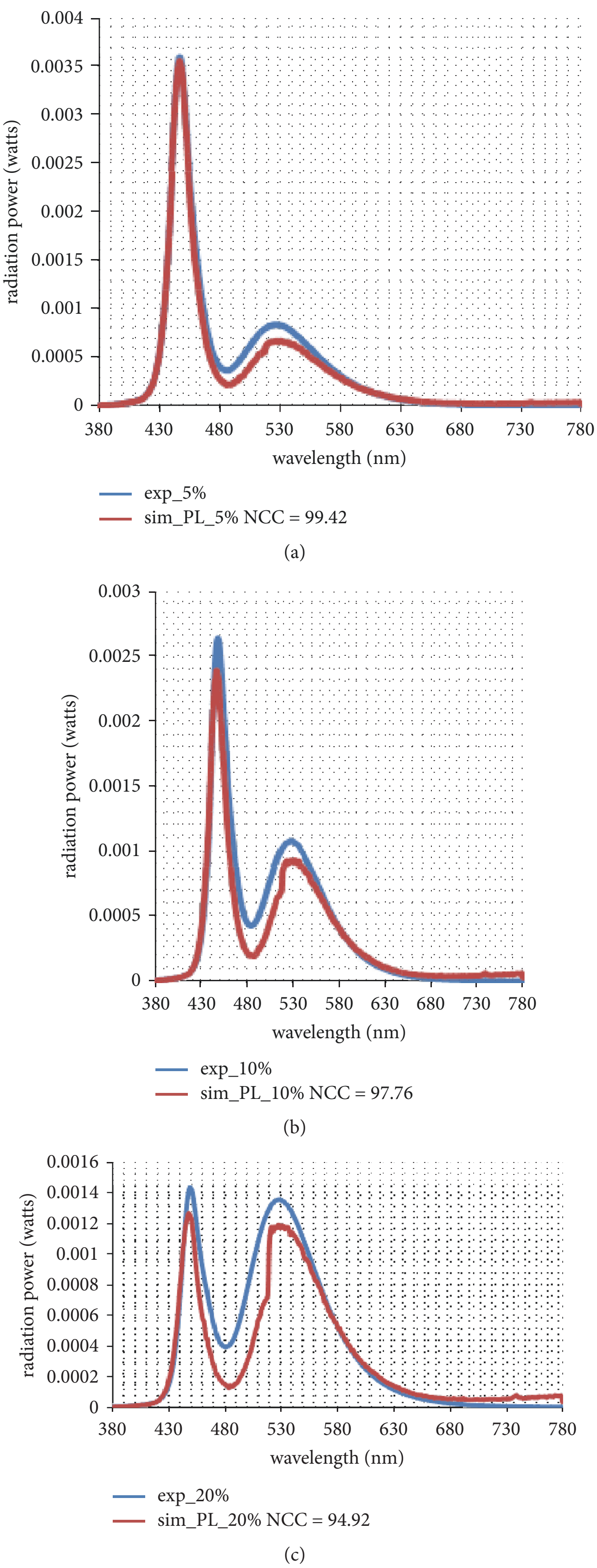

Figure 8: Radiation power of phosphor G-531 with three weight concentrations: (a) 5 wt%; (b) 10 wt%; and (c) 20 wt% with the blue LED excitation.

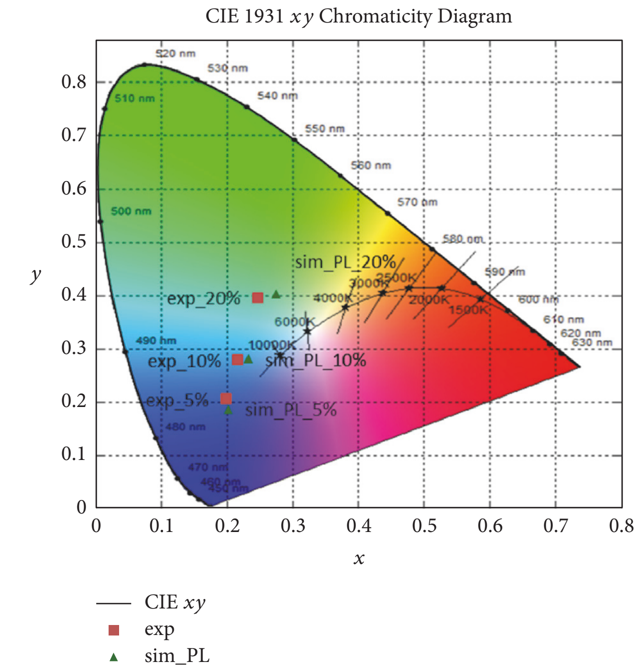

Figure 9: Chromaticity diagram of empirical and simulated data for G-531 phosphor with three different weight concentrations excited by a blue LED.

4. Conclusions

In this study, all the phosphors were excited under a blue LED with a peak power spectrum value of 447 nm. The power of the emission spectra of the red phosphors (R-645, R-626) and green phosphors (G-531, G-529) increased with an increase in the phosphor concentration. However, the deviations between the simulation and empirical curves tended to increase as the weight percentages increased, and further studies are needed to improve the results. When a 5% weight concentration of R-645 phosphor or a 2.11% weight concentration of R-626 phosphor was combined with the blue LED, chromaticity coordinates near the magenta area were obtained. When an 8% weight concentration of G-529 phosphor was combined with a blue LED, the mixed light was within the cyan spectrum.

To produce a mixed white light with a color temperature of around 4000 K with phosphor Y-561 and the blue LED, the concentration of phosphors was calculated from the intersection coordinates of the two lines on the CIE chromaticity diagram: the first being the locus of blackbody radiation at 4000 K; the other line being the connection points between the blue LED spectrum and the Y-561 phosphor emission spectrum. The chromaticity coordinates of this point were $x = 0.3804$ and $y = 0.3768$. The simulations for the packages revealed that the semispherical type used the least amount of Y-561 phosphor to achieve a color temperature of 4000 K.

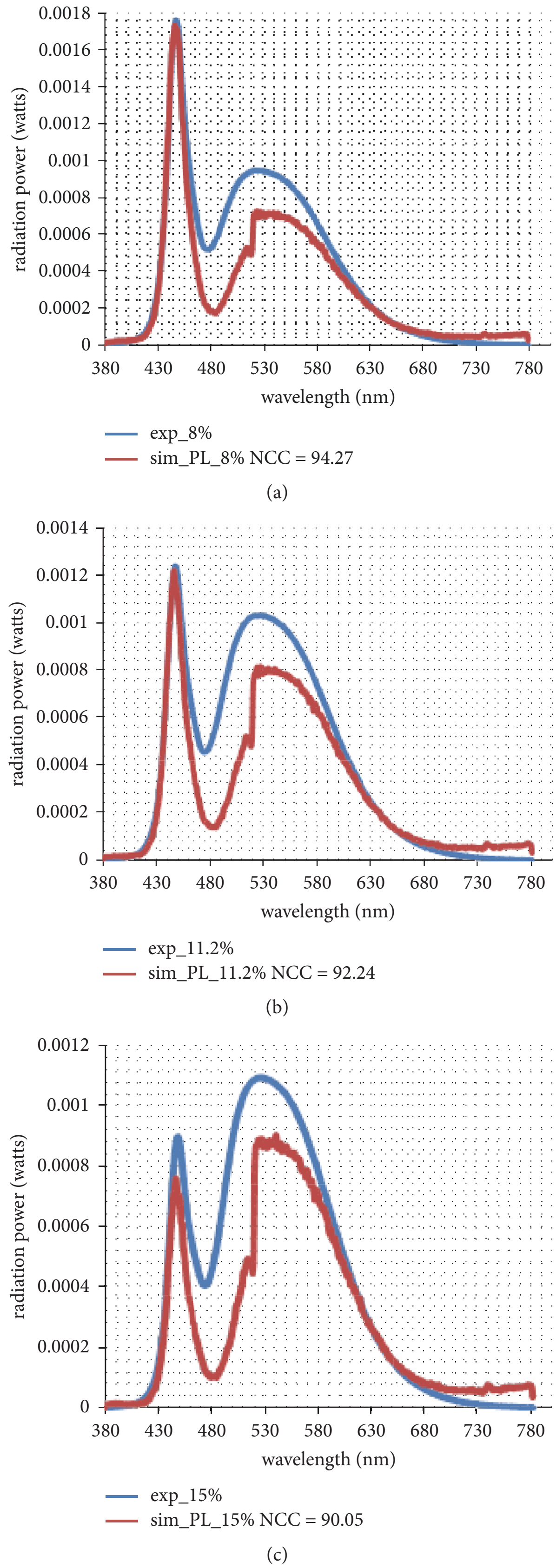

Figure 10: Radiation power of G-529 phosphor with three weight concentrations: (a) 8 wt%; (b) 11.2 wt%; and (c) 15 wt% excited by the blue LED.

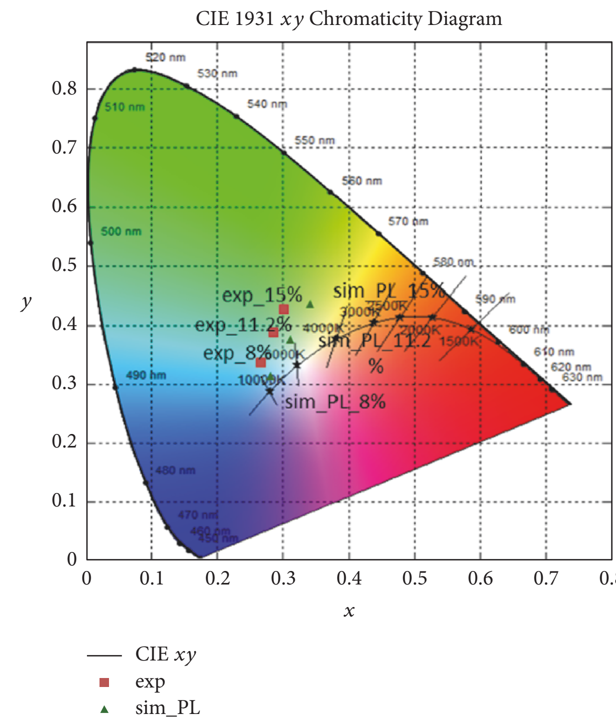

Figure 11: Chromaticity diagram of G-529 phosphors with three different weight concentrations excited by a blue LED.

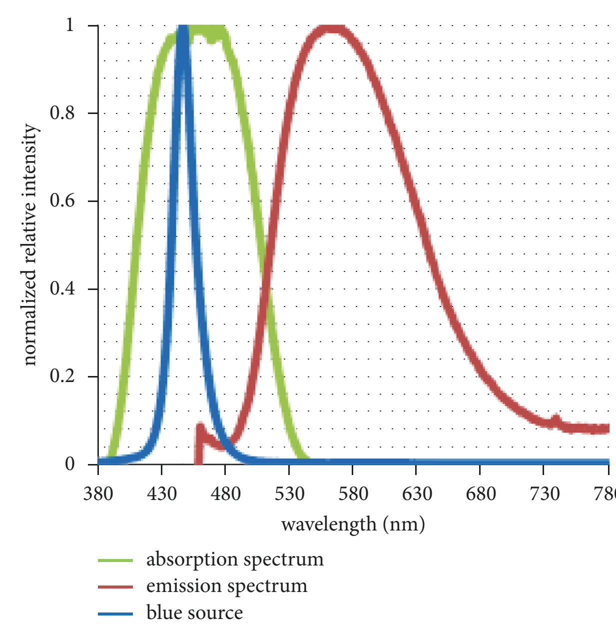

Figure 12: Power spectrum of the blue LED and the emission and absorption spectra of Y-561 phosphor.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

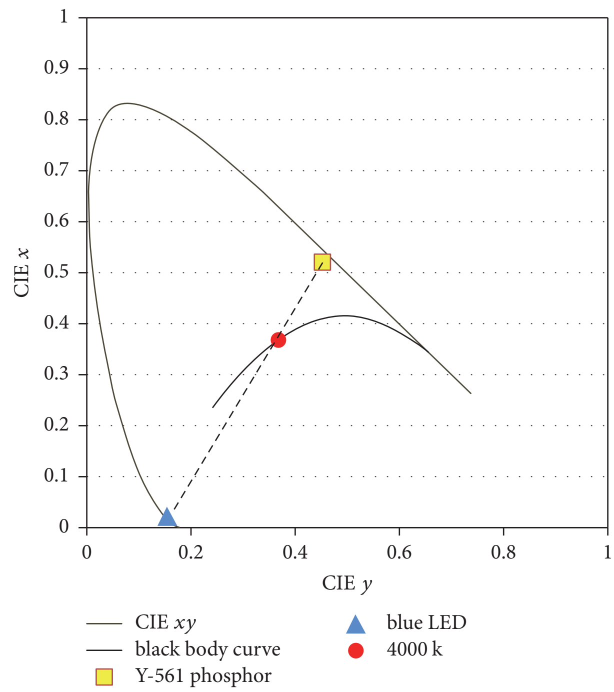

FIGURE 13: Schematic for location determination of white light from the points in the CIE chromaticity diagram of the blue LED and yellow Y-561 phosphor.

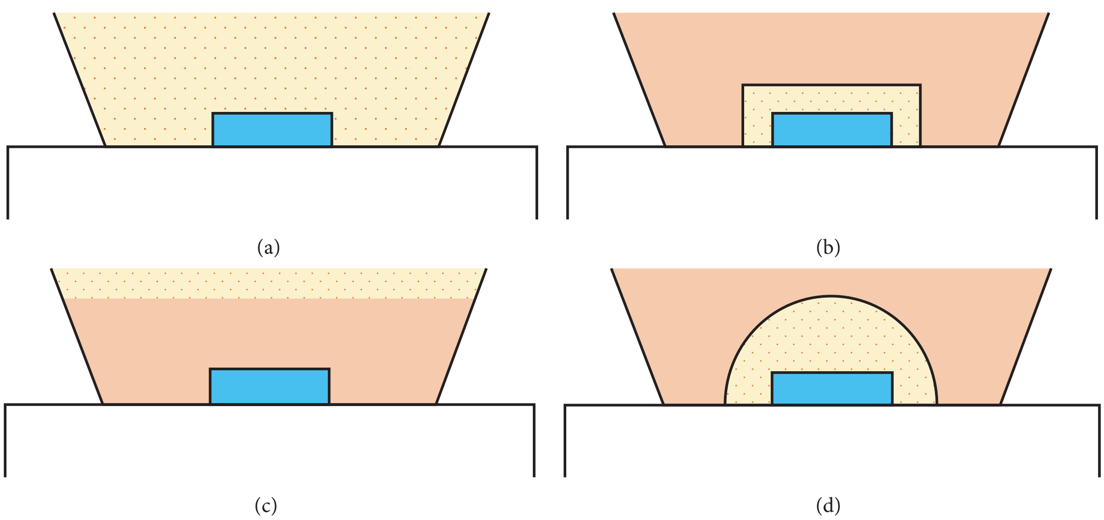

FIGURE 14: Four types of packages for simulation: (a) dispensing; (b) conformal; (c) remote; (d) semispherical.

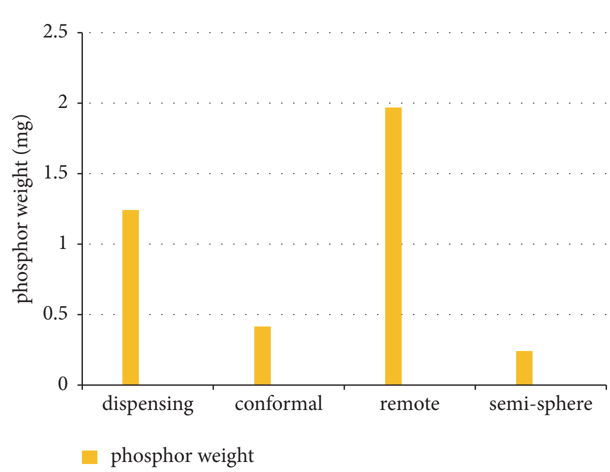

FIGURE 15: Comparison of light efficiency with phosphor weight for the four package types.

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