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Light extraction enhanced white light-emitting diodes with multi-layered phosphor configuration

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Abstract: Phosphor-converted white light–emitting diodes (LEDs) with separate red and yellow phosphor layers are investigated under current regulation conditions. This novel packaging scheme of bi-layered phosphors leads to more than 18% increase in luminous flux compared to conventional random mixed phosphor case at the same correlated color temperature. Lower junction temperatures of bi-layered phosphor white LEDs are also observed. This advantage in the thermal characteristics is due to the reduced back reflection of light inside the packages. It is also found that the phosphor conversion efficiency of bi-layered phosphor scheme is higher than that of mixed phosphor case. This is attributed to the enhanced light extraction from the LED packages. In addition, the chromaticity coordinates shifts compared bi-layered phosphor with mixed phosphor white LEDs are almost the same under current regulation conditions. The technology of bi-layered phosphor white LEDs with high efficiency and high color rendering index provides an appropriate solution for general white LED lighting.

OCIS codes: (230.0230) Optical Device; (230.3670) Light Emitting Diodes.

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1. Introduction

With the increased market penetration of solid state lighting, the high-brightness light emitting diodes (HB LEDs) have a remarkable growth for general illumination applications in recent years, while LEDs provide some advantages in terms of lifetime, stability as well as efficiency [1,2]. However, continues improvements are still needed in light extraction and thermal conduction from the HB LED packages [3,4]. Blue or UV LEDs combined with phosphor materials can generate white light by converting the radiation generated by LEDs to a complementary color. In general lighting applications, the phosphor–converted LEDs need to have a broadband covered visible spectrum in order to achieve high color rendering index (CRI); otherwise, two or more phosphors with different emission spectra are required. However, due to the light trapping and inelastic scattering between phosphor materials, the more emission power of LEDs is lost as the phosphor concentration increases in the LED packages [5]. Phosphor arrangement and geometry can have an important role in enhancing power efficiency and reducing light trapping in an LED package. Novel phosphor arrangements, e.g., the scattered photon extraction (SPE) package [6], remote phosphor with hemispherical dome [7,8] as well as the enhanced light extraction by internal reflection (ELiXIR) [9,10] have been proposed based on experiments and ray-tracing studies. Other studies were also demonstrated that low concentration phosphor mixture has advantages in output luminous flux and in the shift of color coordinates [11]. These new designs are based on the concept of reducing the back scattering and inelastic scattering of light emitted from LED chips and down-converted from phosphor materials.

Light extraction efficiency of a phosphor-converted LED package also affects the thermal properties of the package. As more light is trapped inside the packages or back-reflected to LED die, the junction temperature of LED increases [5]. The increased junction temperature degrades the light output and also reduces the long-term operating reliability of LED [12], [13]. Therefore, how to increase the light extracted from phosphor-converted LEDs is a key design parameter of LED packages.

In this paper, the red and yellow phosphors were used in the LED packages in order to get broadband spectrum, which has higher CRI. A novel packaging configuration with multi-layered phosphor LEDs was demonstrated to have higher light output at the same correlated color temperature (CCT) compared to the conventional mixed phosphor LEDs. Experimental results show that this new configuration has higher phosphor conversion efficiency than conventional mixed monolayer phosphors. The lower junction temperatures were also measured in multi-layered phosphor LEDs due to less light scattered back to LED dies. This new design shows the same illumination characteristics as conventional mixed phosphor LEDs under different current regulation modes. This is a practical package design for high CRI LEDs having multiple phosphor emissions.

2. Experimental

The materials used in this experiment include GaN based blue power LED chips made by Bridgelux Inc. with the chip size of 45x45 mil and the dominate wavelength of 455 nm, 5mm leadframes with silver coating surface, silicone resin, and inorganic silicate and calcium sulphide phosphor particles, which are made from Intematix, Inc. and Phosphor Technology, Inc. respectively, emitting yellow and red light. The white LEDs were made by: 1) attaching

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each LED chip into each leadframe by using silver paste; 2) curing the LED packages at 175°C for 1 hour; 3) dispense clear silicone layer and partially cure the packages; 4) dispensing mixture of silicate phosphor and silicone, which have the red and yellow phosphor concentration of 0.7% and 15 wt. %, respectively, or dispensing red-phosphor-silicone mixture followed by partially curing and then by dispensing yellow-phosphor-silicone mixture; 5) fully curing dispensed materials. The dispensed materials in each package were carefully weighed at each time they were dispensed to make sure that: 1) same amount of clear material is used in each package; 2) the height of encapsulation is same or approximately same in each package. In order to achieve light output with the same CCT for both types of the studied LED packages, amount of red-phosphor-silicone mixture and yellow-phosphor silicone mixture is adjusted while the height of encapsulation is maintained approximately the same. Two types of LED packages were shown in Fig. 1, which have different phosphor configuration. Figure 1(a) shows the LED, which has mixed yellow and red phosphors (mixed-RY LED); whereas Fig. 1(b) shows the LED, which has bi-layered configuration of red and yellow phosphors (BL-R/Y LED). For both types of LEDs, phosphor-on-top arrangement was employed to enhance phosphor efficiency since high incident light fluxes significantly reduce the quantum efficiency of phosphor and lead to LEDs with a lower lumen output [7]. Phosphor saturation effects are reduced as phosphor layers are away from LED [11].

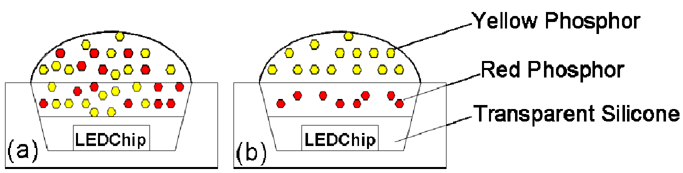

Fig. 1. Schematic cross-sectional view of the white LED package: (a). Mixed red and yellow phosphor structure; (b). Bi-layered red/yellow phosphor structure

The adjustable pulse current, which have duty cycle of 0.1%, and constant direct current sources with corresponding indicated forward voltage were supplied by the power generator from Everfine Co., Ltd. Each LED was driven at six current conditions, i.e., 50 mA, 100 mA, 200 mA, 350 mA, 500 mA and 600 mA under pulse and constant current modes. The corresponding light-emitting characteristics of LEDs, which are in terms of light output, correlated color temperature and chromaticity coordinates, were measured by spectral light measurement system from LabSphere Inc. In pulse current operation of LEDs, the pulse width was set of 30 ms in order to fit the saturation time of light output measurements. The input power of the pulse current did not affect the junction temperature significantly [14,15]. Therefore, the junction temperatures of LEDs under the pulse current operation are basically the same as ambient temperature. On the other hand, for LEDs under constant current operation, a direct current was supplied. The junction temperatures of LEDs increased and finally reached thermal equilibrium with ambiance. The corresponding junction temperatures of LEDs were determined by the forward voltage method under constant current mode [16]. The diode forward voltage method consists of two series of measurements, a calibration measurement and real junction temperature measurement. In the calibration measurement, the LED is placed in a temperature controlled oven and connected to the drive and measurement equipment. After the junction has come to thermal equilibrium with temperature controlled oven, a pulse current, i.e., 10 μs in pulse width, is sourced into the LED to ensure junction temperature is equal to the oven temperature and voltage drop is measured. In real application, a linear expression is fitted with the corresponding voltage drop with various set points of oven temperature in order to get a calibration curve. The calibration curve serves as the reference for the deduction of the junction temperature from DC measurement and establishes the relation between the forward voltage and junction temperature.

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3. Results and discussion

The emission spectra of BL-R/Y and mixed-RY LEDs run at 350 mA are shown in Fig. 2. These LEDs with different phosphor placements have the same correlated color temperature (CCT); i.e., about 4700 K. The phosphor concentrations of yellow and red in BL-R/Y and mixed-RY LEDs are the same, which are 15% and 0.7%, respectively. However, BL-R/Y LEDs have higher radiation flux in red, yellow, and blue components than mixed-RY LEDs. The lumen output of BL-R/Y LEDs is at least 18% higher than that of mixed-RY LEDs. It has been demonstrated that high-concentration phosphor mixture had disadvantages in output luminous flux due to the light trapping and absorption between phosphors materials [17]. The inelastic scattering of light reduces the efficiency since the increased light path length leading to the higher possibility of re-absorption of incident and emitted light. Light path randomization also increases the probability of light incident on high loss areas, such as LED chip. The increased radiation flux of blue, yellow and red components in BL-R/Y LEDs indicate the less scattering of light inside the packages compared with the mixed-RY LEDs.

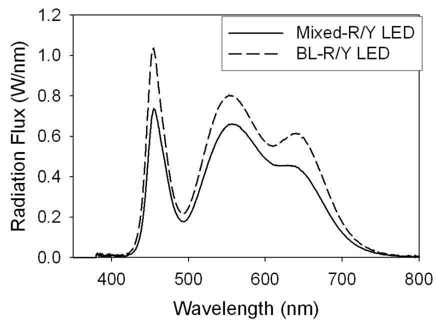

Fig. 2. Emission spectra of BL-R/Y LEDs and mixed-RY LEDs with red and yellow phosphor concentration of 0.7 wt. %, and 15 wt. %, respectively. LEDs are driven at the current of 350 mA

Lower optical efficiency due to light trapping and absorption loss cause by phosphor arrangement degrades the LEDs faster as they are driven at a higher current. Figure 3 shows the radiation power and lumen output of BL-R/Y and mixed-RY LEDs under current regulation from 50 mA to 600 mA. With the increase of drive current, the differences of radiation power and lumen output between BL-R/Y and mixed-RY LEDs become larger. As the drive current increases, heat generation inside the LEDs also increases, resulting in a higher temperature of phosphor materials and LED-chip.

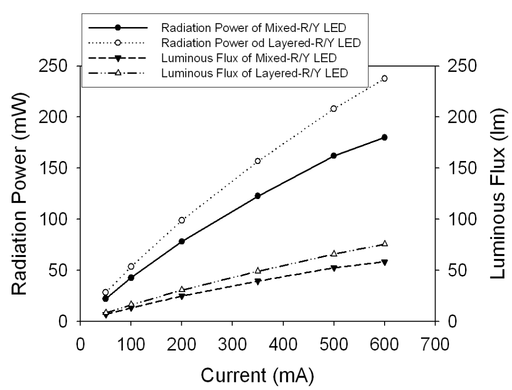

Fig. 3. Radiation power and luminous flux of BL-R/Y LEDs and mixed-RY LEDs driven at the current from 50 to 600 mA

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However, the heat generation inside the mixed-RY LEDs is faster than in the BL-R/Y LEDs due to the more light trapping and backscattering inside the mixed-RY LEDs compared with the BL-R/Y LEDs and the limitation of heat transfer between the LEDs and surrounding environment. The higher rate of heat generation inside the mixed-RY LEDs with the increase of drive current causes a faster increase of phosphor and LED-chip temperature. At a higher temperature, the conversion efficiency of phosphor materials and the quantum efficiency of LED-chips decrease. Therefore, the optical output of the mixed-RY LEDs degrades faster with increasing the drive current. The heat generation rate in the LEDs can be compared by analyzing thermal characteristics of the LEDs

The thermal characteristics of the LEDs can be determined by junction temperature, which were measured by forward voltage method in this experiment [16]. The junction temperatures of BL-R/Y and mixed-RY LEDs are shown in Fig. 4. The BL-R/Y LEDs have lower junction temperatures than mixed-RY LEDs driven at constant current from 50 to 600 mA. The junction temperature differences increase with the increase of drive current. At current of 600 mA, the difference can reach 5 °C in the same testing conditions. The increased junction temperatures are due to the light absorption inside the packages, since a significant portion of light is backscattered by the phosphor and lost within the LED die. The absorbed energy transforms into heat in the die and thus increases the junction temperature of LEDs. This indicates the phosphor arrangement of BL-R/Y LEDs have lower backscattering of light than mixed RY LEDs.

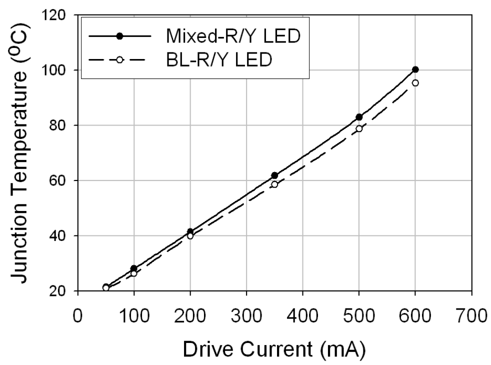

Fig. 4. Junction temperatures of BL-R/Y LEDs and mixed-RY LEDs driven at the current from 50 to 600 mA in the same ambiance

The phosphor conversion efficiency of phosphor-converted white LEDs is defined as the product of phosphor quantum efficiency, η_q , and package efficiency, η_p . Phosphor quantum efficiency is the internal photon conversion process from high energy to low energy, i.e., Stoke's shift; however, package efficiency is related to the light absorption of materials inside LED packages. The phosphor conversion efficiency (η_{PCE}) can be calculated by

$$\eta_{PCE} = \eta_q \times \eta_p = \frac{P_Y + P_R}{P_{B_o} - P_B} \tag{1}$$

where P_Y is radiation power of yellow component and P_R is radiation power of red component; P_{B_o} and P_B are radiation power without and with the mix of phosphor, respectively. The phosphor conversion efficiency of BL-R/Y and mixed-RY LEDs are shown in Fig. 5. Both two types of LEDs are tested under pulse and constant current from 50 to 600 mA. The BL-R/Y LEDs have higher phosphor conversion efficiency than mixed-RY LEDs about 13% under pulse current of 50 to 600 mA. The differences of phosphor conversion efficiency are from the phosphor configurations of the packages. Under constant current at 600 mA, the phosphor conversion efficiency difference between BL-R/Y and mixed-RY

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LEDs drops to 10%. The phosphor heating effects lead to the decrease of phosphor quantum efficiency and thus decrease the differences of overall conversion efficiency of blue light as input current increases.

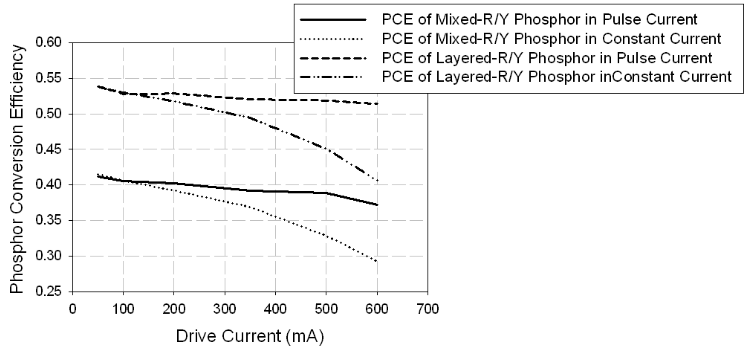

Fig. 5. Phosphor conversion efficiency (PCE) of BL-R/Y LEDs and mixed-RY LEDs driven at the current from 50 to 600 mA under pulse and constant current modes

Under current regulation from 50 to 600 mA, the chromaticity coordinates shift of BL-R/Y and mixed-RY LEDs are shown in Fig. 6. With the increase of drive current, the chromaticity coordinates move to the blue region with the same extent both in BL-R/Y and mixed-RY LEDs under pulse and constant current modes. This indicates the illumination characteristics of BL-R/Y and mixed-RY LEDs are basically the same; however, for BL-R/Y LED packages the chromaticity of LED can be efficiently adjusted by the ratio of blue to yellow and red components, since the yellow phosphor does not absorb red emission from the underlying red phosphor. This is considered that the emission energy loss is associated with re-absorption process by different phosphor emission spectrum within the LED packages.

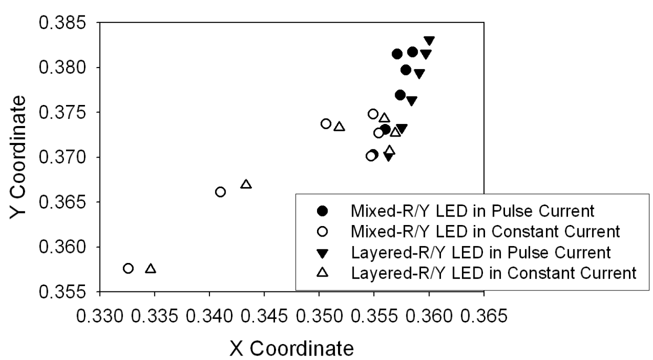

Fig. 6. Chromaticity coordinate shift of BL-R/Y LEDs and mixed-RY LEDs at the drive current from 50 to 600 mA under pulse and constant current modes

4. Conclusions

Phosphor-converted white light–emitting diodes (LEDs) with separate red and yellow phosphor layers are investigated under different current regulation conditions. It is found that the new packaging method leads to at least more than 18% increase in luminous flux compared to conventional random mixed red and yellow phosphor case at the same correlated color temperature. Lower junction temperature of bi-layered phosphor white LEDs is also observed. This advantage in the thermal characteristics is due to the reduced back reflection of light inside the packages. The chromaticity coordinates shifts of bi-layered phosphor white LEDs are almost the same as mixed phosphor white LEDs under current regulation conditions. The technology of bi-layered phosphor white LEDs with high efficiency and high color rendering index provides an appropriate solution for general white LED lighting.

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