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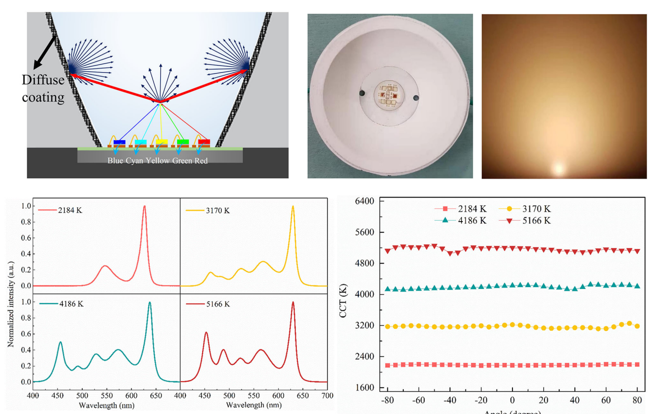

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Angular Color Uniformity Enhancement for Color-Mixed LEDs by Introducing a Diffusing Coating Layer

Xin Zhu, Guangxu Wang, Xin Luo, Jianli Zhang, Junlin Liu, and Xing Guo

National Institute of LED on Si Substrate, Nanchang University, Nanchang 330096, China

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Abstract: In this study, a simple and low-cost method is proposed to enhance angular color uniformity (ACU) of color-mixed light-emitting diodes (cm-LEDs) by introducing a diffuse coating layer. Optical models of the proposed cm-LEDs packaging modules were constructed by Monte Carlo ray-tracing simulation. The simulation results demonstrate the ACU enhancement of the cm-LEDs packaging modules with the application of the diffuse coating layer on the reflection cup. Owing to the strong light scattering and diffuse reflection effects of the diffuse coating layer, the different color light emitted from the different chip are sufficiently mixed. The diffuse coating layer was fabricated by spraying method. Its optical performance was demonstrated by experiments. The correlated color temperature (CCT) deviations of the cm-LEDs applying the diffuse coating layer have been reduced from 1174 K to 138 K at viewing angles ranging from -80° to $+80^\circ$. A lowest luminous flux loss of 3.54% is obtained. The diffuse coating layer could also maintain the excellent ACU performance when the average CCTs changes from about 2000 K to 5200 K. Extremely low CCT deviations were obtained, which are less than 300 K at average CCTs ranging from 2000 K to 5200 K. The results demonstrate that the diffuse coating layer is a feasible and effective method to enhance the ACU of the cm-LEDs.

Index Terms: Color-mixed LEDs (cm-LEDs), angular color uniformity (ACU), diffuse coating layer, correlated color temperature (CCT) deviations, luminous flux loss.

1. Introduction

Due to advantages over traditional light sources in terms of efficiency, life time, reliability and environmental protection, white light-emitting diodes (LEDs) have widely penetrated into many illumination applications, such as backlighting, street lighting, headlamp and interior illumination [1]–[3]. There are two main approaches to obtain white LED sources. One of the most popular methods is using a blue LED excitation long wavelength phosphor (such as red, yellow and green phosphor, etc.) to obtain white light (pc-LEDs) [4]. The other is using color-mixed LEDs (cm-LEDs), which is based on multicolor LED chips (such as red, yellow, green and blue LED, etc.) to produce white light [5]. In the first method, the conversion efficiency of phosphor is limited due to the photon energy loss in the short to long wavelength conversion process [6]. Furthermore, there is a serious reabsorption of short wavelength light by the long wavelength phosphor, which reduces the luminous efficiency [2]. Due to the phosphor aged with time, the light sources faced problems of LED luminous efficiency decline, CCT drift and life reduction, and phosphors would cause pollution to the environment. By contrast, the cm-LEDs would be no wavelength down conversion, and therefore no phosphor conversion losses. Its ultimate “upper potential” might be on the order of 330 lm/W, while that of pc-LEDs is 250 lm/W [7]. Moreover, cm-LEDs is more flexible for chromaticity tuning and hence for “smart” lighting [5]. Due to advantages of cm-LEDs in luminous efficiency and color quality, it is foreseeable that cm-LEDs would be the development trend of solid state lighting technology of the next generation. Recently, we have greatly improved the efficiency of InGaN-based yellow and green LEDs, which makes cm-LEDs become possible. At current density of 20 A/cm^2, the wall-plug efficiency (WPE) of yellow (dominant wavelength of 565 nm) and green (dominant wavelength of 520 nm) LEDs on the silicon substrate have reached 24.3% and 41.3%, respectively [8]. However, the Lambertian light intensity distribution mismatch from each colored LED results in color separation and color nonuniformity. Thus, one of the challenges for cm-LEDs packaging is to produce a better angular color uniformity (ACU).

A bad ACU discomforts the customers’ eyes and limits its illumination applications and extensions. Therefore, it is necessary to improve the ACU of cm-LEDs. In the traditional pc-LEDs, the scattering of phosphor is itself an effective way to realize the ACU improvement. Moreover, changing the morphology of the phosphor layer by different processing methods to make optical path of blue light consistent at all viewing angles is an effective way to realize the ACU improvement [9]–[11]. Adding nano/micro particles in the phosphor layer to enhance light scattering is also a simple method to improve ACU [12]–[14]. To provide a uniform color distribution for cm-LEDs, many different optical elements are used, including diffractive structures, light guides, lenses, prisms, and optical diffusers [15]–[17]. Among these elements, the light guide pipe is attractive for color mixing of cm-LEDs because they can be configured into different shape. Zhao *et al.* performed an experiment to explore the possible use of a circular or rectangular light pipe as the mixing element for cm-LED systems [18]. However, lengths of light guides and mixing rods could be too long for cm-LEDs and this results in high additional efficiency loss. Besides, the packing density and the configuration of LEDs array would affect color mixing and uniform LEDs illumination. Whang *et al.* presented different configurations of LED arrays to achieve uniform illumination distributions and the desired beam angle [19]. zhu *et al.* designed the configuration of LED array and diffuse reflection surface to realized uniform illumination [20], [21]. In these work, the researchers only focus on the improvement of illumination uniformity, and the ACU is not considered. Furthermore, adding nano/micro particles in encapsulation layer could realize light mixing, however it causes a strong back scattering [22]. Microlens arrays (MLAs) fabricated on surface of encapsulation layer is also an effective scattering structure to improve color mixing. Unfortunately, MLAs fabrication is always complex and difficult [23], [24]. It is well known that diffuse reflection coatings are widely used to realize light control, which play an important role in improving the optical performance. A porous scattering coating with a 99% reflectivity was obtained using micro-foam processes by Kuo *et al.* [25]. Kim *et al.* [26] roughened the reflector surface through bead blasting to enhance diffuse reflection and reduce the re-absorption of light by the LED chip. These research focused on the applications of diffuse reflective coatings on reflectors for light extraction, but ignored the applications of diffuse reflective coatings to enhance color mixing. Tang *et al.* [27] fabricated abricated poly(lactic-coglycolic acid) (PLGA) nanofiber films through an electrospinning method. The nanofiber films shows a reflectance of 98.8% and witness a CCT deviation decrease to 1407 K and a luminous efficiency improvement of 11.66% for pc-LEDs. However, the electrospinning method is costly and time consuming [28].

In this study, we propose to realize ACU improvement of cm-LEDs through fabricating a diffuse coating layer on reflector cup by a simple spraying method. Optical models of the proposed cm-LEDs packaging modules were presented by Monte Carlo ray-tracing simulation to study the effect of the diffuse coating layer on the ACU performance of cm-LED packaging modules. Experiments were conducted for performance verification. The cm-LEDs modules were packaged by the reflector cup with diffuse coating layer and their optical performances were investigated in detail.

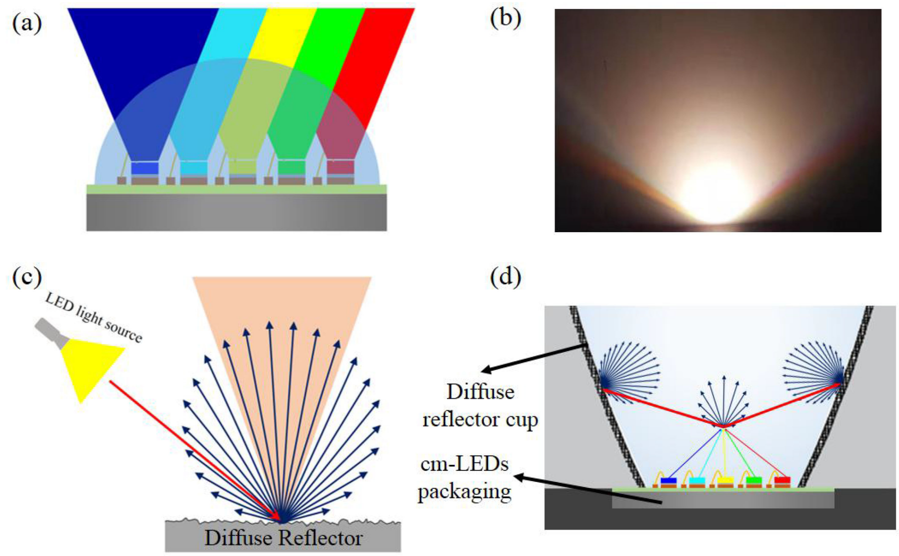

Fig. 1. (a) The schematic of typical color mixing of the cm-LEDs packaging module, (b) Light pattern produced by the cm-LEDs, (c) The schematic of diffuse reflection, and (d) cm-LEDs with a diffuse reflector cup.

2. Principle and Simulation

For the cm-LEDs, the light emitted from the packaging module shows different CCTs at various view angles due to Lambertian light intensity distribution mismatch, which is caused by the difference in spatial location distribution of multi-color LED chips. The light emissions of the cm-LEDs packaging modules without additional optics is shown in Fig. 1(a). The light from different colored LED chips would refract on the curvature surface of the lens and produce different emitted patterns of the colored LED chips, as shown in Fig. 1(b). There are some colorful stripes on the edge of the light pattern. The rays of different colors are spatially separated after redirected by the curvature surface of the primary lens. This causes color fringes and colored shadows.

In this paper, a diffuse reflection surface is used for cm-LEDs packaging to improve color uniformity. Diffuse reflection, as shown in Fig. 1(c), is the reflection of light from a surface that a ray incident on the surface is scattered at many angles rather than at just one angle as in the case of specular reflection [26]. An ideal diffuse reflecting surface is to show Lambertian reflection, meaning equal luminance in all directions. Therefore, the diffuse reflection could improve color mixing. The schematic of cm-LEDs packaging with a diffuse reflector cup is shown in Fig. 1(d).

Ray-tracing simulations have been performed to confirm the benefits of color mixing of a diffuse coating layer. Conducting the Monte Carlo ray-tracing simulation thtough a commercial software, namely, TracePro (Lambda Research Corporation), we simulated optical performance of the cm-LEDs packaging with specular and diffuse reflector cups. We assumed that refractive index $n_{\mathrm{silicone}} = 1.54$, $n_{\mathrm{air}} = 1.0$ (above cup), specular reflector cup reflectance $R_{\mathrm{specular}} = 98\%$, and diffuse reflector cup reflectance $R_{\mathrm{diffuse}} = 90\%$. The height of reflector cup was set as 7 mm, LED chip size was 1 mm $\times$ 1 mm $\times$ 0.2 mm. The LED chip included p-GaN, multiple quantum wells (MQWs), n-GaN, and Si substrate. The upper surface of the Si substrate layer was coated with an Ag reflective layer (reflectance of 92%) to reflect the light emitted from the MQW active layer. The chip layer material refractive index was set as $n_{\mathrm{p\text{-}GaN}} = 2.42$, $n_{\mathrm{MQWs}} = 2.54$, and $n_{\mathrm{n\text{-}GaN}} = 2.45$, respectively, and absorption coefficient was $\eta_{\mathrm{p\text{-}GaN}} = 5$ /mm, $\eta_{\mathrm{MQWs}} = 8$ /mm, and $\eta_{\mathrm{n\text{-}GaN}} = 5$ /mm, respectively. In addition, the optical properties of the upper surface of the package substrate was set as 70% total reflection coefficient and 15% diffuse reflection coefficient. Fig. 2 shows the simulation results of light pattern on the target plane of cm-LEDs with a specular and diffuse reflector cup. There are some color separations in the light pattern of cm-LEDs packaging with the specular reflector

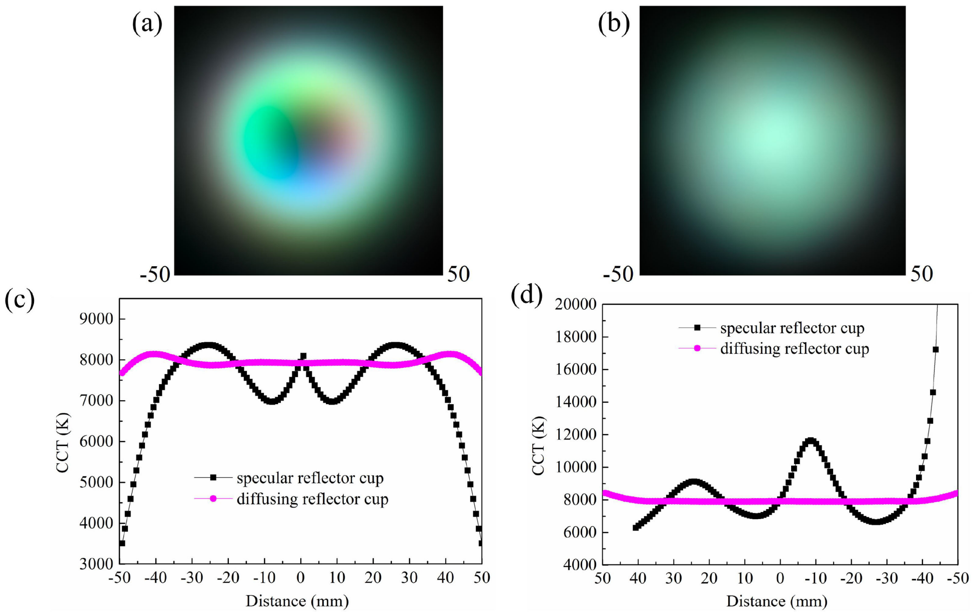

Fig. 2. The ray-tracing simulation light pattern of cm-LEDs (a) with a 7 mm specular reflector cup and (b) with a 7mm diffuse reflector cup. (c) and (d) the cm-LEDs CCT distribution from left to right and from top to bottom corresponding to (a) and (b).

cup (Fig. 2(a)), while the using of diffuse reflector cup resulted in remarkable improvement of color uniformity (Fig. 2(b)). The simulated CCT distributions of the cm-LEDs with a specular and diffuse reflector cup are shown in Fig. 2(c) and (d), respectively. It can be noted that the CCT distribution curves of the diffuse reflector cup are flatter when compared with that of the specular reflector cup. In specular reflection, each incident ray is reflected at the same angle to the surface normal [29]. For diffuse reflection, a ray incident on the surface is scattered at many angles rather than at just one angle [30]. Therefore, diffuse reflection enhances the probability of different color light traveling in all directions, increases the color mixing between different color light, and improves the color uniformity obviously.

3. Experiment

3.1 Sample Preparation

The high concentration titanium dioxide (TiO_2) nanoparticle and polyester resin composite was chosen as the coating materials. As shown in Fig. 3, the parabolic reflector of aluminum plates were used as the deposition substrates for coating layer. TiO_2 coating is sprayed on the surface of reflector cup through the compressed air sprayer, where the spray pressure was set as 60 psi and the distance between the sprayer and the collector was about 20 cm. Subsequently, the reflector cups with TiO_2 coating were baked in an oven at 50 °C for 30 minutes for the curing of the TiO_2/polyester resin composite.

For the packaging of high-power cm-LEDs, the multi-color LED chips were directly bonded on the MCPCB (Metal Core Printed Circuit Board) substrate to produce diode arrays. The vertical structure LED chips with the size of 1 mm $\times$ 1 mm $\times$ 0.2 mm were bonded on the substrate. For the LED chips, we used blue LED chip with a dominant wavelength of 460 nm, cyan LED chip with a dominant wavelength of 490 nm, green LED chip with a dominant wavelength of 525 nm, yellow LED chip with a dominant wavelength of 565 nm, and red LED chip with a dominant wavelength of 620 nm. Each color chips were electronically connected by gold wire bonding process in series. Here, we used the strong scattering ability of the diffuse coating layer to realize color mixing of the

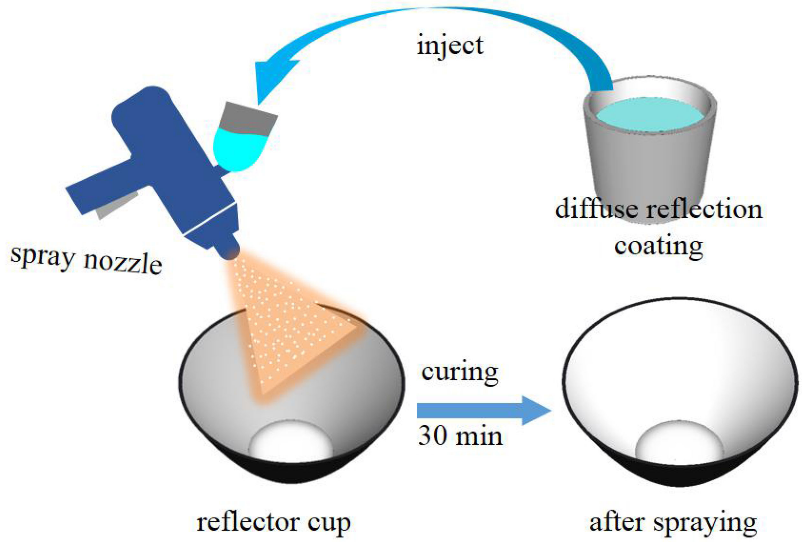

Fig. 3. Schematic of fabrication of diffuse reflection structure on the surface of reflector cup.

light emitted from different color chips. The reflector cup with diffuse coating layer was assembled on the top of substrate. Then silicone (Dow Corning, OE6636) was prepared with a weight ratio of A:B = 1:2 and filled up with the reflector cup to enhance light extraction from LED chips. Finally, the entire packaging module was baked at 150°C for 1 h for silicone curing.

3.2 Optical Performance Measurement and Characterization

In this paper, optical images of cm-LEDs modules were measured by digital microscope (BX51M, OLYMPUS, Japan). The average CCTs, luminous efficiency, and color rendering index (CRI) of each LED packaging module were measured by an integrating sphere (HAAS-2000, Everfine, China). The angular CCT distributions of the LED modules were measured by a spatial spectral distribution measuring instrument (GO-SPEX100, Everfine, China). During the testing process, the tested LED light sources rotate around an angle of (γ/Gamma plane) $\pm 90^\circ$ and rotate around itself with an angle of (C plane) $\pm 180^\circ$ (or 0-360°). The bidirectional reflectance distribution function (BRDF) properties were measured by BRDF Measurement System (Customization). The diffuse reflectance measurements were conducted by an ultraviolet to visible light spectrophotometer equipped with a 60 mm-diameter integrating sphere (dual-beam UV-Vis spectrophotometer TU-1901).

4. Result and Discussion

4.1 Optical Performance of Diffuse Coating Layer

Fig. 4(a) shows the cm-LEDs packaging module with a parabolic reflector cup of aluminum plates. Fig. 4(b) presents the cm-LEDs packaging module and the TiO_2 coating layer is covered on the reflector cup uniformly. The corresponding light pattern projected on a target surface of cm-LEDs packaging modules with specular and diffuse reflector cup are illustrated in Fig. 4(c) and (d). With the application of the TiO_2 coating layer, the color separation is eliminated and the color uniformity is improved obviously. Fig. 4(e) shows the optical image of the surface morphology of diffuse coating layer. The TiO_2 nanoparticle and the irregular structures on the surface of coating layer cause the light scattering and diffuse reflection effects [31]. The optical properties of the diffuse coating layer were systematically tested, including the BRDF and the diffuse reflectance. The asymmetric

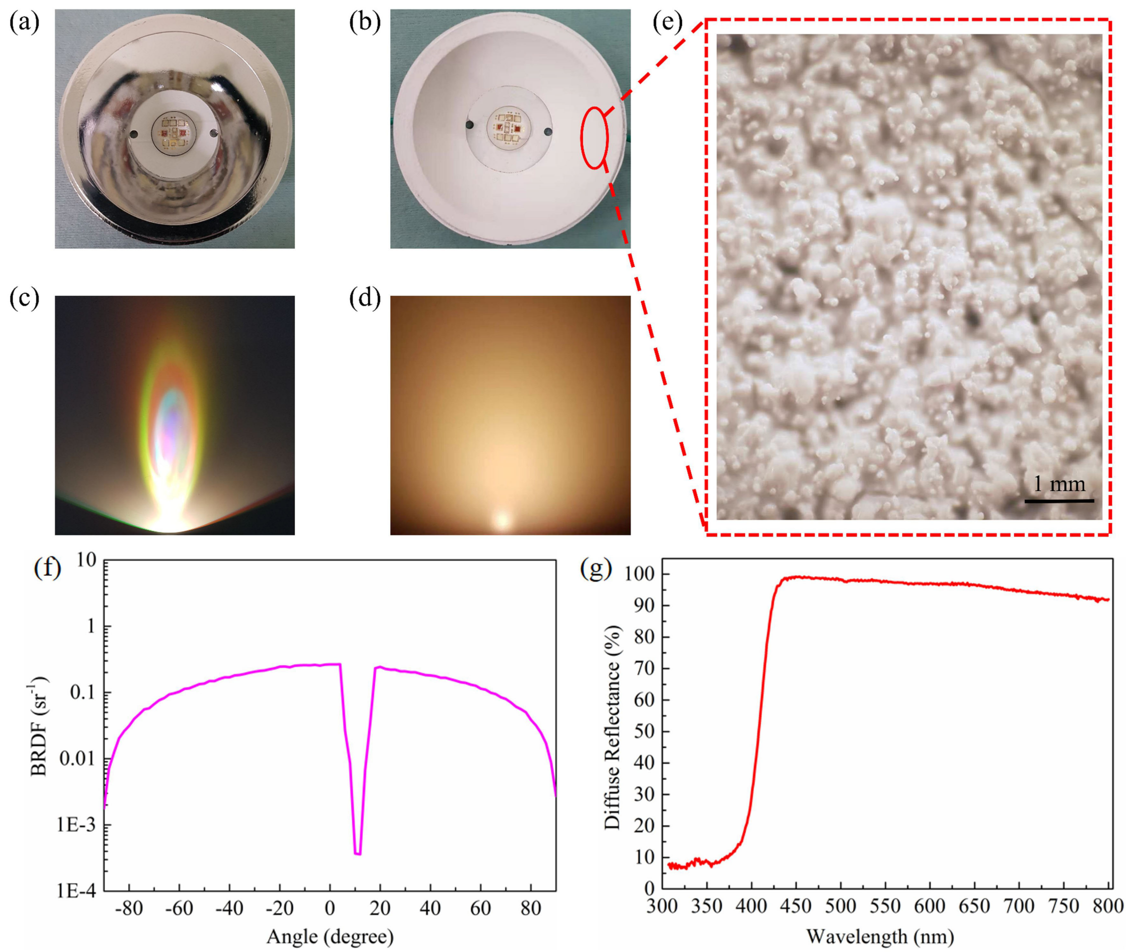

Fig. 4. The cm-LEDs modules assembled with (a) a specular reflector cup and (b) a diffuse reflector cup. The projected light pattern of cm-LEDs source (c) without and (d) with diffuse reflector cup. (e) Digital optical micrograph of diffuse coating layer. (f) The distribution of the measured BRDF of the diffuse coating layer. (g) The diffuse reflectance of the diffuse coating layer.

BRDF has been widely employed to characterize scattering properties [32], here, it was utilized to study the diffuse reflectance characteristics of the TiO_2 coating layer. The large diffuse reflectance and a flatter BRDF curve could enhance light scattering property and light extraction efficiency [27]. Fig. 4(f) shows the distribution of the BRDF of the diffuse coating layer. The BRDF changes slightly and there is no specular reflection peak in the distribution curve. It implies that light is dominantly scattered and is partly reflected along the specular direction [32], [33]. The average diffuse reflectance in the 430-780 nm wavelength range is about 96.36% (shown in Fig. 4(g)). The BRDF and diffuse reflectance measurement results show that the diffuse coating layer contributes greatly to the light scattering. The light scattering on its surface may change the direction of light transmission, thus enhancing the light mixing.

4.2 Application of Diffuse Coating Layer on 3000K cm-LEDs for ACU Improvement

The cm-LEDs packaging without reflector cup, with a specular, and with a diffuse reflector cup were denoted as sample 1, sample 2 and sample 3. The spatial spectral distribution of four C planes (C0°/180°, C45°/225°, C90°/270°, and C135°/315°) was recorded as shown in Fig. 5(a). To measure the CCT distribution accurately, the distance between the CCT recorder and the LED

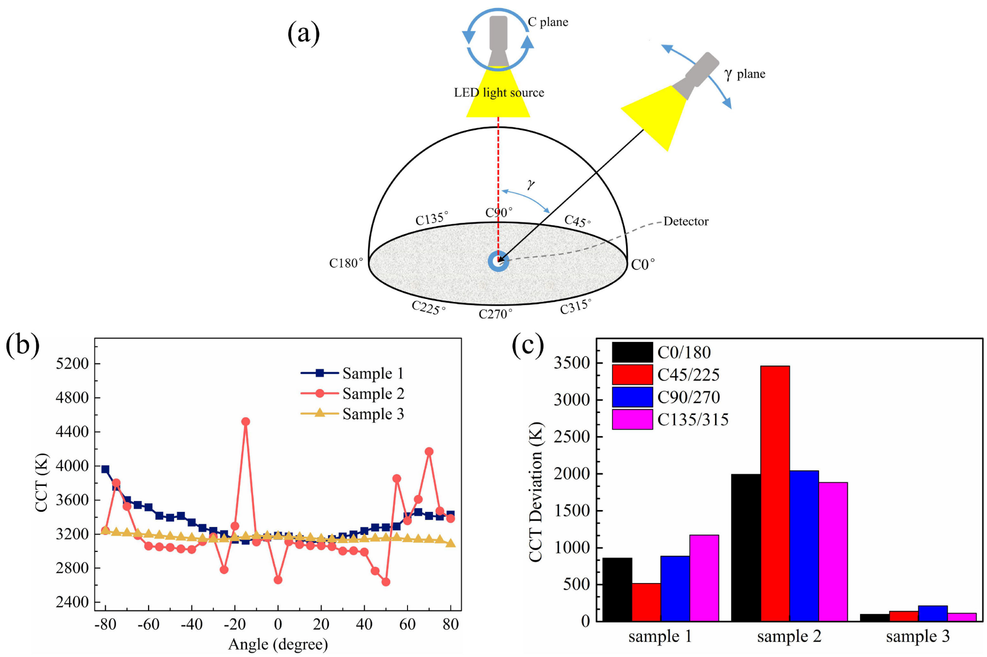

Fig. 5. (a) The schematic of the measurement of color uniformity. (b) Angular color distributions and (c) CCT deviation of cm-LEDs packaging without reflector cup, with a specular and a diffuse reflector cup at the average CCT of about 3000 K.

packaging module was set as 1 m. On each C plane, the CCT of the LED packaging module was recorded every 5° for the viewing angle changing from $-80°$ to $+80°$. For each sample, the CCT distribution of the C plane with the maximum CCT deviation is indicted in the Fig. 5(b). The CCT deviations of all the four C plane of three samples are shown Fig. 5(c). Here, the CCT deviation is defined as the difference between the maximum and minimum CCTs on the corresponding C plane. It can be noted that the CCT distribution curve of the sample 1 is concave with the maximum CCT occurring on the side. The CCT at large view angle is much higher, caused by the light escaping without sufficiently color mixing. Due to the mismatching of Lambertian intensity radiation of each LED chip, the light intensity of different wavelength chip is various in the free space, which causes the color separation and large CCT deviation. For the sample 2, the CCT distribution curve shows a sharp fluctuation, which mainly caused by specular reflection that each incident ray is reflected at one angle to the surface normal. However, the CCT distribution curve of sample 3 is more flat. The reduction of CCT at large view angles attributes to the light scattering and diffusion reflection ability of the coating layer, which improves the ACU, and the corresponding CCT deviation is smaller (shown in Fig. 5(b)). At an average CCT of about 3000 K, the maximum CCT deviation of sample 1 and sample 2 is about 1174 K and 3459 K, respectively, while it is only about 213 K for the sample 3. For a TiO_2 coating layer, the light scattering on its surface change the transmission direction of light with different wavelength, thus enhancing the color mixing.

The diffuse coating layer deposited on the LED reflector shows significant light scattering properties, which effectively realizes color mixing and achieves a uniform CCT distribution. As a key parameter that influence the color mixing and light extraction of the cm-LEDs, the effects of the height of reflector cup was studied. In theory, the higher the height of the reflective cup, the better the color mixing performance (due to the higher the proportion of diffuse reflection). But in practice, we also need to consider the size of the structure and the light extraction property. In this study, we used reflector cups with a height range of 3 to 13 mm. The spatial spectral distributions of cm-LEDs packaged with different height of diffuse reflector cup were measured. Fig. 6(a) shows the angular CCT distributions at plane of the maximum CCT deviation. The result shows that the

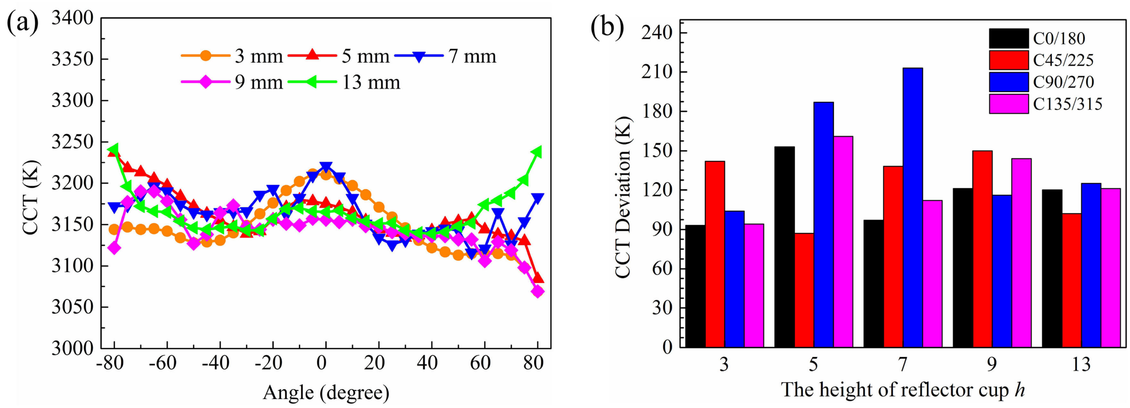

Fig. 6. (a) The angular CCT distributions at plane of the maximum CCT deviation of cm-LEDs modules with different height of the diffuse reflector cup. (b) CCT deviations of cm-LEDs modules with different height of reflector cup *h*.

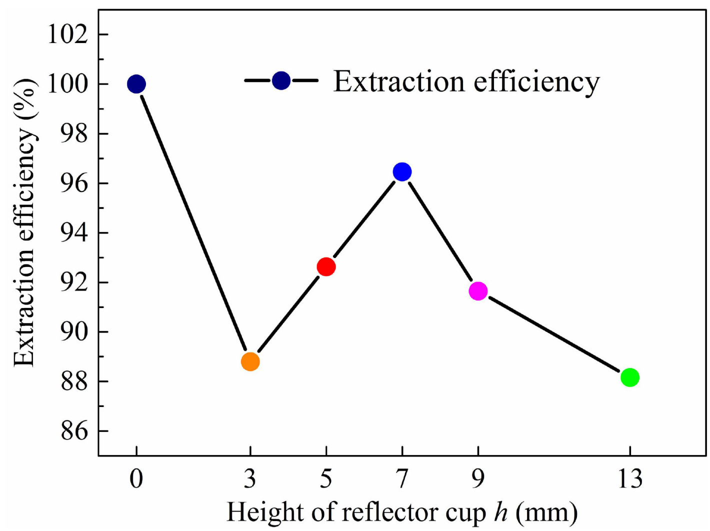

Fig. 7. Extraction efficiency as a function of the height of reflector cup h. The height of 0 mm is that the cm-LEDs module is packaged with a hemisphere lens.

CCT distribution of all the samples exhibits a minor fluctuation. The CCT deviations of different C plane as a function of the height of reflector cup *h* are shown in Fig. 6(b). The CCT deviations of all C plane less than 300 K are obtained. Compared with the maximum CCT deviation of 1174 K (shown in Fig. 5(b)) by the sample without reflector cup, the maximum CCT deviation of the sample with a 13 mm diffuse reflector cup is only 125 K. The diffuse reflection surface could effectively reduce the CCTs of large viewing angle and enhance the ACU.

The light extraction efficiency (LEE) is also an important factor when introducing the diffuse coating layer for cm-LEDs packaging. Here, we defined the LEE as the ratio of luminous flux of cm-LEDs packaging modules with diffuse reflector cup to that of cm-LEDs packaging modules without reflector cup. As shown in Fig. 7, the LEE decreases overall with the application of diffuse coating layer. The measured average diffuse reflectance of the coating layer is about 96.36% (430–780 nm). Consequently, a small amount of the incident light is absorbed by the diffuse coating layer, which leads to a small LEE reduction. With the height of diffuse reflector cup increasing from 3 mm to 13 mm, the LEE increases initially and then decreases. The diffuse reflector cup with a height of

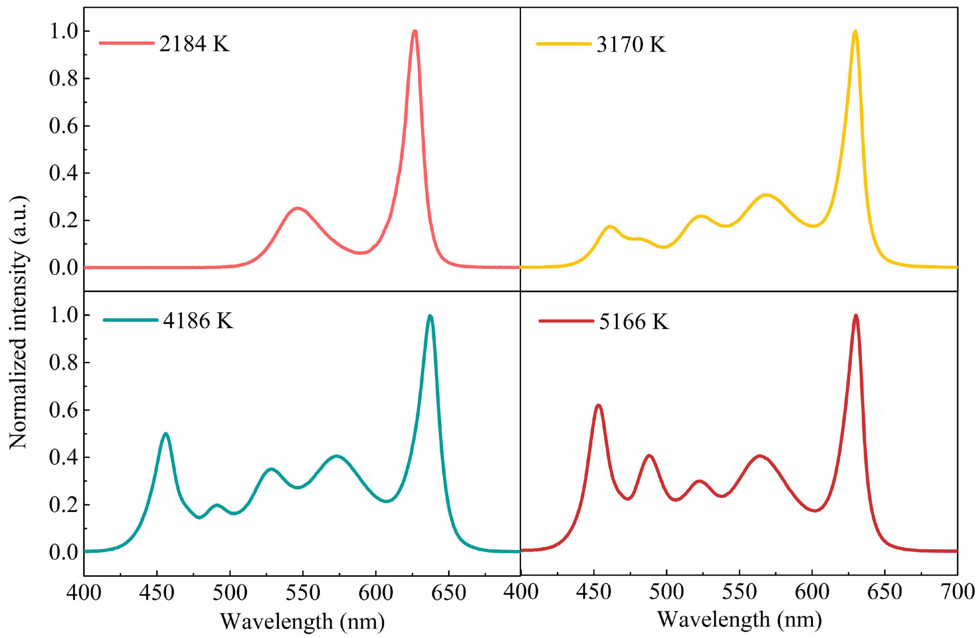

Fig. 8. (a) The normalized spectral power distributions of cm-LEDs with different average CCTs.

7 mm exhibits the maximum LEE of about 96.46%. When the height is lower than 7 mm, the lower the height, the larger the probability of the light being reflected to the LED chips and substrate due to the total internal reflection of silicone-air interface. The LEE reduction may be mainly caused by the absorption loss of the chips and substrate. When the height is larger than 7 mm, more emitted light could be reflected and scattered by the diffuse coating layer. The absorption of the coating layer may be dominant and the LEE reduction is increased with the height as more light reflects on the diffuse reflector cup surface. The optimal diffuse reflector cup height exhibits a luminous flux loss of only 3.54% with a CCT deviation of 213 K. Therefore, by using the proposed packaging structure, the diffuse coating layer exhibits an excellent ACU and a high LEE.

4.3 Application of Diffuse Coating Layer on cm-LEDs With Different Average CCTs for ACU Improvement

To adequately study the effect of the diffuse coating layer on the ACU performances of cm-LEDs, we prepare the cm-LEDs with different average CCTs. The spectral power distributions of cm-LEDs packaging with different average CCTs are shown in Fig. 8. Fig. 9(a) shows the angular CCT distributions of the cm-LEDs with the diffuse coating layer, when the average CCT ranges from about 2000 K to 5200 K. For cm-LEDs with different average CCTs, the angular CCT distribution curves are flat. Fig. 9(b) presents the corresponding CCT deviations of the cm-LEDs with the diffuse coating layer. The maximum CCT deviations in the whole space are 46 K, 213 K, 276 K, and 291 K at the average CCTs of 2184 K, 3170 K, 4186 K, and 5166 K, respectively. The experimental results demonstrate that the diffuse coating layer significantly reduces the CCT variation and improves the ACU of cm-LEDs with different average CCTs.

The corresponding luminous efficiency and general color rendering index (CRI) Ra of the cm-LEDs modules with different average CCTs are shown in Table 1. Notably, the average luminous efficiency of all modules are about 140 lm/W. In addition, the Ra of all modules is above 90, except for the modules with average CCT of 2184 K. According to Fig. 8, we can find that the cm-LEDs with average CCT of 2184 K is a blue light free source. Its spectrum is synthesized by the yellow

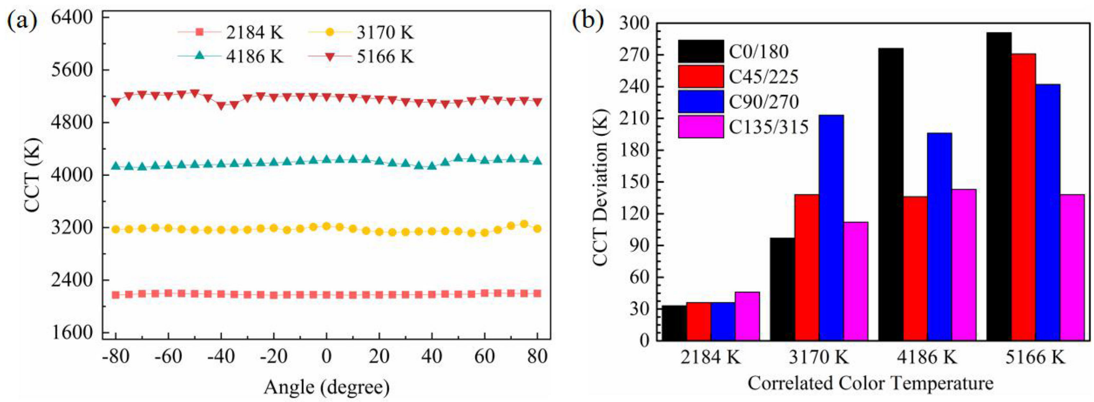

Fig. 9. (a) The angular color distributions and (b) CCT deviation of cm-LEDs modules with a diffuse reflector cup at different average CCTs.

TABLE 1
The Luminous Efficiency and Ra of cm-LEDs Packaging of Different CCTs

Average CCT (K)	Luminous efficiency (lm/W)	Ra
2184	145.0	77
3170	143.5	95
4186	141.2	92.7
5166	139.9	92.9

and red LED chips, hence its CRI is only 77. The results indicate that these cm-LEDs modules packaging with diffuse coating layer achieve a high luminous efficiency and an excellent CRI.

In this way, optical diffuse coating layer can be easily prepared by a simple process of compressed air spraying method, which does not involve chemical or high temperature treatment. Furthermore, these results demonstrate we can not only achieve the improvement of the ACU, but also realize an excellent LEE by using diffuse coating layer. The strong diffuse reflection properties of the coating layer indicate that it is suitable for application in the cm-LEDs packaging.

5. Conclusion

In summary, this study proposed a simple and low-cost method to improve ACU of cm-LEDs by introducing a diffuse coating layer. Optical models of the proposed cm-LEDs packaging modules were presented by Monte Carlo ray-tracing simulation and the results demonstrate the ACU enhancement of the cm-LEDs packaging modules using diffuse coating layer. Experiments were conducted for performance verification. By using a simple spraying process, TiO_2 coating layer was fabricated on the reflector cup. With the application of diffuse coating layer on the cm-LEDs packaging, it could effectively change the light traveling and mix the rays evenly, which leads to the improvement of the ACU. This positive effect is more prominent with the increase of height of the diffuse reflector cup. Furthermore, the effects of the diffuse coating layer on LEE are investigated.

Our results indicate that by applying the diffuse coating layer on the cm-LEDs module with an average CCT of about 3000 K, the CCT deviation decrease from 1172 K to 138 K with a luminous flux loss of only 3.54%. Moreover, we confirmed its feasibility to color mixing at different desired average CCTs. By using the diffuse coating layer, the maximum CCT deviation less than 300 K was obtained for the average CCTs ranging from 2000 K to 5200 K. This study provides a feasible and efficient method for enhancing the optical performance of the cm-LEDs devices.

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