Effect of red-emitting $SrB_8O_{13}:Sm^{2+}$ phosphor on the color rendering property of white LEDs

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In this study, red-emitting $SrB_8O_{13}:Sm^{2+}$ phosphor is proposed to enhance the color rendering property (CRP) of white light-emitting diodes (WLEDs). Through LightTools we carry out the simulations by employing the two phosphor geometries like the conformal phosphor geometry and the in-cup phosphor geometry. To verify the obtained results, the scattering properties of phosphor layer after adding $SrB_8O_{13}:Sm^{2+}$ are computed by using Mie-scattering theory. Moreover, the relationship between the lumen output and the extinction coefficient is presented through the Lambert-Beer law. The principal merits of this solution is to increase the CRP of 8500 K WLEDs to a value greater than 86.

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1. Introduction

With the purpose of replacing the traditional lighting sources, white light-emitting diodes have been recomended in recent years [1-3]. In most of these studies, we need a substance which can meet some basic requirement of the experiment like excellent luminescence, characteristics, long lifetime, and impressive stability, and YAG:Ce phosphor absolutely become the brightest candidate. However, it becomes a really challenge to get efficient phosphor, thereby it will be a trouble in meeting the rising demand of white light-emitting diodes (WLEDs) [4]. In this circumstance, YAG:Ce phosphor is associated with newfangled substance in enlarging the excitation spectrum of WLEDs and gets high CRP or lumen output. In some Sheu's group researches, red phosphor was applied in conjunction with trichromatic LED chips to generate white light with the CRP of 92 at the mean correlated color temperature (CCT) of 2900 K [5]. While, in order to achieve the CRP of 96 at the mean CCT of 2000 K, Gou's team proposed the optimal spectra based on filtering billions [6]. Moreover, Yuan's group apply Sn-doped fluosilicate glass to enrich the CRP at CCT of 5620 K [7]. Briefly, there are numerous studies that have contributed to the improvement of CRP of WLEDs. However, almost of them just focus on single-chip white LED lamps having CCTs less than 8500 K. Meanwhile, the improvement of CRP for multi-chip WLEDs with CCTs more than 8500 K is really a difficult task. Correspondingly, how to increase CRP while still maintaining lumen output is crucial, which decides the quality of WLEDs.

$SrB_8O_{13}:Sm^{2+}$, which is known as a red-emitting phosphor, has high efficiency. Furthermore, $SrB_8O_{13}:Sm^{2+}$ has been used widely in high and low-pressure discharge lamps thanks to the advantages of excellent thermal and chemical stability [8-10]. However, there was very few studies that $SrB_8O_{13}:Sm^{2+}$ is applied to improve the CRP of WLEDs. On contrary, in this research red $SrB_8O_{13}:Sm^{2+}$ phosphor is proposed in order to make CRP more than 86. This can be gained by supplementing the deficiency of red light. It can be clarified by the scattering property including the scattering coefficient, the average cosine of phase function, the reduced scattering coefficient and the scattering cross-section, which are computed by following Mie-scattering theory. Moreover, according to the Lambert-Beer law, we demonstrated that both the concentration and size of $SrB_8O_{13}:Sm^{2+}$ have significant influences on the transmitted light power.

2. Computational simulation

2.1. Constructing WLED models

The optical simulations were carried out by using the commercial software package LightTools. The simulation model comprises the conformal phosphor geometry (CPG) and in-cup phosphor geometry (IPG), shown in Fig. 1. The model is used to reflect the impact of the size and concentration of $SrB_8O_{13}:Sm^{2+}$ on the performance of WLEDs with CPG and IPG, respectively.

In order to evaluate the similarity between our WLED model and the real WLED sample with 8500 K, the initial WLED is without added $SrB_8O_{13}:Sm^{2+}$ particles, see Fig. 1 (a). We compare them by using the normalized cross correlation (*NCC*) in intensity angular distribution.

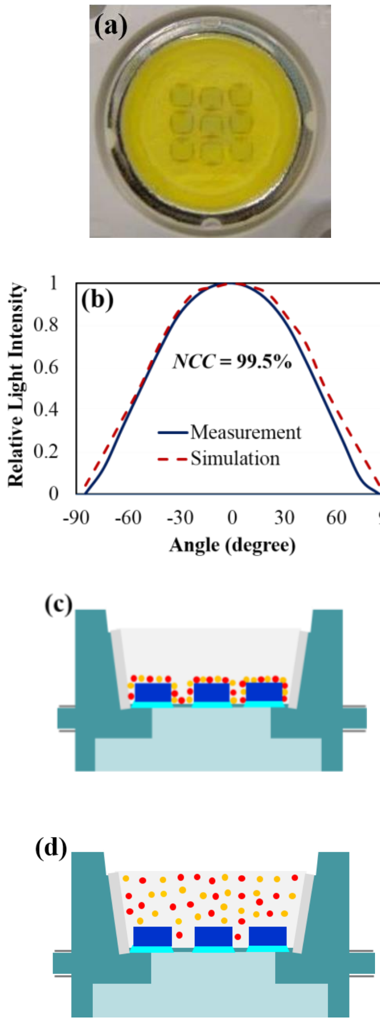

Fig. 1. Illustration of phosphor-converted WLEDs as doping $SrB_8O_{13}:Sm^{2+}$: (a) The actual WLEDs; (b) The calculation of normalized cross correlation (c) CPG and (d) IPG

$$NCC = \frac{\sum_n [I(\theta_n)_e - \bar{I}_e][I(\theta_n)_s - \bar{I}_s]}{\sqrt{\sum_n [I(\theta_n)_e - \bar{I}_e]^2 \sum_n [I(\theta_n)_s - \bar{I}_s]^2}} \tag{1}$$

Here I_s and I_e are the simulated and real experimental values of the relative light intensity, respectively. Θ_n is the n-th angular displacement, $\bar{I}_s$ and $\bar{I}_e$ are the average values of simulations and optical measuring experiments accomplished by a goniophotometer. The results of the *NCC* related experiments are shown in Fig. 1(b). The *NCC* values is higher than 99.5% for both CPG and IPG, so the WLED models are appropriate to be used in the computational simulation. The phosphor layer of CPG is conformally coated on 9 LEDs, but the phosphor particles is dispersed in the silicone lens in IPG. These phosphor layers consist of not only YAG:Ce but also $SrB_8O_{13}:Sm^{2+}$ particles as well as the silicone glue, which respectively has the refractive indices of 1.83, 1.93 and 1.5. In addition, the average radius of YAG:Ce phosphor particles is set to 7.25 μm for all packages, that is also a value of real particle size. The concentration of phosphor is varied for optimizing the color rendering property.

$$W_{YAG:Ce} + W_{silicone} + W_{SrB_8O_{13}:Sm^{2+}} = 100\% \tag{2}$$

$W_{silicone}$, $W_{YAG:Ce}$ and $W_{SrB8O13:Sm2+}$ are the weight percentages of the silicone, phosphor and $SrB_8O_{13}:Sm^{2+}$ in the phosphor layer, respectively. In order to make the same color of WLEDs product when the concentration or size of $SrB_8O_{13}:Sm^{2+}$ phosphor varies, the YAG:Ce phosphor concentration should be inversely modified to provide same CCT value.

2.2. Computing scattering properties

By following the Mie theory, it can be defined the optical properties of phosphor compounding, the scattering coefficient μ_{sca}, and scattering phase function p [11]. The relationship between the scattering coefficient (SC) and the wavelength as well as the size of $SrB_8O_{13}:Sm^{2+}$ particles is described by the following equations:

$$\mu_{sca}(\lambda) = \frac{c}{\bar{m}} \bar{C}_{sca}(\lambda) \tag{3}$$

$$p(\lambda,\theta,\phi) = \frac{\int p_D(\lambda,\theta,\phi) C_{sca,D}(\lambda) f(\mathrm{D}) \mathrm{dD}}{\int C_{sca,D}(\lambda) f(\mathrm{D}) \mathrm{dD}} \tag{4}$$

Here, *f(D)* is the size distribution function, c is the phosphor concentration (g/cm^3), $P_D(\lambda,\theta,\phi)$ and $C_{sca,D}$ are the scattering phase function and the scattering cross-section (SCS) of the phosphor having particle diameter D. While $\bar{C}_{sca}(\lambda)$ and $\bar{m}$ are the scattering cross-section and the particle mass of the phosphor integrated over *f(D)*, in turn. These two parameters can be identified by Eq. (4) and Eq. (5), respectively:

$$\bar{C}_{sca}(\lambda) = \frac{\int C_{sca,D}(\lambda) f(\mathrm{D}) \mathrm{dD}}{\int f(\mathrm{D}) \mathrm{dD}} \tag{5}$$

$$\bar{m} = \frac{\int m_i(\mathrm{D}) f(\mathrm{D}) \mathrm{dD}}{\int f(\mathrm{D}) \mathrm{dD}} \tag{6}$$

$$C_{sca}(\lambda) = \frac{P_{sca}(\lambda)}{I_{inc}(\lambda)} \tag{7}$$

$$p_D(\lambda,\theta,\phi) = \frac{P_{sca}^{far}(\lambda,\theta,\phi)}{P_{sca}(\lambda)} \tag{8}$$

$$\mathrm{g}(\lambda) = 2\pi \int\int_{-1}^{1} p_D(\lambda,\theta,\phi) f(\mathrm{D}) \cos\theta d \cos\theta dD \tag{9}$$

$$\delta_{sca} = \mu_{sca}(1-\mathrm{g}) \tag{10}$$

where $I_{inc}(\lambda)$ and $g(\lambda)$ are the irradiance intensity and the anisotropy factor, $P_{sca}^{far}(\lambda,\theta,\phi)$ and $P_{sca}(\lambda)$ are the far-field scattering power distribution and the scattered power by phosphor particles, in turn. Moreover, a reduced scattering coefficient (RSC) δ_{sca} is presented to define the scattering event of $SrB_8O_{13}:Sm^{2+}$ particles. The scattering property of WLEDs is simulated and computed at the wavelength region from 380 nm to 780 nm.

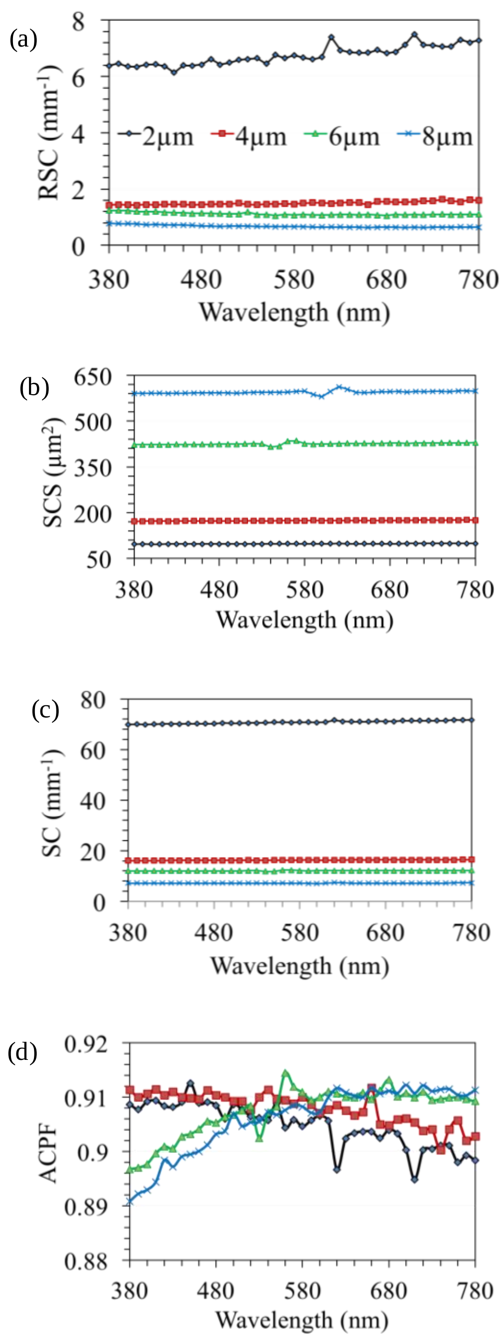

Fig. 2. The scattering properties of phosphor layer as a function of the size of $SrB_8O_{13}:Sm^{2+}$ for CPG: (a) RSC, (b)SCS, (c) SC, (d)ACPF

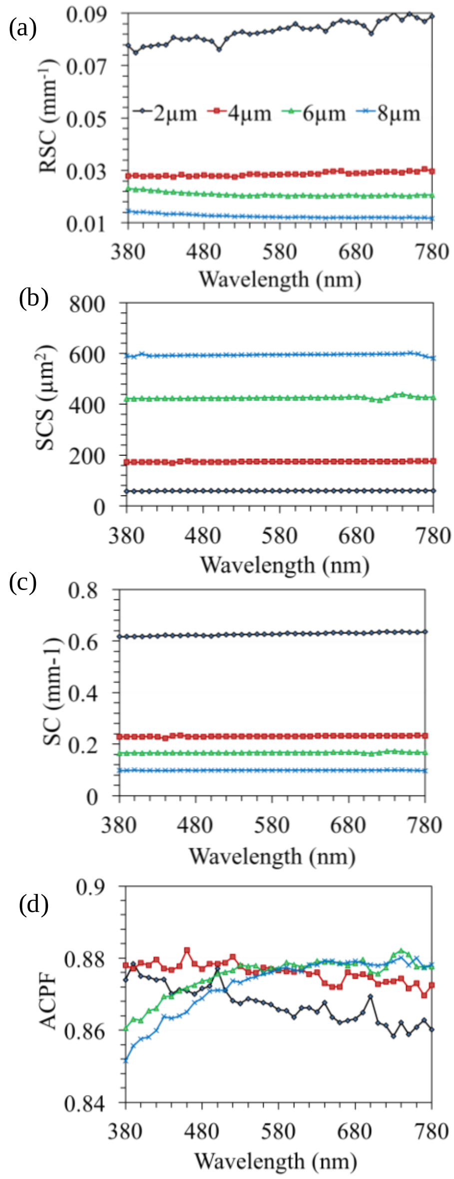

Fig. 3. The scattering properties of phosphor layer as a function of the size of $SrB_8O_{13}:Sm^{2+}$ for IPG: (a) RSC, (b)SCS, (c) SC, (d)ACPF

To portray the scattering properties of $SrB_8O_{13}:Sm^{2+}$ phosphor, the reduced scattering coefficient and the scattering cross-section are calculated as expressed in Fig. 2 and Fig. 3, in turn. Due to the preponderant ability of scattering for smaller particles regardless of wavelength and phosphor geometry [11], the RSC values of $SrB_8O_{13}:Sm^{2+}$ with small size (2 μm) are less stable than those with larger size, as shown in Fig. 2(a) and Fig. 3(a). Meanwhile, the deviation of reduced scattering coefficient at larger $SrB_8O_{13}:Sm^{2+}$ sizes (4 μm to 8 μm) is insignificant. It implies that higher scattering uniformity can be achieved within the wavelength range of vision. We also find that the SCS values grows with the $SrB_8O_{13}:Sm^{2+}$ sizes for all the wavelengths, that leads to an incident power concentrates in scattering power in the light propagating as be seen in Fig. 2(b) and Fig. 3(b). This indicates that the scattering ability of $SrB_8O_{13}:Sm^{2+}$ phosphor primarily depends on $SrB_8O_{13}:Sm^{2+}$ size is stronger than its wavelength. Correspondingly, in order to explain the optical characteristics of WLEDs we should make use of the description of the scattering properties of phosphor compounding.

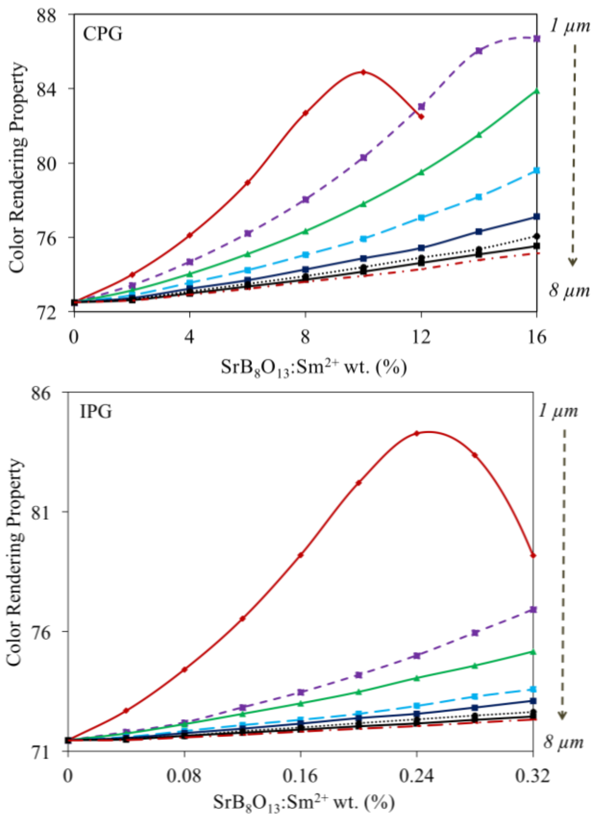

Fig. 4. The CRP at average CCTs of 8500 K as changing concentration and size of $SrB_8O_{13}:Sm^{2+}$: CPG (top) and IPG (bottom)

Without a shadow of doubt, the mixture of $SrB_8O_{13}:Sm^{2+}$ and YAG:Ce particles will produce a scattering enhancement in WLEDs. To make clear about the scattering ability of the phosphor compounding, the SCs are presented at four typical $SrB_8O_{13}:Sm^{2+}$ sizes: 2 µm, 4 µm, 6 µm, 8 µm. From Fig. 2(c) and Fig. 3(c), it can be seen that the SCs falls down with the growth of $SrB_8O_{13}:Sm^{2+}$ size. This implies that the scattering ability for larger $SrB_8O_{13}:Sm^{2+}$ particles also reduces inside the phosphor compounding. This brings benefits to the color of quality, but the luminous efficacy is not. Therefore, it is very important to choose suitable $SrB_8O_{13}:Sm^{2+}$ before adding it to the phosphor compounding. Moreover, the SCs within the wavelength range of vision are almost the same. Consequently, when merging $SrB_8O_{13}:Sm^{2+}$ phosphor, we can receive the higher scattering uniformity and since color quality can be better. Moreover, the average cosine of phase function (ACPF) for various $SrB_8O_{13}:Sm^{2+}$ sizes is computed by using Mie-theory. At 2 µm size, the ACPFs of $SrB_8O_{13}:Sm^{2+}$ phosphor tend to significant change with respect to wavelength, as demonstrated in Fig. 2(d) and Fig. 3(d). However, the deviation of ACPF becomes smaller at 4 µm. It means that the high scattering uniformity attains at the sizes of 4 µm. As the $SrB_8O_{13}:Sm^{2+}$ particle size increases continually, the scattering ability on the incident light of phosphor compounding becomes weaker. In conclusion, color quality may be really affected by these above reasons.

3. Results and discussions

In this section, we simultaneously compared and analyzed the lumen output and CRP in different sizes and concentration of $SrB_8O_{13}:Sm^{2+}$. Firstly, the color rendering indexes were calculated and displayed on Fig. 4. Fig. 4(top) illustrates the influence of $SrB_8O_{13}:Sm^{2+}$ concentration on CRP of CPG configuration. It can be observed that the CRP grows in accordance with the weight percentage of $SrB_8O_{13}:Sm^{2+}$ phosphor in a continuous range from 0% to nearly 10 %. When the $SrB_8O_{13}:Sm^{2+}$ weight vary from 8% to 16%. The higher color rendering ability is acquired. In particular, optimal color rendering index can be achieved exceeds 86 in this case. As for IPG, the $SrB_8O_{13}:Sm^{2+}$ concentration ranges continuously from 0 % to approximately 0.32 %. The high color rendering ability with different CCTs can be gained when the $SrB_8O_{13}:Sm^{2+}$ percentage ranges from 0.16% to 0.32%, as shown in Fig. 4(bottom). The optimal color rendering index of WLEDs can beyond 84 in this case, which is 25.8 % higher than that of the non-$SrB_8O_{13}:Sm^{2+}$ case, i.e. when the $SrB_8O_{13}:Sm^{2+}$ concentration is equal to 0 %. However, the CRP has a decreasing tendency in correlated with the increasing of the concentration and size of $SrB_8O_{13}:Sm^{2+}$ beyond a point where the red-light starts to be over-dominant, thereby that causes color rendering ability to be reduced for both CPG and IPG.

In Fig. 5, it is easy to realize the performances of lumen output corresponding with extinction coefficient for CPG and IPG, which are shown the similar phenomenon with respect to the concentration and size of $SrB_8O_{13}:Sm^{2+}$. On the one hand, the simulation confirms that CPG has a better overall CRP than that of IPG. By following the fact is that the blue-yellow-red light patterns are kept synchronizing because of the conformal geometry of phosphor layer. On the other hand, IPG can provide higher overall lumen output since the phosphor composite is supported by the silicone lens, which reduces the losses due to light absorption by chips. Here, we can put the Mie-scattering theory into practice to derive the relationship of luminous output to the $SrB_8O_{13}:Sm^{2+}$ weight rigorously. The transmitted light power can be calculated by the Lambert-Beer law [12]:

$$I = I_0 \exp(-\mu_{ext} L) \tag{11}$$

In the equation 11, I_0 is the incident light power, L is the phosphor layer thickness (mm) and μ_{ext} is known to be the extinction coefficient, which can be expressed as: $\mu_{ext} = N_r.C_{ext}$, where N_r is as the number density distribution of particles (mm^{-3}). C_{ext} (mm^2) is the extinction cross-section of phosphor particles.

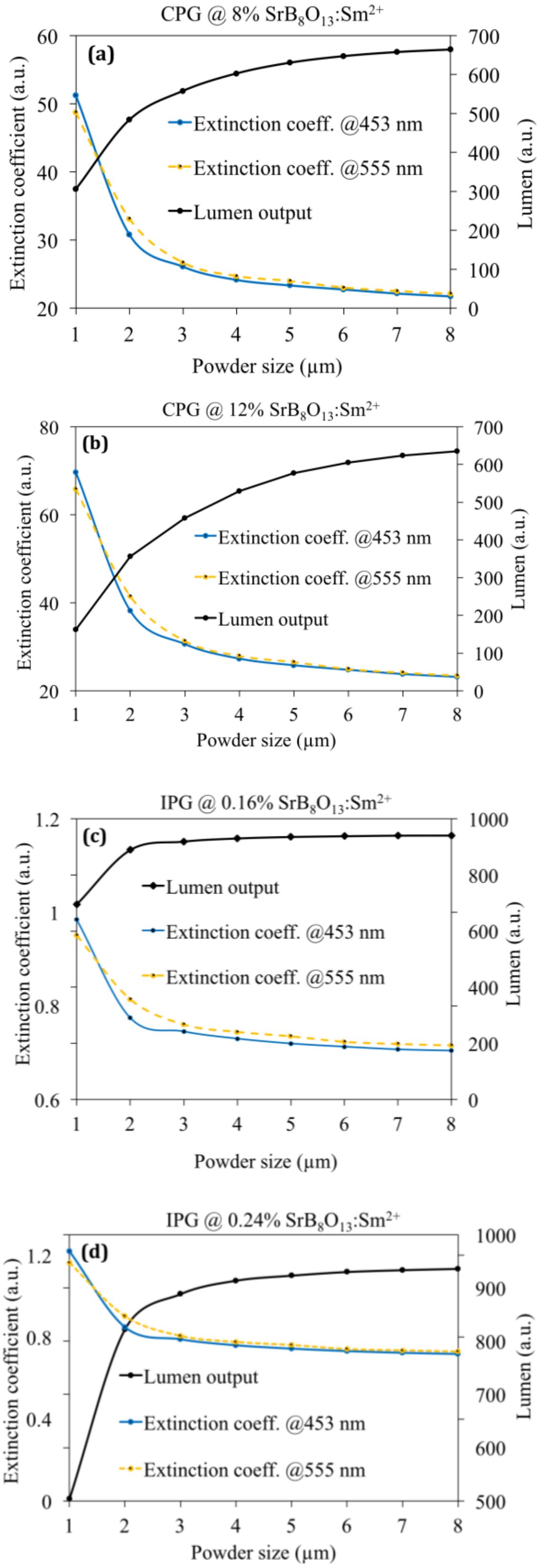

Fig. 5. Relation between the obtained lumen output of phosphor-converted WLEDs and the calculated extinction coefficient after doping SrB_8O_{13}:Sm^{2+}: (a) CPG with 8% SrB_8O_{13}:Sm^{2+}; (b) CPG with 12% SrB_8O_{13}:Sm^{2+}; (c) IPG with 0.16% SrB_8O_{13}:Sm^{2+}; (d) IPG with 0.24% SrB_8O_{13}:Sm^{2+}

With the thickness of phosphor layer is fixed for both CPG and IPG, both the number density distribution of particles N_r and the extinction cross-section C_{ext} are functions of the concentration and particle size of SrB_8O_{13}:Sm^{2+}. Hence, transmitted light power I changes accordingly with these 2 parameters. As the SrB_8O_{13}:Sm^{2+} particles size increases from 1 µm to 8 µm, continuously, the composite becomes more and more transparent to visible light, results in less scattering and absorption, thereby increasing lumen output and decreasing CRP. According to (1), the transmitted light power increases exponentially with the decreasing of the extinction coefficient, which is a direct results from the enlargement of SrB_8O_{13}:Sm^{2+} particle size. As a result, the higher luminous output can be emitted in comparison with zero size case SrB_8O_{13}:Sm^{2+} (0%). Reversely, the extinction coefficient tends to increase at higher concentration of SrB_8O_{13}:Sm^{2+}. With red-light component is compensated to WLEDs excessively, the transmitted light power I is forced to reduce. Consequently, the lower lumen output is emitted in comparison with the non-SrB_8O_{13}:Sm^{2+} case.

4. Conclusions

In this paper, the relationship between the key performance factors of WLEDs is the main topic, which we investigated and the detailed subject is CRP, lumen output, and the size and concentration of added SrB_8O_{13}:Sm^{2+} particles. Both conformal and in-cup phosphor packages are considered. It can be found that the size and concentration of SrB_8O_{13}:Sm^{2+} have contrary effects on CRP. In fact, the CRP grows with the increasing of SrB_8O_{13}:Sm^{2+} concentration while reducing with the expansion of SrB_8O_{13}:Sm^{2+} size. However, at high concentration of SrB_8O_{13}:Sm^{2+}, CRP starts to reduce. This leads to an optimal point, in which CRP values can exceed 86 for CPG. Moreover, the increasing of the SrB_8O_{13}:Sm^{2+} size also enhances the lumen output of WLEDs, which is confirmed by the Lambert-Beer law and the Mie-scattering theory.

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