

Improvement of light quality by DBR structure in white LED

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Abstract: This study demonstrates the application of DBR structure into the remote phosphor structure to improve the angular correlated color temperature (CCT) deviation in white light-emitting diodes (WLEDs). In the experiment, the LED device with DBR structure yielded a higher luminous efficiency than a conventional structure. The CCT deviation can be improved from 1758K to 280K in a range of -70 to 70 degree and the luminous flux increases more than 10% due to the enhancement of the light extraction of the blue light. Moreover, the reflectance of the different DBR structures is analyzed with different angles to reveal the reasons of such improvements. As the result, this LED device with DBR structure shows the great potential to use as the next generation lighting source.

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OCIS codes: (230.3670) Light-emitting diodes; (230.2090) Electro-optical devices.

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1. Introduction

Recently, white light-emitting diodes (LEDs) have become increasingly popular due to their compactness, long-lifetime and energy-saving features [1–4]. Generally, white LEDs were fabricated by putting a blue chip and yellow phosphor together. There were many crucial factors, including luminous efficiency, color rendering index (CRI) and correlate color temperature, to determine the characteristics of a white LED [5]. Techniques such as nano-structure of the blue chip, the high aspect ratio cone-shape nano-patterned sapphire substrate [6], air voids between GaN nano-pillars and the overgrown GaN layer [7,8] and pattern sapphire substrate methods were reported to improve the light extraction and lumen efficiency for the white LEDs. Furthermore, the dual layer phosphor structure and the imprinting textured phosphor structures were also employed to enhance the lumen efficiency [9,10].

Besides the lumen efficiency, the uniformity of correlated color temperature (CCT) is another important parameter in white LED fabrication which could be defined by the difference of high color temperature (blue emission) and low color temperature (yellow emission) at the various angles [11]. An uneven angular distribution of CCT can lead to non-uniform white light emission and the unwanted phenomenon such as "yellow ring" can be observed in the device [12]. For the conformal phosphor structure, the uniformity of angular CCT was homogenous because of the smaller delta CCT. However, this structure had the worse light extraction due to the large ratio of the light reflection [13]. Liu *et al.* discussed five types of remote phosphor packaging methods, and other factors such as the surface

curvature of the phosphors, the location of the phosphors, in order to characterize and further improve the color homogeneity of the white LEDs [14–16]. Besides the package, ZrO₂ nanoparticles were also employed to improve the color uniformity for white LED. However, some of these methods could enhance the uniformity of CCT at the cost of the lumen efficiency of the LED [17,18]. Consequently, it is an importance topic to strike a balance between both the lumen efficiency and CCT uniformity for a LED device.

Distributed Bragg reflector (DBR) is an optical mirror which is composed of multiple pairs of two different dielectric layers with different refractive indices and in an alternative order to achieve high reflectivity [19]. Its design is versatile and suitable stop-band can be set by changing thicknesses of dielectric layers [20,21]. To use this structure wisely, different purpose can be achieved by various designs. Oh *et al.* designed the eighth-wave thick TiO₂ and quarter-wave thick SiO₂/TiO₂ long-wave pass filter DBR layer and inserted it between YAG phosphor and blue chip, hoping to enhance the color purity level and the luminous efficacy [22,23]. Therefore, how to use the DBR layer to improve the optical characteristic for white LED including lumen efficiency and CCT uniformity is possible and important.

This study developed the remote phosphor structure with the optimized reflective HfO₂/SiO₂ DBR to improve the lumen efficiency and uniform angular CCT for white LED. The results demonstrate that the superfluous blue rays could be reflected and promotes the re-excitation of phosphor to enhance the luminous efficacy and color uniformity. Moreover, the reflections of the Lambertian blue ray with different angles were analyzed to verify the experiment results.

2. Experimental methods

Figure 1(a) shows the schematic and actual cross-sectional photograph of a remote phosphor package covered by DBR structure. The fabrication procedure is described as below: First, prepare the parts for the LEDs: YAG phosphor, silicone and 5070 package. Second, mix the YAG phosphor with silicone to form phosphor slurry. Third, dispense the transparent slurry (without phosphor), and then the phosphor slurry to form remote-phosphor structure. Finally, the DBR structure with different pair numbers can be laid on top of the package to finalize the process. The light source is a 24 mil blue chip whose emission wavelength is approximately 450nm at 120 mA. This remote phosphor device has a broadband wavelength distribution (490–680 nm), and the CCT is controlled at about 5000K at 120 mA. In this study, the remote phosphor structure with three different of DBR films is used to optimized the best condition to obtain the uniform the blue and yellow ray output, which improve the angular CCT deviation.

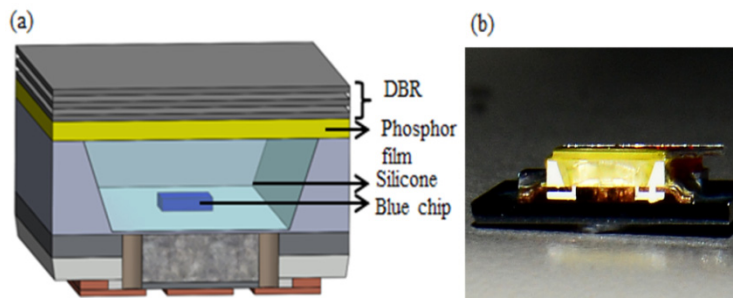


Fig. 1. (a) The cross section of the remote LED package with the DBR thin film onto the package. (b) The actual cut-off picture of a finished LED package.

Figure 2 shows the reflectivity spectra for the three kinds of HfO₂/SiO₂ DBR film with 2.5, 3.5, and 5.5 pairs at different wavelength range. The HfO₂ layer and SiO₂ layer were deposited at the rate of 1.5 Å/s and 2Å/s respectively in an e-gun system with an oxygen partial at the rates of pressure of 1.9×10^{-5} torr and the deposition temperature of 25° C. To

design the quarter-wavelength mirror stack properly, the refractive indices of 1.96 for HfO_2 and 1.55 for SiO_2 are used, and the film thicknesses of 57.4nm for HfO_2 and 72.58nm for SiO_2 are obtained. The substrate to hold the coated dielectric layers is glass and the center wavelength of the DBR is design at 450nm to have the more blue photons reflected.

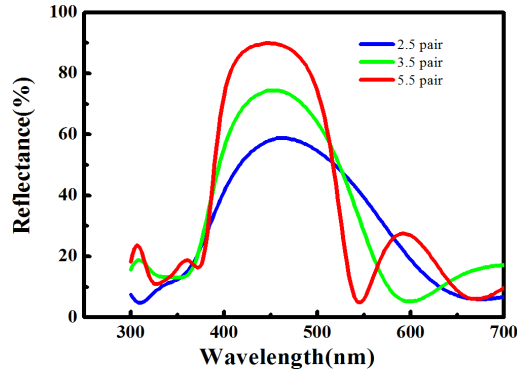


Fig. 2. Experimental optical reflectance spectra for 2.5 pair, 3.5 pair, and 5.5 pair $\text{HfO}_2/\text{SiO}_2$ DBR film with central wavelength of 450nm.

3. Results and discussion

The emission spectra are measured at 120 mA as shown in Fig. 3(a). From the measured spectra, the suppression of the blue rays and the growth of the yellow rays can be observed. The proportions between blue and yellow colors can seriously change the resulting CCT and its uniformity. In Fig. 3(b), the current dependent luminous flux was measured for different pairs of DBR structure. The increase of output lumen can be expected since the DBR can improve the phosphor excitation to increase the numbers of yellow photons leading to lumen enhancement. However, caution needs to be taken as we observed the same level of output between 3.5 and 5.5 pair samples. This saturation of lumen output can be an indication that signals too many blue photons are now confined in LED due to high reflectivity.

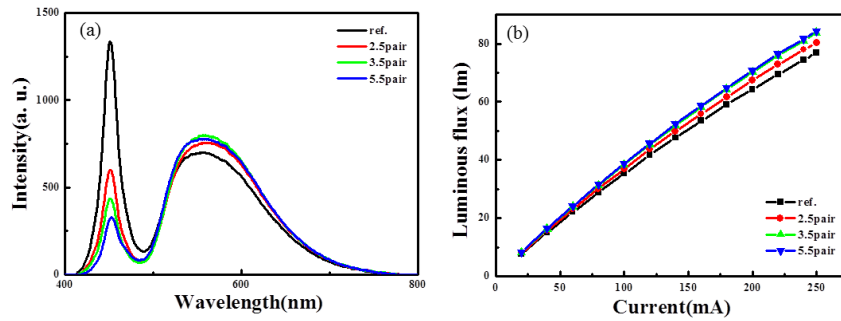


Fig. 3. (a) The emission spectra and (b) the luminous flux for the 2.5pair, 3.5pair, 5.5pair and without covered DBR layers LED samples at the current from 0 to 250mA.

Figure 4 marks the color coordinates of the LEDs with different DBR structures on the CIE 1931 color map. All of them are located within the white region. As the pair of DBR layers increased, the chromaticity coordinates gradually shift to the yellow region due to the higher blue photon consumption and the more induced yellow photons.

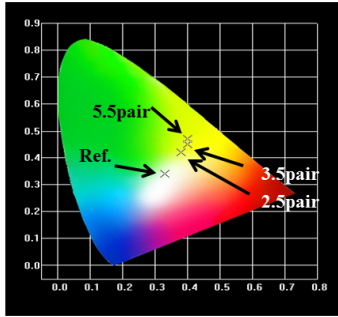


Fig. 4. The CIE 1931 color coordinates of remote LED covered by 2.5pair, 3.5pair and 5.5pair DBR layers.

To evaluate the uniformity of the LED CCT, the parameter called ΔCCT is defined as the difference between the CCT(max) and the CCT(min) [24]. As shown in Fig. 5(a), the diagram shows the angular distribution of CCT of the remote phosphor LED with and without DBR structures. From the plot, the CCT deviations for the conventional, 2.5-pair films, 3.5-pair films and 5.5-pair films were 1735 K, 140 K, 954K and 680 K, respectively. The conventional remote phosphor structure has the largest ΔCCT and causing the yellow ring phenomenon in Fig. 5(b). This yellow ring phenomenon has been studied extensively, and its cause could be attributed to the inherent Lambertian pattern of blue rays [24,25]. With the DBR structure and the reduction of delta CCT, this phenomenon can be eliminated significantly, such as in Fig. 5(c) (the 2.5 pair case).

In Fig. 5(d), the LED package even demonstrates the phenomenon of blue ring when the DBR layer increases to 3.5 pairs. Although the use of DBR films can scatter the normal blue ray and modified the unfavored Lambertian pattern. The addition of DBR pairs can't always reduce the ΔCCT because the suppression of the blue rays in the normal direction can reach the threshold point that turns the yellow photons into the dominant source at the normal direction, like those in 3.5 and 5.5 pair devices.

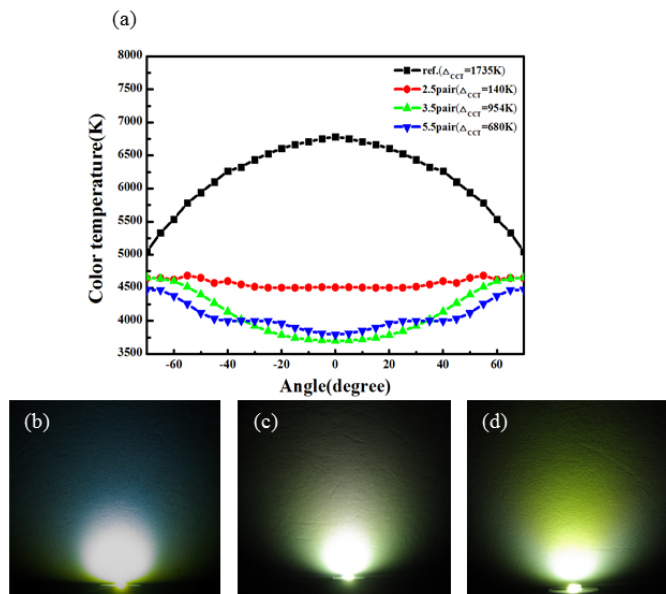


Fig. 5. (a) The spectrum of angular-dependent CCT at 0.12A with 2.5 pair, 3.5 pair and 5.5 pair of the DBR and the far-field images for (b) no pair of DBR film, (c) 2.5 pair of DBR film and (d) 3.5 pair of DBR film on the remote phosphor LED package.

To further analyze the Δ CCT issue, it is important to understand the angular dependence of our DBR structure. In Fig. 6, the measured angular reflectivity from 20° to 60° of the DBR structures is presented. The color in these contour plots represents the reflectance while the X-axis is the incident angle of the light and the Y-axis is the wavelength of the incident photons. The 3.5 and 5.5 pairs of DBR structures have a very high reflectance around 450nm region and much lower yellow reflection across different angles. This difference leads to the serious reduction of blue rays in the normal direction and thus lowers the CCT at the center in the Fig. 5(a). Meanwhile, the ratio of reflectivity between blue and yellow photons of the 2.5 pairs DBR sample is much smaller in all directions, and thus maintains a relatively flat CCT pattern.

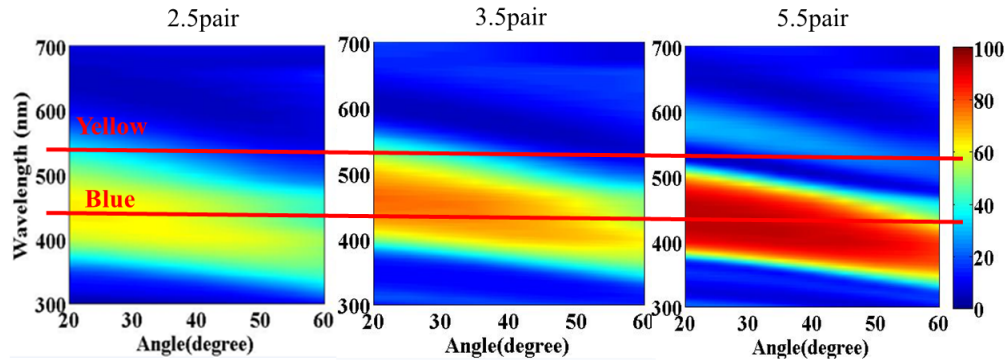


Fig. 6. The reflectance of wavelength at variation angle measured by U4100.

In addition to reflectance measurement, the monochromatic light source can be used for simulating the real LED situation. As shown in Fig. 7, the far-field angular emission patterns of yellow and blue light with different pairs of DBR can provide the supportive evidence on the Δ CCT variation. From the measured monochromatic emission pattern, there are major differences in the blue light (Fig. 7(a)) among the reference 2.5 pair, 3.5 pair and 5.5 pair samples at the low angles (between ± 20 degrees). This is expected since the DBR can reflect the blue photons very efficiently in these directions. However, there are limited differences in yellow photons (Fig. 7(b)) for all DBR samples. The dramatic decrease of blue lights in 3.5 pair and 5.5 pair sample at the center is thus the direct cause of the much lower CCT at the center in Fig. 5(a). Meanwhile, the blue to yellow light pattern of the 2.5 pair DBR sample shall be more proper to keep a constant CCT across various angles of light emissions.

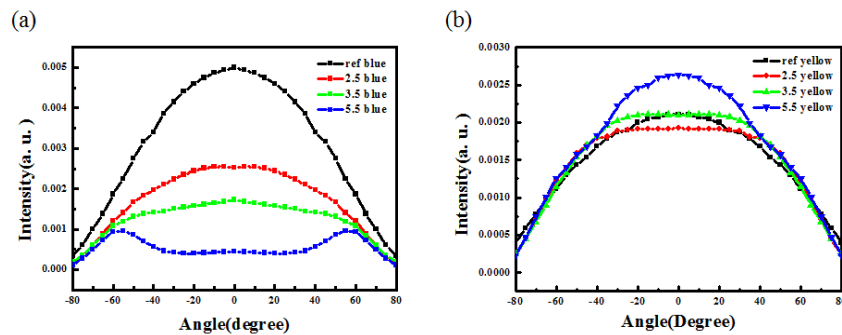


Fig. 7. The far-field emission scheme of (a) blue light and (b) yellow light respectively for each DBR covered and without covered remote LED packages.

4. Conclusion

In conclusion, the white LED with the 2.5pair, 3.5pair and 5.5pair DBR can improve the CCT deviation from 1735K to 140K, 954K and 680K in a range of -70 to 70 degree. The 2.5 pair DBR sample exhibits superior performance in Δ CCT against the 3.5pair, 5.5pair and the reference DBR samples. Adding the DBR layers upon the remote phosphor LED can reflect the Lambertian blue rays and enhance the re-excitation of the phosphor and a 10% enhancement of the luminous flux is recorded. We believe the incorporation of the DBR structure into the regular white LED packages can be beneficial to the performance of the device, and this method should be considered for the next generation package of solid state lighting.

Acknowledgment

The authors express their gratitude to Epistar for their technical support. This research was funded by the National Science Council, Taiwan (NSC102-3113-P-009-007-CC2, and NSC 103-2917-I-009-179).