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Study on the Improvement of the Color Rendering Index of White LEDs by Using red Quantum dots

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Red quantum-dot (QD) walls and films were applied to conventional 6-inch white LED (light-emitting diode) lightings, consisting of blue LED chips and yellow phosphors, to improve the color rendering index (CRI). The emission spectra, the CRI, the illuminance, and the luminance properties of six different configurations were investigated. The vertical QD wall surrounding the LED chips and defining the emission area played an important role in improving the R9 CRI for strong, saturated red while the QD film laminated on either the bottom or the top surface of the diffuser plate formed a vertical cavity, enhanced the color conversion efficiency, and increased the average CRI Ra and Re. This study clearly suggests that appropriate QD configuration can be used to increase the CRI of conventional white LED lightings at nearly no expense to the luminous efficiency.

Keywords: Illumination, Quantum dot, White LED, Color rendering index

I. INTRODUCTION

The illumination technology is going through revolution from traditional light sources, such as incandescent lamps and fluorescent lamps, to the solid-state lighting, white light emitting diode (LED) being the most representative technology [1]. White LED is, in general, realized by combining blue LEDs and color conversion materials, such as phosphors and quantum dots [2]. Typical white LEDs consist of blue LEDs at the wavelength of $\sim$ 450 nm and yellow phosphors to generate white light. The most representative yellow phosphor is Ce-doped YAG (Yttrium Aluminum Garnet), which has good temperature characteristics, high resistance to moisture and reliability. The resulting emitting spectrum consists of a relatively sharp, blue peak and a broad yellow peak. The ratio of these two spectral components determine the correlated color temperature of the white LED.

In spite of the high efficiency, good reliability and long lifetime, YAG-based white LEDs have one serious drawback, which is a relatively low color rendering index (CRI) due to the insufficient amount of red component. The CRI R9, which is the individual CRI for the strong red color, of the conventional white LED is very low. There are several approaches for enhancing the CRI of white LEDs, one way being the addition of red phosphor to the white LED [3]. Another way is to apply the red quantum dot (QD) to enhance the red component in the white spectrum [4,5]. The red QD can be included in the white LED in terms of various ways as, for example, one of the color conversion materials in the resin, a QD

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film, QD caps, etc. The color of QD can be controlled easily in terms of the size of QD and the associated quantum confinement effect which is promising for display and lighting technologies [6–8]. The main application of QD materials is to use them as color conversion materials in the backlight for liquid crystal display applications [9–12]. However, research activity for QD application in lighting technology has been increased [13–16].

However, the development of new QD-based lighting needs time and cost, which is not favorable for commercialization. One simple way to adopt QD materials in lighting technology is to use the commercial white LED lighting into which a QD component is incorporated. The purpose of the present study is to investigate the optimized structure of the QD-based white LED lighting for enhancing CRI. A red QD film was applied to a commercial white LED in various ways, which could increase the CRI substantially.

II. EXPERIMENT

A commercial 6-inch, 15-W white LED lighting was purchased and a red QD film was laminated on the reflector as shown in Fig. 1(a). A diffusive reflection film (reflectance more than 95%) was formed beneath the QD layer. Total 36 white LEDs are arranged in a concentric manner on a circular PCB (printed circuit board) to secure appropriate luminance and illuminance uniformities, and a diffuser plate (thickness: 2 mm) was put over the LEDs to further homogenize the light. The distance between the upper surface of the QD film on the PCB and the bottom surface of the diffuser plate was 24.0 mm. The QD film (thickness: 0.15 mm) was fabricated at the GLVISION Co. and CPRI (Cheorwon Plasma Research Institute). The red QD was CdSe/ZnS, and its thermal stability was significantly enhanced in terms of replacement of inorganic ligands [17]. The host material of the QD film was PET (Polyethylene terephthalate). No barrier film was necessary for the QD film to ensure long-term reliability. The weight % of red QD in the film was 5%.

The white LED shown in Fig. 1(a) was modified by adding additional QD films: (1) a vertical QD wall with a radius of 120 mm and a height of 23.2 mm was set

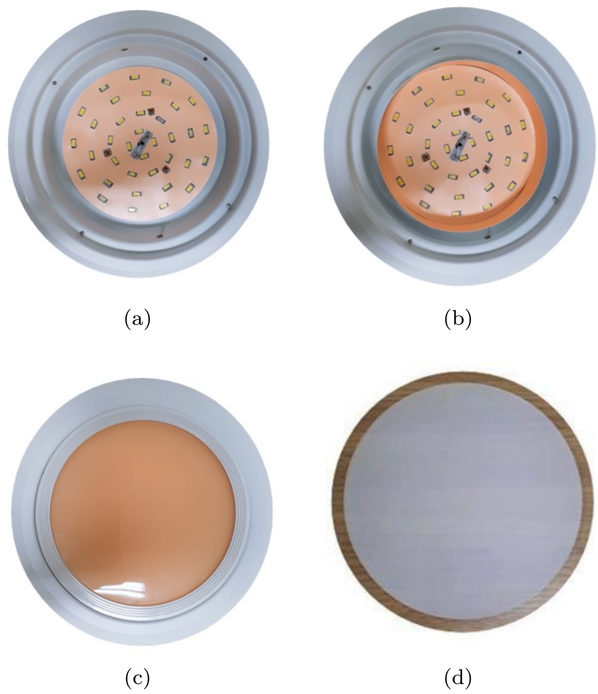


Fig. 1. (Color online) (a) A 6-inch white LED where the red QD film was laminated on the PCB board. (b) The same white LED with the circular QD wall. (c) The same white LED with the QD film attached on the top of the diffuser plate. (d) The photo of the diffuser plate.

around the LEDs as shown in Fig. 1(b), and (2) a QD film was attached either on the top or the bottom of the diffuser plate made from PMMA (poly(methyl methacrylate)) as shown in Fig. 1(c). The QD wall consisted of a red QD film and a diffusive reflective film to enhance the reflectance of the incident light. The total thickness of the QD wall was 0.26 mm. The Fig. 1(d) shows the photo of the diffuser plate. It is a weak diffuser and the on-axis transmittance of the diffuser along the normal direction was 31.8%. Figure 2 shows six different configurations of the QD-based white LED lighting. The spectrum, the illuminance, the correlated color temperature (CCT) and the color rendering index were measured by using the illuminance meter (SPIC-200A, Everfine). The reflectance spectra of all standard test color samples (R1 – R15) defined by the CIE, as well as the emitting spectrum of the standard light source, are included in the equipment, thus the measured spectrum is usually multiplied by each reflectance spectrum of the standard sample and the color differences between the test light and the standard light for each color sample are calculated and averaged. The illuminance meter was placed

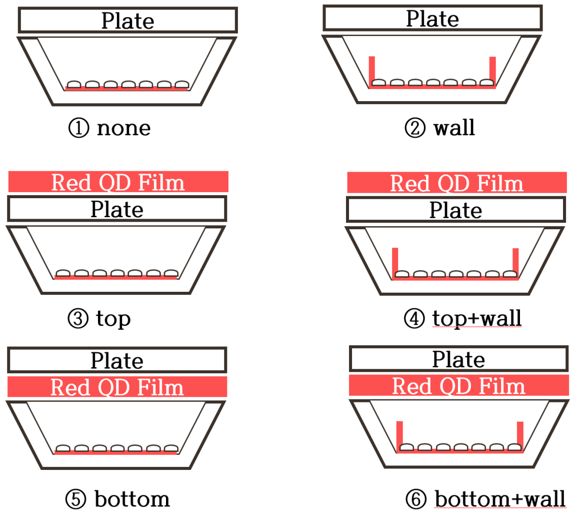


Fig. 2. (Color online) Six different configurations of the QD-based white LEDs. "None" indicates that the QD film is laminated only on the PCB. "Plate" indicates the diffuser plate.

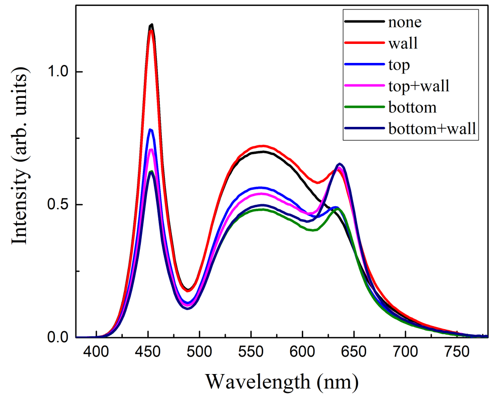


Fig. 3. (Color online) The emitting spectra of the QD-based white LEDs under six different configurations as shown in Fig. 2.

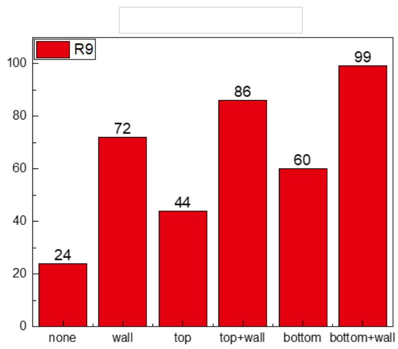
below the LED lighting at a distance of 20 cm. The on-axis luminance on the center point of the lighting was measured by using a spectroradiometer (PR670, Photo Research).

III. RESULTS AND DISCUSSION

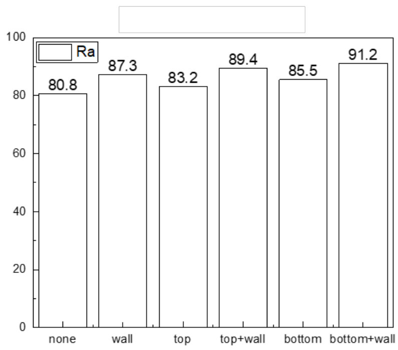
Figure 3 shows the emitting spectra of QD-based LED lightings under six different configurations as shown in Fig. 2. In the case of "none" configuration, i.e., the basic configuration where the QD film is laminated on the PCB, the enhancement of the red component is very weak indicating that the lamination of the QD film on the PCB is not effective for the efficient color conversion. The red component near $\sim$ 630 nm in the emitting spectrum becomes enhanced as additional QD films are added in the "none" configuration. Especially, the red peak becomes maximum under two cases of "top+wall" and "bottom+wall" configurations. At the same time, the heights of the blue and yellow peaks decrease significantly. Under these two configurations, the excitation sources (blue and green components from white LEDs) have high chances to meet the red QDs at both QD wall and either top or bottom QD film laminated on the diffuser plate. The unconverted light is partly reflected back from the diffuser plate and then has additional chance for the color conversion.

Figure 4(a) shows the comparison of R9, which is the individual CRI for the "strong, saturated red". Figures 4(b) and (c) show the Ra and Re CRI for the six configurations, respectively. Ra is the average CRI for eight standard CIE samples of R1 – R8 while Re is the extended average CRI for R1 – R15. Among the individual CRIs, R9 is a very important index for achieving high CRI because red component plays an important role in many applications. Fig. 4(a) shows that the R9 has high values above 70 under three conditions, i.e., "wall", "top+wall" and "bottom+wall" configurations. It suggests that the existence of the QD wall is important for securing high R9. The light emitted from white LEDs striking the QD wall can easily be transformed into red light. Without the wall, the white light will strike the inclined side wall of the lighting without any color change. The QD wall plays a role of horizontal cavity while the QD film on the diffuser plate and another QD film on the PCB forms vertical cavity. These two cavities recycle the excitation light efficiently and enhance the color conversion efficiency.

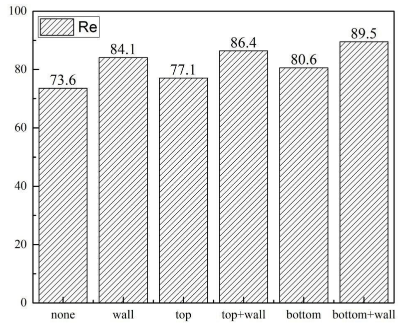
The "bottom+wall" configuration displays a higher R9 of 99% than the "top+wall" configuration. The upward light will strike the QD film first in the "bottom+wall" configuration, but it will meet the diffuser plate first in the "top+wall" configuration. In the latter case, part of the white light will be reflected down from the diffuser



(a)



(b)



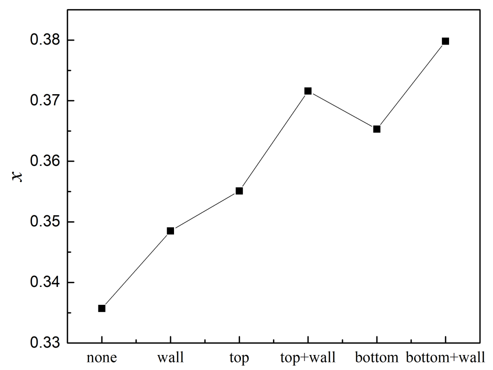
(c)

Fig. 4. (Color online) (a) CRI for the red color (R9), (b) the average CRI for R1 – R8 and (c) the extended average CRI for R1 – R15 of six configurations.

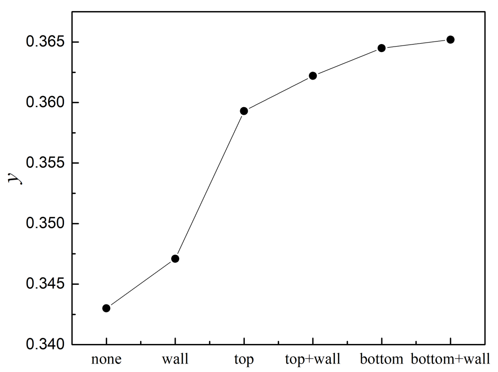
plate resulting in lower color conversion efficiency and thus slightly lower R9. Thanks to the substantial increase in R9, the average CRI Re, which includes R9 in its evaluation, also exhibit larger values above 84 for the "wall", "top+wall" and "bottom+wall" configurations as shown in Fig. 4(c). In addition, the Ra values are also above 87 for these three cases. These values are much larger than the "none" configuration of Ra=80.8 suggesting that QD wall and QD film can be incorporated into the commercial white LEDs to improve the overall color rendering performance.

The inclusion of red QD in the white LED changes the color coordinates and the CCT. Figures 5(a) and (b) show the changes in the color coordinates for the six different configurations. Both x and y increase as more QD film and QD wall are included in the LED lighting. As the color conversions of the "top+wall" and "bottom+wall" configurations were the most significant, the shifts of their color coordinates are the largest. Especially, the change in x is larger than that in y because x is associated with the portion of the red component in the emitting spectrum. These changes are clearly seen from the CIE1931 chromaticity diagram as shown in Fig. 5(c) where the left and the right diagrams denote the case of "none" and "bottom+wall" configurations, respectively. The CCT of "none" configuration was 5692 K while that of "bottom+wall" configuration was 3595 K resulting in nearly 2000 K difference. This result clearly indicates that the CCT of conventional LED lighting can easily be tuned by simply adding appropriate QD components in the lighting fixture.

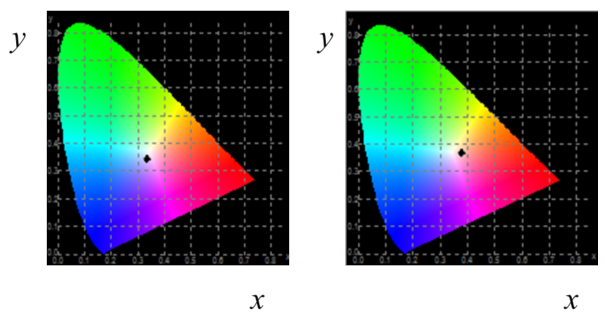
Figures 6(a) and (b) show the illuminance and the on-axis luminance of the LED lighting for six configurations. These values were normalized with respect to those of the "none" configuration. The luminance and illuminance values of the "wall" and the "top+wall" configurations are larger than those of the "none" configuration. This is partly due to the high reflectance of the QD wall. The reflectance of the inclined side wall was approximately 80% while that of the QD wall (the diffusive reflective film supporting the QD layer) was more than 95%. The existence of highly-reflective horizontal cavity is part of the origin of the higher brightness of the QD-adopted white LED. However, this conclusion does not apply to the "bottom" and the "bottom+wall" configurations. In these two cases, the CCT values are much lower than the "none", "wall", and the "top" configurations, which indicates that the blue and the green components were converted to red components more substantially via the red QDs. It can be clearly confirmed from the change in the spectrum shown in Fig. 3. Considering the fact



(a)



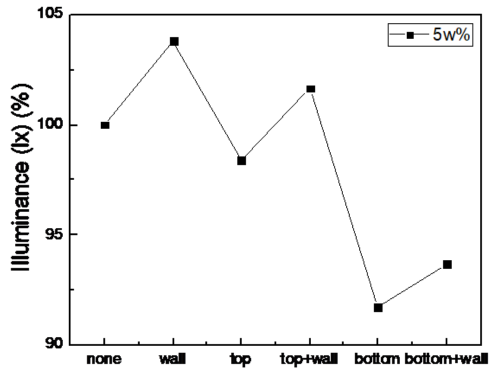
(b)



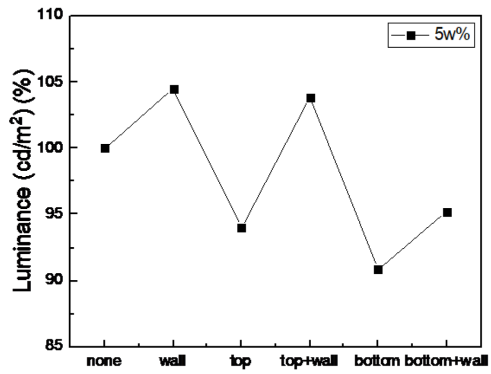
(c)

Fig. 5. (Color online) (a) and (b) The changes in the color coordinates. (c) The color coordinates of the "none" configuration(left) and the "bottom+wall" configuration(right) on the CIE1931 chromaticity diagram.

that the contribution of the green spectral component to the luminous flux is very substantial, the decreased luminance and the illuminance can partly be explained in terms of the reduced green component in the "bottom"



(a)



(b)

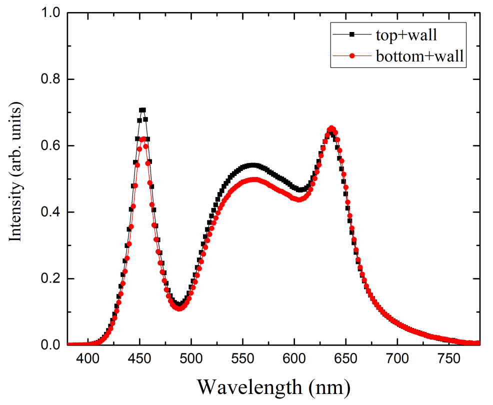
Fig. 6. (Color online) (a) The illuminance and (b) the on-axis luminance of the LED lighting for six configurations.

and the "bottom+wall" configurations.

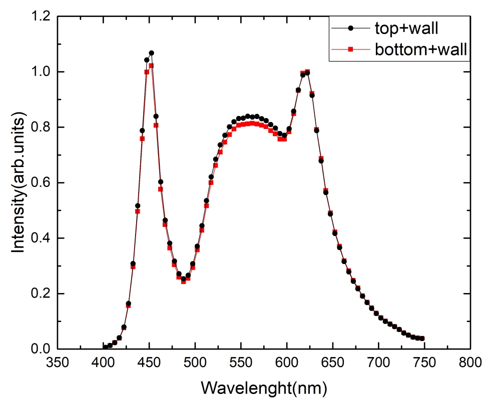
Finally, the relatively high luminance and illuminance values of the "top+wall" configuration are in contrast to the two cases of "bottom" and the "bottom+wall" configurations because the CCT of this configuration is also very low (CCT = 3847 K) similar to the other two cases. If we look at the emitting spectra of these two configurations as shown in Fig. 7(a), we can notice that the heights of the blue and yellow peaks of the lighting with the "top+wall" configuration are higher than those with the "bottom+wall" configuration although the heights of the red peaks are nearly the same. The higher height of the yellow peak of the lighting with the "top+wall" configuration contributes to the luminance and the illuminance more substantially. One explanation of this result is that, in the case of "bottom+wall" configuration, much

Table 1. The relative luminance, the relative illuminance, the CCT and CRI values of the white LED lighting for six configurations.

Configuration	Relative Luminance (%)	Relative Illuminance (%)	CCT (K)	R9	R_a	R_e
None	100	100	5692	24	80.8	73.6
Wall	104.5	103.8	4586	72	87.3	84.1
Top	94.0	98.4	4688	44	83.2	77.1
Top+wall	103.9	101.6	3847	86	89.4	86.4
Bottom	90.9	91.7	4307	60	85.5	80.6
Bottom+wall	95.2	93.7	3595	99	91.2	89.5



(a)



(b)

Fig. 7. (Color online) Emitting spectra of the "top+wall" and the "bottom+wall" configurations obtained from (a) experiment and (b) simulation.

portion of the white light emitted from the LEDs is directly incident on the QD film laminated on the bottom surface of the diffuser plate and is partly converted into red light. However, the unconverted light striking the diffuser plate is partly reflected back toward another QD film on the PCB contributing to the color conversion. On the other hand, the unconverted white light (consisting of blue and yellow peaks) in the QD film laminated on the top surface of the diffuser plate can escape from the lighting more efficiently. This partly explains the higher blue and green peaks of the lighting with the "top+wall" configuration compared to the "bottom+wall" configuration. In addition, the converted red light from the QD film on the bottom surface of the diffuser should pass through the diffuser plate and part of it will be reflected back, which means lower transmittance for the red light formed in the vertical cavity.

In order to confirm this suggestion, a ray-tracing technique was used to simulate the "top+wall" and the "bottom+wall" configurations. The dimensions and the materials of the simulation model were the same to those of the white LED lighting which was used for the experiment. The absorption spectra, the excitation spectra and the emission spectra of red QDs were adopted from the reference [18]. The thickness of the film and the mean free path of red QDs were both 0.6 mm. Figures 7(a) and (b) show the experimental and the simulated emitting spectra of the two cases, respectively. Two spectra obtained from the simulation were normalized in terms of the height of the red peak near 625 nm. Consistent with the experimental results, the heights of the blue and the yellow peaks were lower in the case of "bottom+wall" configuration indicating that our suggestion is correct.

IV. CONCLUSIONS

Conventional white LEDs consisting of blue LED chips and yellow phosphors lack red component resulting in low CRI. Red QD films were incorporated in the conventional 6-inch white LEDs to improve the CRI. The vertical QD wall surrounding the LED chips played an important role in improving the R9 for the saturated red, while the QD film laminated on either the bottom or the top surface of the diffuser plate enhanced the color conversion efficiency and increased the average CRI Ra and Re. In the case of "wall" and "top+wall" configurations, the overall efficiency was comparable to that of the basic structure. This study clearly suggests that appropriate QD configuration can be used to increase the CRI of conventional white LED lightings at nearly no expense of luminous efficiency.

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