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Influence of $CaCO_3$, CaF_2, SiO_2, and TiO_2 Scattering Particles' Concentration on Color Rending Index and Color Quality Scale of the Conformal Packaging Multi-chip White LEDs

Tran Hoang Quang Minh[1], Nguyen Huu Khanh Nhan[1], Nguyen Doan Quoc Anh[2]

[1]Optoelectronics Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[2] Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
tranhoangquanminh@tdt.edu.vn, nguyenhuukhanhnhan@tdt.edu.vn, nguyendoanquocanh@tdt.edu.vn

Abstract: In the last three decades, light emitting diodes (LEDs) had a huge improvement in technical implication due to its excellent advantages such as long lifetime, compactness, high luminous efficiency, environment factor, and low cost. In this paper, the improvement of optical properties (color rending index and color quality scale) of the white LEDs by adding scattering enhancement particles $CaCO_3$, CaF_2, SiO_2, and TiO_2 to the yellow-emitting YAG:Ce phosphor compounding was investigated. In the beginning, we built the physical model of multi-chip W-LEDs (MCW-LEDs) by using commercial LightTools 8.1.0 program. After that, we investigated, calculated and analyzed the influence of scattering enhancement particles on the color rending index (CRI) and color quality scale (CQS) of MCW-LEDs. Finally, the results were demonstrated the Mie-scattering theory with using the Mat lab software. The results indicated that all $CaCO_3$, CaF_2, SiO_2 and TiO_2 particles are influenced by the optical properties of MCW-LEDs. The highest CRI and CQS of W-LEDs can be obtained by adding $CaCO_3$ particles. This results and discussion provided important technical implication for materials development of MCW-LED applications.

Keywords: $CaCO_3$; CaF_2; SiO_2; TiO_2; MCW-LEDs; color rending index; .color quality scale, scattering particle.

1. Introduction

The last four decades have seen a growing trend towards in rapid development of light emitting diodes (LEDs) with compound semiconductor technology. Since the first red LEDs that was invented by Holonyak and Bevacqua in 1962 [1], considerable efforts have been put into the study to obtain brighter LEDs. In the decades that followed, LEDs were used extensively in digital displays and signaling applications. However, only around 1995 high brightness and blue LEDs were developed, which made it possible to use LEDs for general lighting. Nowadays, MCW-LEDs have attracted considerable attention from both general lightings manufacturers and consumers due to its excellent properties for display technology, including high brightness, low power consumption, long lifetime, fast response as well as climate impact resistance [2]. LEDs have a narrow emission spectrum. Generally, there are three different approaches which can be used for generating white light based on LEDs: (1) by mixing reds, greens, and blues, i.e. red–green–blue (RGB) LEDs, (2) by using an ultraviolet (UV) LED to stimulate RGB phosphors, and (3) by using a blue-emitting diode that excites a yellow-emitting phosphor embedded in the epoxy dome; the combination of blue and yellow light makes a white-emitting LED. The last method is commonly used in general lighting applications because of its simple procedure [3-7].

In this research, we concentrate on investigating the effect of scattering enhancement particles $CaCO_3$, CaF_2, SiO_2 and TiO_2, which commonly is employed for manufacturing higher-quality, on the color rending index (CRI) and color quality scale (CQS) of MCW-LEDs.

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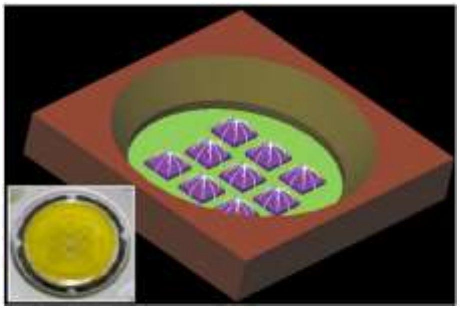
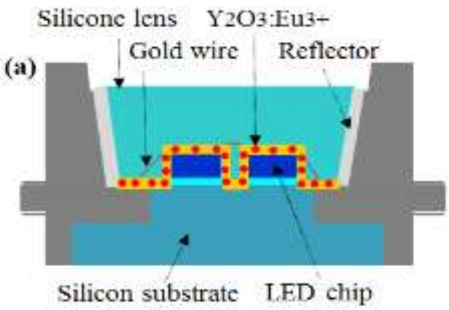
This paper has been divided into four parts. The first part deals with the physical model of 8500K W-LEDs by using commercial LightTools 8.1.0 program. In the second part, by varying concentration of scattering enhancement particles $CaCO_3$, CaF_2, SiO_2 and TiO_2 to YAG:Ce phosphor compounding, the CRI, and CQS is investigated and analyzed. Finally, the results can be convinced by using the Mie-scattering theory with Mat lab software. In this study, the results showed that the highest CRI and CQS of W-LEDs could be obtained by adding $CaCO_3$ particles. This result is the prospective solution for higher-quality manufacturing W-LEDs in the near future.

2. The MCW-LEDs physical model

a.



b.



c.

Figure 1. (a) The actual MCW-LED with conformal phosphor layer, (b) the physical model of MCW-LEDs, (c) the conformal phosphor structure

The simulations were carried out using the commercial software package Light Tools. The simulation comprised the setup of the conformal phosphor package (CPP) with average CCT of 8500 K. Firstly, to guarantee that our simulation results reflect precisely the impact of our considered parameters and are not biased by other factors such as LED's wavelength, waveform, light intensity, and operating temperature, we use the real-world model of the MCW-LEDs. This model possesses the best optical-thermal stability, hence, can minimize the variations caused by uninterested parameters. Secondly, to make the comparison fair, the same silicone lens and structures are used for CPP. Specifically, we set the depth, the inner and the outer radius of the reflector to 2.07 mm, 8 mm and 9.85 mm, respectively. Nine LED chips are covered by either CPP or IPP, which respectively have fixed thickness of 0.08 mm and 2.07 mm. Each blue chip has a dimension of 1.14 mm by 0.15mm, the radiant flux of 1.16 W, and the peak wavelength of 453 nm (Fig.1(a), 1(b)). Fig.1(c) shows that the phosphor layer of CPP is coated conformally on 9 LEDs. To maintain the average CCT of 8500 K, the YAG:Ce concentration changes to the concentration of $CaCO_3$, CaF_2, SiO_2, and TiO_2. The refractive index of the diffusors such is 1.66, 1.44, 1.47 and 2.87, respectively. The diffusers are assumed to be spherical and have radius 0.5 µm. The average radius of the phosphor particles are 7.25 µm and have a refractive index of 1.83 at all wavelengths of light. The refractive index of the silicone glue is 1.5. The diffusional particle density is varied for optimizing illumination CCT uniformity and output efficiency.

$$W_{phosphor} + W_{silicone} + W_{diffusor} = 100\% \qquad (1)$$

$W_{silicone}$, $W_{phosphor}$ and $W_{diffusor}$ are the weight percentages of the silicone, phosphor, and diffuser of the phosphor layer in the W-LEDs, respectively. If the weight percentage of the diffuser is increased, the weight of YAG:Ce phosphor needs to be reduced for maintaining the mean CCT value of 8500 K.

3. Results and discussion

CRI and CQS are the main optical properties of W-LEDs. In this article, by varying scattering particles' concentration from 0% to 35 %, CRI and CQS were calculated and displayed in Fig. 2. From result we can see that if the red-light is compensated enough by the scattering particles, resulting in higher CRI. The highest CRI values is presented at 10% SiO_2 and 20% $CaCO_3$ cases in comparison with other substances. On another side, Fig. 3 show the influence of scattering particles' concentration on CQS of W-LEDs. In this case, CQS of $CaCO_3$ and TiO_2 cases increased remarkably. However, CQS of CaF_2 and SiO_2 slightly increased. The highest CQS can be obtained around 70 with 35% concentration TiO_2 and $CaCO_3$.

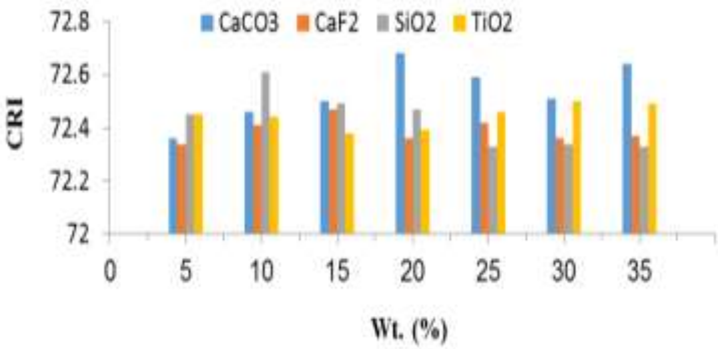


Figure 2. The influence of the $CaCO_3$, CaF_2, SiO_2 and TiO_2 particles concentration on CRI

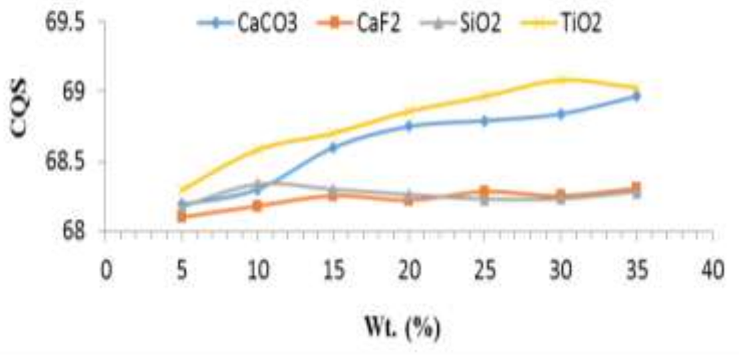


Figure 3. The impact of the $CaCO_3$, CaF_2, SiO_2 and TiO_2 particles concentration on CQS

The result can be investigated and demonstrated by Mat lab software using Mie-scattering theory [8,9,10]. The scattering coefficient $\mu_{sca}(\lambda)$ can be calculated by expression:

$$\mu_{sca}(\lambda) = \int N(r)C_{sca}(\lambda, r)dr \quad (2)$$

Where $N(r)$ is the number density distribution of diffusional particles (per cubic millimeter), C_{sca} is the scattering cross sections (per square millimeter).

$$N(r) = N_{dif}(r) + N_{phos}(r) = K_N.[f_{dif}(r) + f_{phos}(r)] \quad (3)$$

$N(r)$ is composed of the diffusive particle number density $N_{dif}(r)$ and the phosphor particle number density $N_{phos}(r)$. $f_{dif}(r)$ and $f_{phos}(r)$ are the size distribution function data of the diffusor and phosphor particle. K_N denotes the number of the unit diffusor for one diffuser concentration and K_N can be obtained by:

$$c = K_N \int M(r)dr \quad (4)$$

To obtain K_N, we should first know the mass distribution $M(r)$ (milligrams) of the unit diffusor. $M(r)$ can be expressed by:

$$M(r) = \frac{4}{3}\pi r^3[\rho_{dif} f_{dif}(r) + \rho_{phos} f_{phos}(r)] \quad (5)$$

$\rho_{diff}(r)$ and $\rho_{phos}(r)$ are the density of diffusor and phosphor crystal.

In this case, C_{sca} is normally calculated by the following:

$$C_{sca} = \frac{2\pi}{k^2}\sum_{0}^{\infty}(2n-1)(|a_n|^2 + |b_n|^2) \quad (6)$$

Here k is the wave number $(2\pi/\lambda)$, and a_n and b_n are the expansion coefficients with even symmetry and odd symmetry, respectively. These coefficients calculated by:

$$a_n(x,m) = \frac{\psi_n'(mx)\psi_n(x) - \mathrm{m}\psi_n(mx)\psi_n'(x)}{\psi_n'(mx)\xi_n(x) - \mathrm{m}\psi_n(mx)\xi_n'(x)} \quad (7)$$

$$a_n(x,m)=\frac{m\psi_n^{'}(mx)\psi_n(x)-\psi_n(mx)\psi_n^{'}(x)}{m\psi_n^{'}(mx)\xi_n(x)-\psi_n(mx)\xi_n^{'}(x)} \tag{8}$$

Where x is the size parameter, m is the refractive index of the scattering diffusive particles, and $\psi_n(x)$ and $\xi_n(x)$ are the Riccati - Bessel function.

This theoretical result can be modified in the following angular scattering amplitudes simulation of Fig.4 and Fig.5. On the another way, Fig. 6 show the varying of the scattering coefficients of $CaCO_3$, CaF_2, SiO_2 and TiO_2 particles while the scattering particles' concentration change continuously from 0% to 35 %.

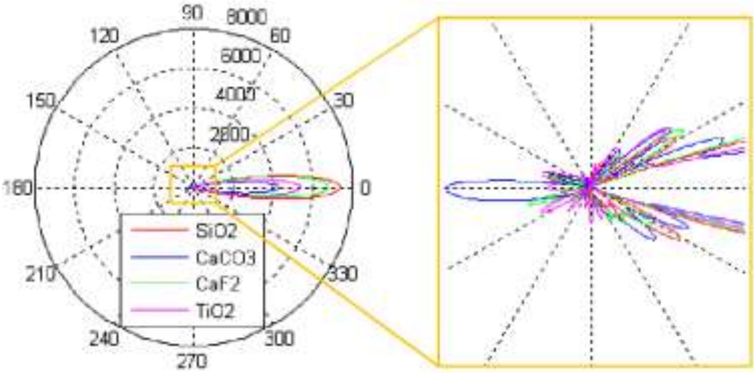


Figure 4. The angular scattering amplitudes of $CaCO_3$, CaF_2, SiO_2 and TiO_2 particles for blue light = 455 nm.

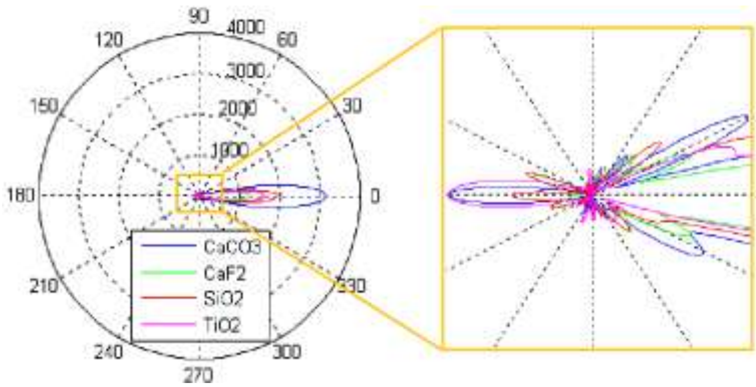


Figure 5. The angular scattering amplitudes of $CaCO_3$, CaF_2, SiO_2 and TiO_2 particles for yellow light = 595 nm.

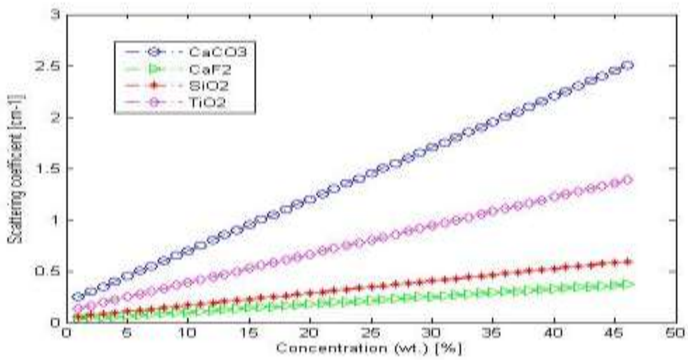


Figure 6. Scattering coefficients of $CaCO_3$, CaF_2, SiO_2 and TiO_2 particles

3. Conclusion

In this research, the influence of $CaCO_3$, CaF_2, SiO_2, and TiO_2 on CQS and CRI of 8500 K MCW-LEDs was proposed and demonstrated. From the results, some conclusions could be offered:

1) The CRI and CQS had an increasing tendency when the concentration of $CaCO_3$ and TiO_2 increases;

2) Meanwhile, CQS and CRI of CaF_2 and SiO_2 cases grow slightly with their concentration;

3) The best CRI and CQS of W-LEDs can be obtained in $CaCO_3$ case. Summary, $CaCO_3$ particles should be chosen for improving the CQS and CRI of W-LEDs.

This study provides important technical implication for the material development of MCW-LEDs applications. In the further works, the influence of $CaCO_3$, CaF_2, SiO_2, and TiO_2 particles' size on optical properties of MW-LEDs is necessary to present, investigated and demonstrated.

4. References

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TRAN Hoang Quang Minh received his Ph.D. from Tomsk Polytechnic University, Tomsk, Russian Federation. His research interests include high-voltage power systems, relay protections and optoelectronics. He serves as Lecturer in the Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam.

NGUYEN Huu Khanh Nhan optained his Ph.D. from the Institute of Research and Experiments for Electrical and Electronic Equipment, Moscow, Russian Federation. He serves as Lecturer in Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research interests include VLSI, MEMS and LED driver chips.

NGUYEN Doan Quoc Anh received his Ph.D. from National Kaohsiung University of Applied Sciences, Taiwan. His research interests focus on optoelectronics, including multi-chip white light LEDs, free-form lenses, and optical materials. He serves as Lecturer in Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam.