The influences of calcium fluoride and silica particles on improving color homogeneity of WLEDs

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ABSTRACT

The LEDs lighting device with phosphor ingredient (pcLEDs) is among the most common lighting methods in recent years and evaluated by chromatic uniformity and lighting capacity. Therefore, we introduce the phosphor particles that can improve the scattering efficiency (SEPs) to apply in pcLEDs at 8500 K correlated color temperature (CCT) with the expectation to produce better pcLEDs by enhancing both quantity and quality of emitted light. Combining various materials such as CaF₂ and SiO₂ with yellow Y₃Al₅O₁₂:Ce³⁺ phosphor composition in the pcLEDs simulation created by the LightTools program is the mechanism of this research. The simulated pcLEDs are tested and the results will be verified with Mie-scattering theory. The observation of the simulation leads to the conclusion about the scattering coefficients of SEPs at 455 nm and 595 nm wavelengths. The calculation showed that CaF₂ is better for color homogeneity yet suffer from luminous flux deficiency as the concentration gets higher. On the other hand, SiO₂ is the scattering enhancement material that can maintain high luminous flux regardless of its concentration.

Keywords: CaF₂, Luminous flux, Mie-scattering theory, SiO₂

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1. INTRODUCTION

To improve the WLED quality, color homogeneity, luminous flux, and color rendering index are the focus points, despite the fact that these criteria can induce inner scattering of WLED [1-5]. A conventional method to create a pcLEDs is to combine the yellow Y₃Al₅O₁₂:Ce³⁺ phosphor with the silicone glue. The blue light after reaching the coating yellow Y₃Al₅O₁₂:Ce³⁺ phosphor is consumed thus stimulates the yellow light and can be employed to create white light with a color temperature of choice [5-8]. The white LEDs with conformal phosphor configuration similar to the one used in this paper usually has a yellow ring that can cause irritation to the viewer’s eyes. The cause of this incident is the imbalance of emitted blue and yellow radiation comes from the light source which resulting in inhomogeneous spatial color distribution [9, 10]. For further explanation, the scattering process weakens the blue light due to it being absorbed by the phosphor layer but boosts the yellow light that is the product of blue light converted from the phosphor layer. The range and
properties in the phosphor layer are distinct from the wavelengths, therefore, upon understanding the concept we instantly adapt it to change color homogeneity of pcLEDs. Wang’s group has the purpose of reducing color deviation from 761K to 171K at the average CCT of 600K. Their study subjects are pcLEDs with chromatic phosphor SiO$_2$, B$_2$O$_3$, PbO, Y$_2$Al$_2$O$_3$:Ce$^{3+}$ particles merged with silicone adhesive and placed in glass composite [11]. Besides, Lin’s group is in charge of assembling the HfO$_2$/SiO$_2$ DBR film to adjust the color deviation of pcLEDs at approximately 5000 K from 1758 K to 280 K [12]. Moreover, Yu’s group tests the remote micro-patterned phosphor film on pcLEDs at 5537 K and study its effectiveness in reducing the color deviation to 441 K [13]. The results confirm that applying these phosphor configurations is beneficial for the quality of spatial color homogeneity. Even though the benefits are undoubtedly valuable but they could not be widely used due to the high producing cost and difficult manufacturing requirements. Therefore, SEPs such as TiO$_2$, ZrO$_2$, microspheres and SiO$_2$ are more practical materials that can mix with yellow phosphor to create new phosphor compositions are being used [14-18]. The research conducted by Lee with his partner in 2010 which dispersed TiO$_2$ on pcLEDs to examine the possibility that color homogeneity can benefit from adding 0.1% TiO$_2$ to the encapsulated phosphor component. As a result of many attempts to enhance color homogeneity, numerous findings have been announced, such as Yang’s group demonstrated that using CaCO$_3$ can boost the scattering features of pcLEDs, specifically the spatial color homogeneity is greatly increased when adding 10% of CaCO$_3$[19]. Similarly, Anh’s group discovered that adding the SEP SiO$_2$ in the phosphor composition of pcLEDs can result in positive change relate to spatial color homogeneity. Besides, other aspects of SiO$_2$ can also affect pcLEDs, the positioning within pcLEDs influence the color quality, likewise the chromatic performance is also influenced by the magnitude of SiO$_2$ molecule [20]. From the results of other research, SEPs are good for the overall improvement of pcLEDs, however, an optimal SEP that can yield the biggest development is still undiscovered. The SEPs usage does not end there, previous research confirms that pcLEDs with one chip and emitted yellowish light can benefit from the improvements of color deviation and lumen output if the structure employs SEPs. Besides the type of SEPs, choosing the concentration and size for the SEP particle is important as it could enhance lighting performance and color quality with a suitable setting. This research aims to testify the influences of the CaF$_2$ and SiO$_2$ particles nominated above on optical properties of pcLEDs as well as measures their particular effect on enhancing the pcLEDs performance. The focus is to find optimal SEP material for different types of pcLEDs with distinct demands and explain how the SEPs improve color homogeneity and luminous flux using Mie theory along with Monte Carlo simulation. The contents of the article from this point onward are arranged into 3 sections with section 2 analyzes the inner circulation of light inside pcLEDs and contributes basic information for further experiments mentioned in section 3. Besides, section 3 also discuss the results about optical characteristics from the experiments. In section 4, we summarize the paper and give conclusions on the topic.

2. ANALYSIS ON THE SCATTERING EFFECT

Light scattering effect is a phenomenon caused by SEPs when it is in the pcLEDs with conformal phosphor structure according to the Mie-scattering theory and will be calculated with the help of MATLAB [21-25]. The following equations are the instruments for calculating the scattering coefficient $\mu_{\text{sca}}(\lambda)$, the anisotropy factor $g(\lambda)$, the decreased scattering coefficient $\delta_{\text{sca}}(\lambda)$ and the scattering amplitude functions $S_1(\theta)$ and $S_2(\theta)$:

$$\mu_{\text{sca}}(\lambda) = \int N(r) C_{\text{sca}}(\lambda, r) \, dr$$  \hspace{1cm} (1)

In (1), the $N(r)$ is the amount of diffusive molecule (mm$^3$), also known as diffusivity density distribution. $C_{\text{sca}}$ stands for scattering cross section (mm$^3$). $\lambda$ is the wavelength in nanometers and the radius of the SEPs particles are presented as $r$ (mm).

The scattering coefficients of CaF$_2$ and SiO$_2$ are computed and shown in Figure 1. From 380 nm to 780 nm, these scattering coefficients are different, which means there’s a difference in bright scattering. It is easy to see that the scattering coefficient of CaF$_2$ larger than SiO$_2$. Therefore, the color quality in the case of using CaF$_2$ would be better than SiO$_2$. However, it is necessary to identify the luminous flux that obtains when using these particles. The larger the scattering coefficient will benefit for color homogeneity, but not beneficial for luminous flux. The larger the scattering coefficient means the larger the scattering process, the light rays are mixed more times before the outside and result in a low color deviation. The scattering coefficient can be used to evaluate the level of scattering in pcLEDs. And this is the key point to controlling color homogeneity and luminous flux. For CaF$_2$ and SiO$_2$, the selection of appropriate concentration is important. Besides the size of CaF$_2$ and SiO$_2$ particles must also be of interest.
3. RESULTS AND DISCUSSION

This part shows the optical properties of SEPs pcLEDs mentioned above simulated by LightTools 8.1.0 program. The physical model is presented in Figure 2 (a) and components details are in Figure 2 (b). The measurements of the model reflector are 2.1 mm in depth, 8 mm inner and 10 mm on the surface. The arrangement within the pcLEDs can be observed from the cross-section Figure 2 (c). Finally, Figure 2 (d) illustrate the result of simulated LED device.

Figure 2. (a) Photograph of WLEDs sample, (b) Manufactoring parameter of WLEDs, (c) Illustration of 2D WLEDs model, (d) the simulated WLEDs model

The structure have 9 LED chips placed at the base under the phosphor materials. The density of the phosphor layer is fixed at 0.08 mm. SEPs are deemed as 0.5 \( \mu \)m spherical with the refractive indexes for CaF\(_2\) is 1.44, SiO\(_2\) is 1.54. Phosphor particles radius is 7.25 \( \mu \)m on average with 1.83 refractive index disregard to position in the visible spectrum. The silicone glue used in the experiment has its refractive index unchanged at 1.5. The distribution of particle density can change depends on the requirements for CCT uniformity and lighting efficacy.

\[
W_{\text{phosphor}} + W_{\text{silicone}} + W_{\text{SEP}} = 100\%
\]
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According to the formula above, $I_0$ is the optical power of incident light and $L$ is the density of phosphor coating (mm). $\mu_{\text{ext}}$ indicates the extinction coefficient that is computed by this equation: $\mu_{\text{ext}} = N_rC_{\text{ext}}$, where $N_r$ stands for the number density distribution of particles (mm$^{-3}$) and $C_{\text{ext}}$(mm$^2$) is the extinction cross-section of phosphor particles. Based on (4), a conclusion can be made that the higher the concentration of SEPs the lower the luminous flux of WLEDs. This incident is due to the emission energy being damaged by the increase of light scattering inside of the phosphor layers and high concentration of SEPs that cause back-scattering effect.

\[
I = I_0 \exp(-\mu_{\text{ext}}L) \tag{4}
\]

![Graph showing the comparison of luminous flux of pcLEDs adding CaF$_2$ (a) and SiO$_2$ (b)](image)

**Figure 4.** Comparison of luminous flux of pcLEDs adding CaF$_2$ (a) and SiO$_2$ (b)

### 4. CONCLUSION

The target of this research is to study the influences that SEPs might have on two quality-deciding properties of white LEDs devices, which are chromatic quality and luminous flux. Through applying the mechanism of Mie-scattering and Monte Carlo in the verification process, the results are approved and certain that with different types of particle the enhancements occur in pcLEDs are distinct. Correspondingly, this encourages the discovery of an optimal SEPs and concentration level for a specific occasion that benefits the optical performance of pcLEDs the most. Our findings in this particular article can serve as a guideline to manufacture WLEDs with predetermined requirements effectively or base knowledge for further development. Specifically, the CCT deviation opposes to the concentration of CaF$_2$ and SiO$_2$ which is a characteristic useful for CCT management, therefore, to reduce color deviation to the lowest possible using CaF$_2$ would be the suitable choice. With that being said, control over CaF$_2$ concentration is desirable as it prevents damage to luminous output caused by an excessive concentration. On another note, SiO$_2$ is the material that benefit the growth of luminous flux in pcLEDs with SiO$_2$ being the material that provides the lumen output.
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