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Enhancement of luminous efficiency by hybrid structure for warm white light-emitting diodes

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Abstract

This study demonstrates the hybrid structure with high lumen efficiency and uniform angular-dependent correlated color temperature (CCT) for warm white LED. Compared to the conventional structures, the hybrid structure combines the advantage of the two different fabrication methods including dispense and pulse spray method together, which can produce the high quality lighting source. The experimental results indicate that the hybrid structure yielded higher lumen efficiency than conventional phosphor structure because of the gradual refractive index difference from the coating layer to the dispense layer. Moreover, the CCT deviations of the hybrid phosphor structure could be reduced to 65 K in range of −70 to 70 degrees. This is attributed to the uniform color mixing of the blue, yellow and red band in the hybrid phosphor structure. In addition, the chromaticity coordinate shift compared to the hybrid structure with the dispense structure are almost the same at a current regulation from 20 mA to 500 mA. We believe that the technology of the hybrid structure with high lumen efficiency and uniform angular-dependent CCT is suitable for in the general lighting application.

Keywords: White light-emitting diodes; Hybrid; Phosphor; Package

Background

Recently, white light-emitting diodes (WLEDs) have been widely applied in the daily life because of their advantages of the small size, high efficiency, and long lifetime, which can be categorized as the environment-friendly lighting sources [1-3]. To date, the phosphor-converted white LED is the main approach by using the concept of the complementary colour to fabricate the white light [4]. Thus, the combination of the blue chip with the phosphor dominates most part of the solid-state lighting (SSL) market [5,6]. In the past decade, there have been many studies focused on enhancing the characteristic of the GaN-based blue chip including the internal quantum efficiency [7], efficiency droop [8] and light extraction [9,10]. Furthermore, the air voids/SiO_2 nanomasks and nanopillar substrates are employed to improve the crystalline quality of the GaN-based epilayer and increase the output efficiency [11,12]. Other than the performance of the blue chip, external package can also play an important part in terms of lumen enhancement. In general lighting application, the usage of blue chips and various phosphor materials can generate the two types of white lights: cool and warm WLEDs [13]. For the cool WLED at approximately 5000 ~ 5500 K, the YAG:Ce phosphor is used to generate the yellow light when pumped by blue source [14]. To achieve the warm WLED at approximately 2700 ~ 3000 K, the red phosphor such as nitride-based phosphor is adopted in package and past results have delivered high color-rendering index (CRI) devices [15,16]. However, the red phosphor suffered from the larger stoke shift and causes the cascade excitation process in warm WLEDs, resulting in lower lumen efficiency [17]. To enhance the luminous flux for the warm white LED, the multi-layered phosphor configuration is used to enhance the luminous flux due to its higher phosphor conversion efficiency [18]. Moreover, Li *et.al* indicated that the conformal-shaped phosphor configuration can achieve high CRI LEDs with lower correlated color temperature (CCT) [19]. The conformal phosphor structure can generate the highly uniform light source with homogenous distribution of angular CCT [20]. However, for the conformal-type phosphor structure, there are 60% backscattering lights reflected to the package [21] and these back-scattering photons are susceptible to reabsorption by the blue chip and thus reducing the luminous efficiency. To solve these problems, the hybrid structure [22] and the dual-layer phosphor structure [23] are employed to enhance the lumen output due to the reduced back light inside the package. From these past experiences, therefore, it is essential to reduce the backscattering light issue when the concentration of the phosphor increased, especially in the warm white LED.

In this study, a hybrid structure is proposed to enhance the light output for warm white LED compared to a conventional phosphor structure at the same CCT. The experimental results indicate that the hybrid structure yielded higher lumen efficiency than mixed and conformal phosphor structure, due to higher lamination intensity at yellow and red bands. Moreover, the CCT deviation of the hybrid structure is approximately the same with the conventional structures, which is beneficial for future application of solid state lighting.

Methods

In this experiment, the hybrid structure was fabricated using the pulse spray coating method and dispensing method [24]. Figure 1 shows the schematic diagram of different types of samples in this experiment: (a) dispense (b) red-yellow coating (c) yellow-red

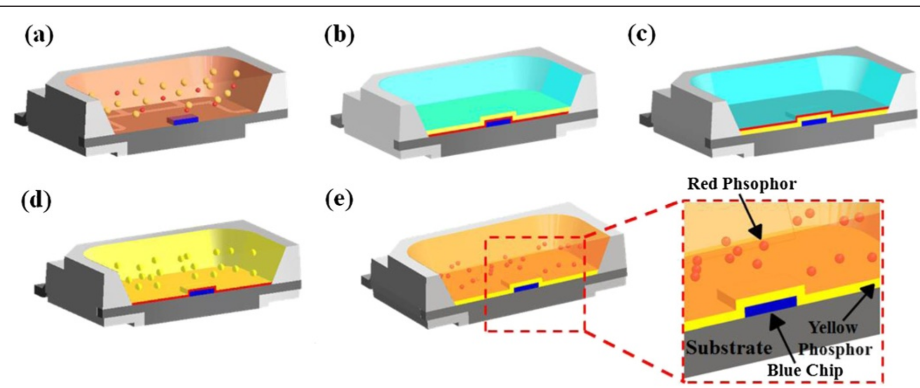

Figure 1 Schematic diagram of five type packaging methods: (a) dispense (b) red-yellow coating (c) yellow-red coating (d) red-yellow hybrid (e) yellow-red hybrid phosphor structures.

Table 1 The concentration of the yellow and red phosphor at different packages

Package	Dispense	Red-yellow coating	Yellow-red coating	Red-yellow hybrid	Yellow-red hybrid
Red phosphor concentration (%)	1.5	50	50	50	2
Yellow phosphor concentration (%)	6	50	50	5	50

coating (d) red-yellow hybrid (e) yellow-red hybrid phosphor structure. Our process flow can be described as follows: First, blue LED chips with peak emission wavelength of 450 nm are placed in the plastic lead-frame package. Then, the gold-wire bonding method was used to connect the positive and negative pads. The radiant fluxes of bare blue LED chips with size of 600 μm × 600 μm were 120 mW at driving current 120 mA. Second, the yellow and red phosphor are mixed with silicone encapsulant to fabricate the structure for dispensing method. For the red-yellow coating and yellow-red coating phosphor structure, the pulse spray coating (PSC) method is employed to spray the phosphor film layer by layer onto the lead-frame package. For the hybrid phosphor structure, the phosphor film is sprayed on the lead-frame package by PSC method. After that, the phosphor powders were then blended with silicone and dispensed onto the lead frame. In this experiment, these LED with different structures are adjusted to fit the requirement of the warm white CCT. Furthermore, the phosphor powder used in the experiment were YAG:Ce^{3+} and $CaAlSiN_3$:Eu^{2+} for the yellow and red emission, which is purchased from Intematix and Mitsubishi Chemical Corporation. The LED blue chip and silicone purchased from Epistar Corporation and Dow Corning Silicone. The refractive index of the phosphor and the silicone is approximately 1.8 and 1.53, respectively. Table 1 shows the concentration of the yellow and red phosphor at different packages. The particle size of the yellow phosphor and red phosphor is about 13 μm and 10 μm.

Results and discussion

Figure 2 shows the PL and PL emission (PLE) spectra for the yellow and red phosphors. The PL spectra were measured under 450 nm excitation sources, whose wavelength is

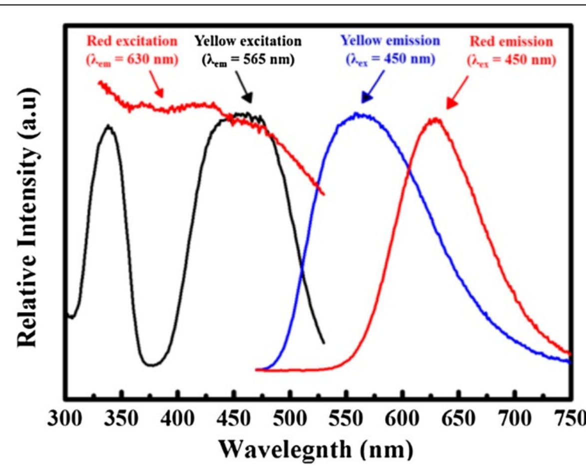

Figure 2 The intensity of yellow ($Y_3Al_5O_{12}$:Ce^{3+}) and red ($CaAlSiN_3$:Eu^{2+}) phosphors.

the same as the blue LED chip. The PL emission bands of the yellow and red phosphors is located as 565 nm and 630 nm, respectively and the full-widths at half-maximun (FWHM) of the yellow and red phosphors are 120 nm and 90 nm, respectively. From the PL and PLE spectra, it is obvious that the PLE spectrum of the red phosphor overlaps with the PL spectrum of the yellow phosphor, which can produce the reabsorption situation between yellow and red photons. Therefore, how to reduce the reabsorption effect become an important issue in the warm white LED. Reference [25] discussions clearly demonstrate that when the hybrid structure is stacked close to the LED chip more red light will be emitted resulting an considerable red-shifted phosphor spectrum of multilayer N-Y LEDs. From the experiment results, the yellow-red coating structure shows the higher lumen efficiency than the red-yellow coating structure. It can be explained by the efficiency of pumping because the yellow-red coating has a better arrangement on the pumping. In the red-yellow coating, the blue photons will be absorbed by the red phosphors first, and fewer yellow phosphors will get pumped to emit yellow photons. The overall converted photons are thus less than the previous case because the red photons cannot pump the yellow phosphors. However, for this two hybrid phosphor structure, the two layouts are almost the same in luminous flux, mainly due to the upper layer of the phosphors are away from the chip. So the backscattering and re-absorption issues are much less severe in both layouts. Thus the luminous fluxes are almost the same. The slightly stronger output from the yellow-red hybrid should stem from the higher portion of yellow photons received by the detector which can increase the lumen readings.

The emission spectra of dispense, coating and hybrid phosphor structure are shown in Figure 3(a). These structures had the same CCT at approximately 3000 K, and all operated at a current of 120 mA and thus the excitation power to all types of structures is 120 mW. From the emission spectra, the hybrid structure produced a higher intensity in yellow components for red-yellow hybrid and yellow-red hybrid phosphor structure. Figure 3(b) shows luminous flux of the dispense, coating and hybrid phosphor structure driven at currents from 20 to 500 mA. Moreover, the luminous flux of the five type packaging methods at 120 mA is shown in Table 2. The red-yellow hybrid phosphor structure exhibits a 4.7%, 19.4% and 6% lumen enhancement over the conventional dispense, the red-yellow coating and yellow-red coating phosphor structure. As the driving current increased, the lumen output differences between the hybrid, dispense and the

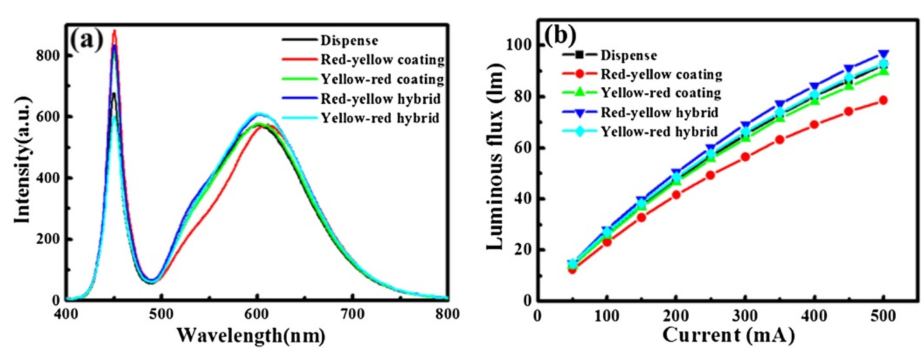

Figure 3 The dispense, coating and hybrid phosphor structure driven at currents from 20 to 500 mA. (a) Emission spectra **(b)** Luminous flux.

Table 2 The luminous flux of the five type packaging methods

Package	Dispense	Red-yellow coating	Yellow-red coating	Red-yellow hybrid	Yellow-red hybrid
Luminous flux (lm)	31.7	27.8	31.3	33.2	32.8

coating structures become larger. Moreover, the advantage of the hybrid structure could provide the gradual refractive index difference from the coating layer to the dispense layer and reduce the reflection loss in the interface [22]. Therefore, the hybrid structure has the higher luminous efficiency than the dispense and coating structures.

Figure 4 shows the angular-dependent CCTs of dispense, coating and hybrid phosphor structure. To evaluate the light quality for white LED, the difference of angular CCT deviation between the normal and large angle is an important standard to evaluate in the SSL application [26]. The larger CCT deviation would lead to the yellow ring phenomenon and generate the non-uniform white color at the different angle [27]. The definition of the CCT deviation is calculated as follows [26]:

$$\Delta CCT = CCT(Max) - CCT(Min), \quad (1)$$

where CCT(Max) and CCT(Min) represent the maximal CCT at the zero degree of viewing angle and minimal CCT at the 70 degree of viewing angle, respectively. Generally, the CCT deviation of the warm white LED is smaller than the cool white LED because the light pass through the higher phosphor concentration in the warm white CCT and the different light could be well mixed, leading to the uniform white light [28]. The CCT deviations of dispense, coating and hybrid phosphor structure is shown in Figure 4 (a). The CCT deviations of the red-yellow hybrid and yellow-red hybrid phosphor structure were 126 K and 65 K, which is slightly higher than the dispense and coating phosphor structure. However, these values are still good enough for the warm white LED in the solid-state lighting source. Moreover, Figure 4 (b-c) shows the far field picture of red-yellow hybrid and yellow-red hybrid phosphor structure and it is obvious that the hybrid structures can exhibit the uniform light.

For the white LED, the color deviation with the different current is used to evaluate the color stability for high-quality lighting applications. Therefore, the chromaticity coordinate shift of the dispense, coating and hybrid phosphor structure at various driving

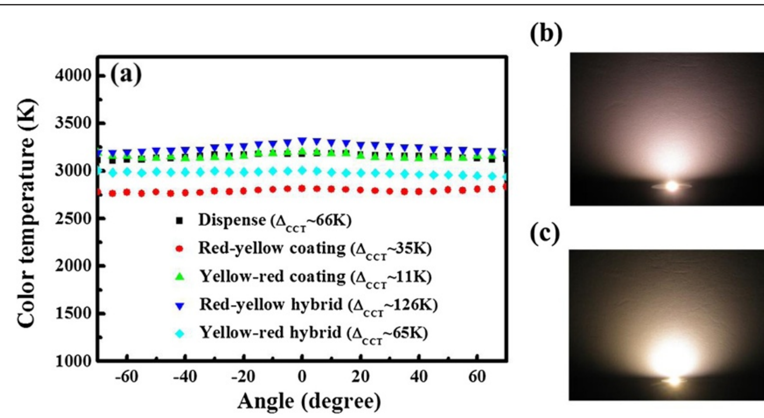

Figure 4 The dispense, coating and hybrid phosphor structure. (a) The angular-dependent correlated color temperature **(b-c)** The far field picture of red-yellow hybrid and yellow-red hybrid phosphor structure.

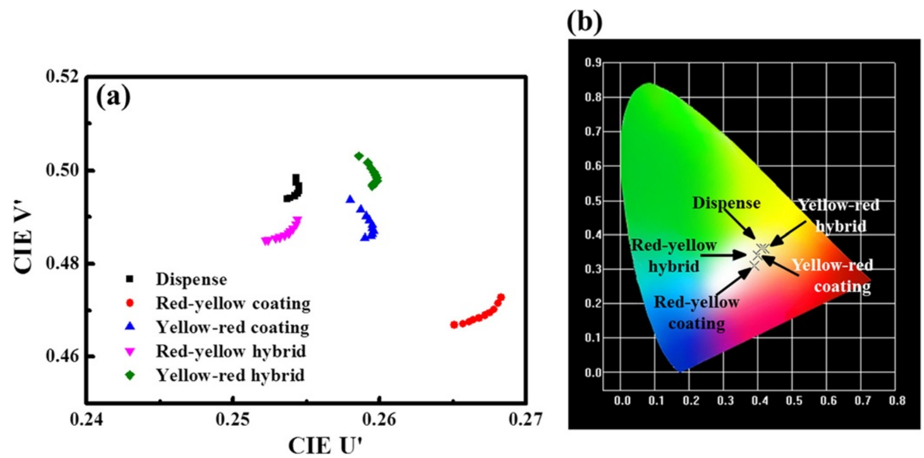

Figure 5 The dispense, coating and hybrid phosphor structure. (a) CIE 1931 chromaticity indices versus various current from 50 mA to 500 mA **(b)** CIE 1931 Chromaticity coordinate.

currents from 20 mA to 500 mA are shown in Figure 5(a). With the increased current, the chromaticity coordinates for both samples move to the blue region. Moreover, the color deviation of a lighting system, ($\Delta u'v'$) is calculated as follows [29]:

$$u' = 4x/(-2x + 12y + 3) \quad (2)$$

$$v' = 9y/(-2x + 12y + 3) \quad (3)$$

$$\Delta u'v' = \sqrt{(\Delta u')^2 + (\Delta v)^2} \quad (4)$$

where u', v' is the chromaticity coordinates in the CIE 1976 diagram, and x and y are the chromaticity coordinates in the CIE 1931 diagram. The $\Delta u'v'$ value indicates spatial color uniformity in (4). Figure 5(a) shows the color chromaticity coordinate deviations at various ambient temperatures from 20 mA to 500 mA. The experimental value ($\Delta u'v'$) indicates that the color deviation value of the red-yellow hybrid and yellow-red hybrid phosphor structure were 0.005 and 0.0065, which is nearly the same as other structures, as shown in Table 3. Consequently, both red-yellow hybrid and yellow-red hybrid phosphor structure results in stable CCT stability and high-quality warm white source.

Another important characteristic of WLEDs is color rendering index (CRI). This index evaluates how different colors look like in the light. Figure 6 shows CRI value of dispense, red-yellow coating, yellow-red coating, red-yellow hybrid and yellow-red hybrid phosphor structure at various Munsell codes. The CRI value is calculated by taking the average color rendering of each Munsell codes [30]. Higher CRI value means the better light quality when compared to natural light source, and this is an important standard for general lighting purpose [31]. The CRI of the proposed red-yellow hybrid

Table 3 The CCT deviation of the five type packaging methods

Package	Dispense	Red-yellow coating	Yellow-red coating	Red-yellow hybrid	Yellow-red hybrid
Chromaticity coordinate shift ($\Delta u'v'$)	0.0047	0.0067	0.0082	0.005	0.0065

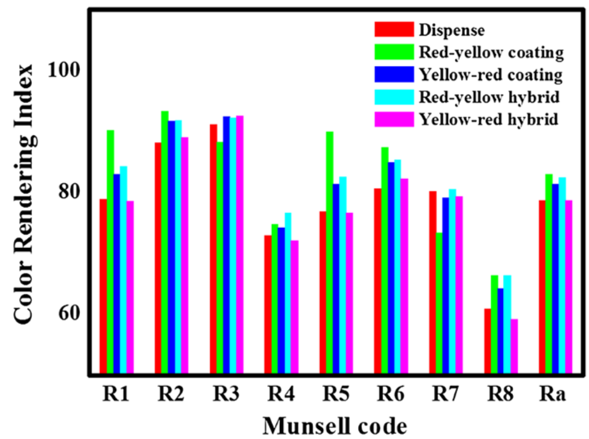

Figure 6 CRI of dispense, red-yellow coating, yellow-red coating, red-yellow hybrid and yellow-red hybrid phosphor structure at various Munsell codes.

warm white LED could achieve 82.4 and this high value meets the CRI requirement for future SSL application (with CRI >80) [32]. Therefore, the technology of red-yellow hybrid phosphor structure with higher lumen output and better CRI value provides an alternative approach to use for the lighting source.

Conclusion

In this study, the hybrid phosphor structure with high lumen efficiency and uniform angular-dependent CCT is demonstrated for the warm white LED. It is found that the hybrid structure could provide the suitable refractive index difference from the coating layer to the dispense layer, resulting in the higher lumen efficiency. For the light quality, both red-yellow hybrid and yellow-red hybrid phosphor structure demonstrates the uniform color temperature in range of −70 to 70 degrees. Moreover, the chromaticity coordinate shift of the hybrid structure and the dispense structure are almost the same from 20 mA to 500 mA of driving currents. Compare with red-yellow coating structure and yellow-red coating structure. Yellow-red coating structure's efficiency is higher. We think the reason is Yellow-red coating structure can reduce stroke shift effect. In this study, we find that the red-yellow coating structure can reduce yellow's absorb percentage. Hybrid structure can reduce the back scatting effect. It is mean the hybrid structure is better than phosphor coating structure. The reason for higher efficiency hybrid structure is reduce back scattering and reduce reabsorption.

Through the hybrid phosphor package type, the finished LEDs could achieve high efficiency and high CRI which are essential features for a high quality solid state lighting source.

Abbreviations

WLEDs: White light-emitting diodes; SSL: Solid-state lighting; CRI: Color-rendering index; CCT: Correlated color temperature; PSC: Pulse spray coating; PLE: PL excitation.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

CWS participated in the design of the study, and contributed in the writing of the manuscript. KJC analyzed the experimental results and contributed in the design of the study. CCL participated in revision of the manuscript and discuss of the results. HVH assisted in the process of the experiment and participated in the discussion. BCL assisted in the process of the experiment and participated in the discussion. KYW fabricated all the samples and measured the optical characteristic and explained lumen flux and lumen efficiency. JRL participated in discuss of the study and measured the angular-dependent correlated color temperature and explained it. MTW participated in discuss of the study and analyzed electroluminescence. JMH participated in discuss of the study and analyzed CRI value. MHS participated in discuss of the study. CCF participated in discuss of the study. HCK participated in discuss of all the results. All authors read and approved the final manuscript.

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