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Benefits of triple-layer remote phosphor structure in improving color quality and luminous flux of white LED

Thuc Minh Bui[1], Phan Xuan Le[2], Dinh Hoang Bach[3], Nguyen Doan Quoc Anh*[4]
[1]Faculty of Electrical and Electronics Engineering, Nha Trang University, Nha Trang City, Vietnam
[2]National Key Laboratory of Digital Control and System Engineering, Ho Chi Minh City, Vietnam
[3]Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[4]Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering,
Ton Duc Thang University, Ho Chi Minh City, Vietnam
*Corresponding author, e-mail: nguyendoanquocanh@tdtu.edu.vn

Abstract

Remote phosphor structure has higher luminous efficiency comparing to that of both conformal phosphor and in-cup phosphor structures. However, it is hard to control the color quality of remote phosphor structure, and this issue has become one of the most researchable objectives to many researchers in recent years. Up to now, there are two remote phosphor structures applied to improve the color quality, including dual-layer phosphor configuration and triple-layer phosphor configuration. The purpose of this research is to select one of those configurations to have multi-chip white LEDs (WLEDs) achieved the highest color rendering index (CRI), color quality scale (CQS), luminous efficacy (LE), and color uniformity. In this research, WLEDs with two correlated color temperatures (CCT) of 6600K and 7700K were applied. The obtained results showed that triple-layer phosphor configuration is more outstanding in CRI, CQS, and LE. Moreover, the color deviation has been significantly reduced, which means the color uniformity has been enhanced with the application of triple-layer phosphor configuration. These results can be proven by scattering properties of phosphor layers based on Mie theory. Thus, the researched results have become a reliable and valuable reference for manufacturing higher-quality WLEDs.

Keywords: color rendering index, dual-layer phosphor, luminous efficacy, mie-scattering theory remote-phosphor, triple-layer phosphor

1. Introduction

With the advantages of small size, high energy efficiency, low cost, and color stability, phosphor-converted white light-emitting diodes (WLEDs) has become a potential light source [1-3]. In WLEDs, the combination of complementary colors, blue light from a blue chip and yellow light from phosphor, is applied. Besides, there is a potential of being used in solid-state lighting of WLEDs, but to achieve this purpose, the enhancement their luminous efficiency must be fulfilled [4-8]. Generally, one of the most common methods applied to fabricate white light is the freely dispersed coating. In this method, transparent encapsulated resin is dispersed on the phosphor package after being combined with phosphor powder. This measure could get the thickness of the phosphor layer easily managed, and also significantly reduce production costs, yet it does not produce high-quality WLEDs [9]. Therefore, the conformal coating method is suggested as a positive alternative. This method is outstanding with its uniform distribution of colors to bring about the angular homogeneity of correlated color temperature (CCT) [10-12]. However, the decrease in luminous efficiency due to the backscattering effect is the downside of using a conformal phosphor structure. In previous research papers, the demonstration of the concept of separating the chip and the phosphor layer of remote phosphor structures is presented [13-20].

The advanced light extraction internal reflection structure, taking the application of a polymer hemispherical shell lens with interior phosphor coating, is considered as a configuration to increase extraction efficiency [21]. Furthermore, luminous efficiency can be improved by reflecting downward light with the usage of an air-gap embedded structure [22]. Obviously, not only luminous efficacy (LE) but also other optical characteristics, including color rendering index

(CRI), color quality scale (CQS), and color uniformity are extremely vital to WLEDs. Therefore, to magnify the optical characteristics of LEDs, there are two improved remote phosphor structures which have been applied: dual-layer phosphor configuration and triple-layer phosphor configuration. For dual-layer phosphor configuration, the yellow phosphor layer is set in the bottom and on the top, there is a red or green phosphor layer. In triple-layer phosphor configuration, the bottom, top and middle positions are the phosphor layers of yellow, red and green, respectively. Additionally, in accordance with the structure of the package, the role of concentration of phosphor to luminous efficiency cannot be underestimated. The re-absorption loss in the phosphor layer will increase as the increase in phosphor concentration appears. Therefore, it lessens the luminous efficiency, especially at lower CCTs [23-25]. Hence, there is an importance in getting the emission of blue and yellow rays improved, as well as preventing the massive amount of light loss from occurring due to the backscattering and reflection.

It is very difficult for manufacturers to choose a suitable remote phosphor structure to enhance optical characteristics for their LEDs, due to the diversity of proposed methods which have been mentioned above. Hence, this paper proposes the best solution for the manufacturers to decide an optimum measure in getting the quality of WLEDs magnified. Furthermore, in support to manufacturers, the attained results will demonstrate specific methods to develop particular optical characteristics.

2. Research Method

The first idea in this research is using the green phosphor layer SrBaSiO4:Eu2+ to increase blue lights in WLEDs, resulting in an increase in emitted luminous flux. The second idea is raising the red lights in WLEDs by applying the red phosphor layer $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$, leading to a growth of CRI and CQS. In this research, WLEDs with nine LED chips set inside were applied, as illustrated in Figure 1 (a). The radiant flux of each blue chip is 1.16 W, with the peak wavelength is 453 nm. As shown in Figure 1 (b), there are the details of LEDs' optical parameters. Figure 1 (c) describes the single-layer remote phosphor structure (Y) with a yellow phosphor layer YAG:Ce^{3+} on the surface of LED chips. Figure 1 (d) is an illustration of the dual-layer remote phosphor structure (YG), which has a red phosphor layer $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ covering over a yellow phosphor layer YAG:Ce^{3+}. While in Figure 1 (e), the dual-layer remote phosphor (YG) consisted of a green phosphor layer SrBaSiO$_4$:Eu^{2+} coating over the LED chips is demonstrated. Besides, there is a triple-layer remote phosphor structure having a SrBaSiO$_4$:Eu^{2+} phosphor layer between the other two phosphor layers presented in Figure 1 (f).

These phosphor layers the thickness of 0.8mm. To maintain the average correlated temperature colors (ACCTs), the concentration of YAG:Ce^{3+} is changed as regard the differences that were made in the concentration of yellow or red phosphor. At each different ACCT with respect to each phosphor layer, YAG:Ce^{3+} concentration is also different. Thus, it makes a difference of scattering characteristics in LED, leading to the discrepancy in optical characteristics. From Figure 2, it is obvious that the concentration of yellow-emitting YAG:Ce3+ phosphor is highest when using Y structure and lowest with the usage of YRG structure, at all ACTTs. Given that all the remote structures are examined at the same ACCT, if the YAG:Ce^{3+} concentration is higher, the scattering ability is increased, and then the attained result is a decrease in emitted luminous flux. On the other hand, the imbalance among the three complementary colors producing white lights, including yellow, red and green, will exist if there is a high level of YAG:Ce^{3+} concentration, which could decline the color quality of WLEDs. Therefore, to accomplish the improvement in both luminous flux and color quality of WLEDs, it is necessary to reduce scattering events and balance three complementary colors yellow, red and green. It is possible to control the color rendering index by increasing red lights. Additionally, the color uniformity and luminous flux could be managed with the green lights. Thus, whether the triple-layer phosphor structure is the most advantageous one in getting optical characteristics controlled? To come up with a clear answer to this question, our team of researchers will carry on giving other important information relating to remote phosphor structure which is emission spectrum.

As can be seen in Figure 3, there is an obvious difference in emission spectra of remote phosphor structures. At 5 different ACCTs, the emission spectrum of Y has the smallest intensity among the others, resulting in an affirmation that Y structure is capable of attaining

the smallest luminous flux. In contrast, YRG structure gets the highest intensity of emission spectrum in a range from 380 nm to 780 nm of the wavelength. In the range from 400 nm to 500 nm, the intensity of spectrum of YG structure is higher than that of YR structure, and therefore, the luminous flux of YG could higher than that of YR. Nevertheless, compared to YG structure, YR structure has higher emitted intensity of luminous flux of YR structure in the range from 650 nm to 750 nm, which could get YR structure had the higher color rendering index than YG structure. However, to assure all the mentioned information above, it is necessary to examine the obtained results in session 3.
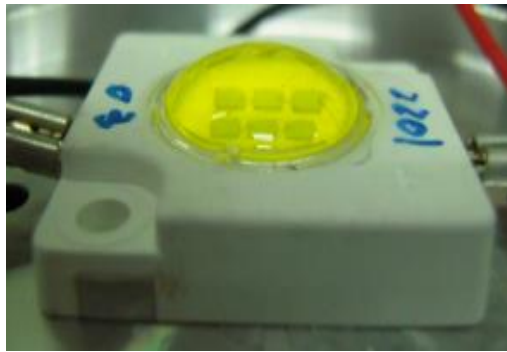
Lead frame: 4.7 mm Jentech Size-S

LED chip: V45H

Die attach: Sumitomo 1295SA

Gold Wire: 1.0 mil
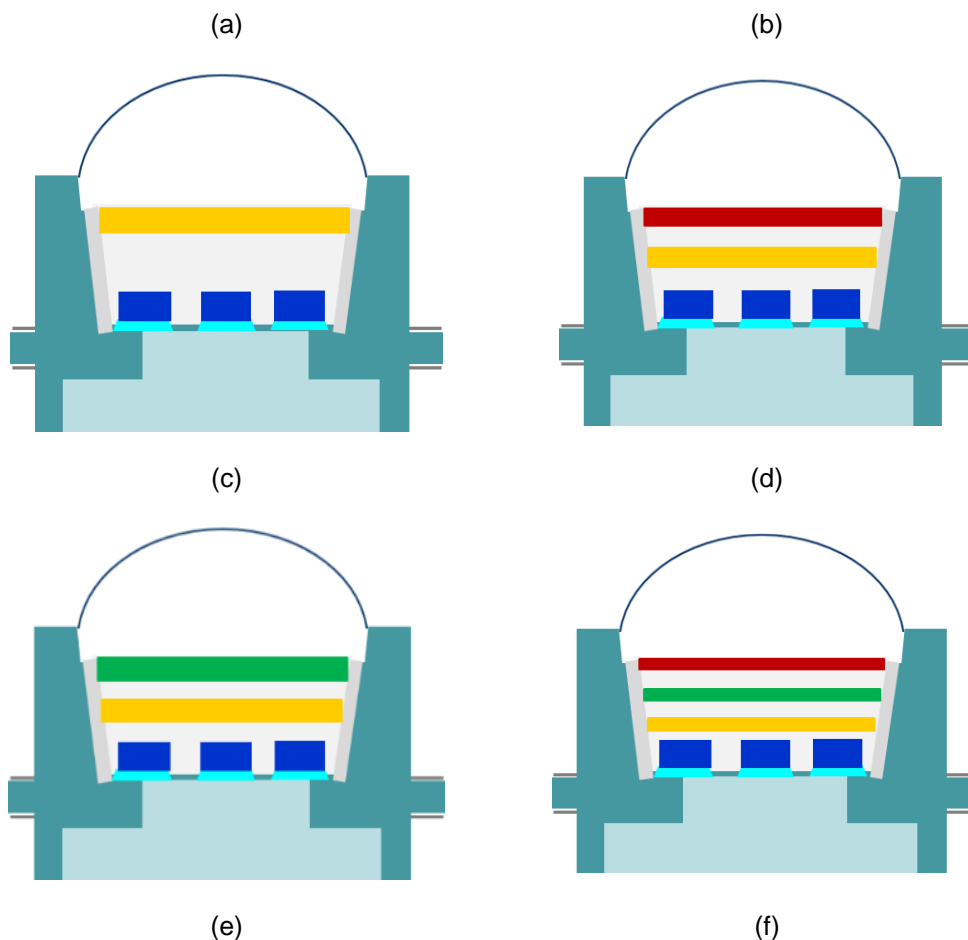Phosphor: ITC NYAG4_EL

(a) (b)

(c) (d)

(e) (f)

Figure 1. Illustration of multi-layer phosphor structures of white LEDs:
(a) the actual MCW-LEDs and (b) its parameters; (c) single-layer phosphor, dual-layer remote phosphor with YR (d) and YG (e), and (f) triple-layer phosphor
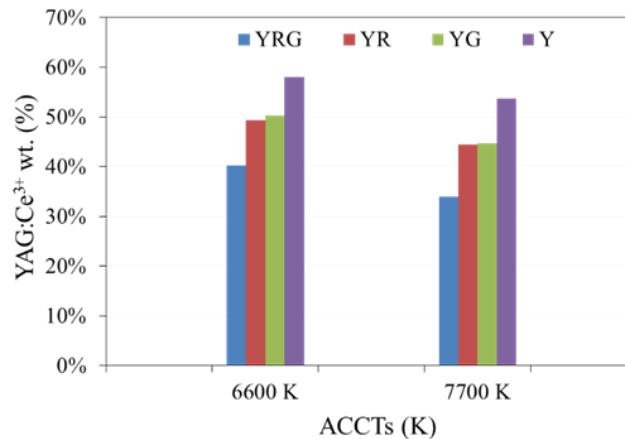
Figure 2. The concentration of yellow-emitting YAG:Ce^{3+} phosphor of each remote phosphor structure at each different ACCT
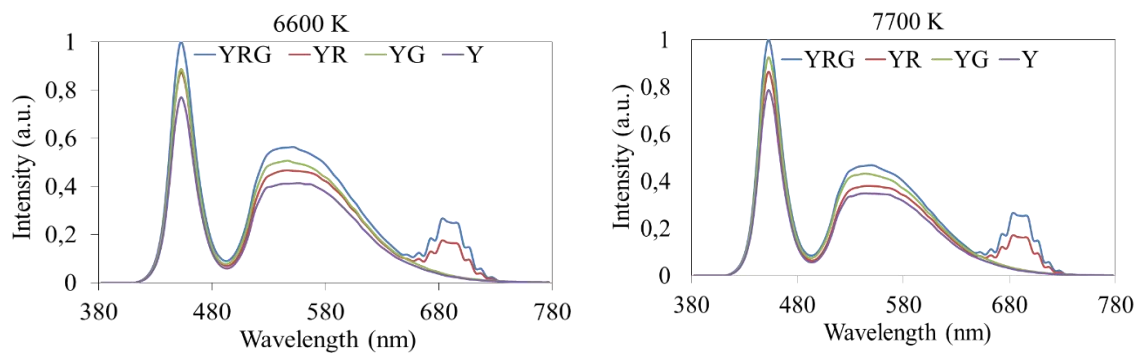

Figure 3. Emission spectra of phosphor configurations

3. Results and analysis

Figure 4 illustrates the comparison among different remote phosphor structure. Obviously, YR structure gets the highest CRI at any ACCT. This result is crucial to remote phosphor structures in improving CRI. While it is hard to control the CRI at a high level of ACCT (more than 6600K), YR layer is able to address this issue. Contributing to the advantage of CRI in YR structure is the additional red lights from the red phosphor layer $Sr_wF_xB_yO_z$:Eu^{2+}, Sm^{2+}. Ranked in the second place of attained CRI value is YRG structure, while in YG structure, the CRI value is the lowest one. Hence, it is possible to affirm that with the aim at CRI, YR structure is the one that could select to mass-produce WLEDs. However, CRI is just one of the indexes that evaluate color quality. In recent years, CQS has become the researched objective of many studies. CQS is the synthesis of three factors: CRI, human preference, and chromaticity coordinates. With the combination of these three factors, CQS has become a great goal and likely to be the most vital index in color quality evaluation. In this study, CQS of remote phosphor structures has been compared in Figure 5. If YR structure reaches the highest CRI, YRG structure achieves the highest CQS. This can be explained by the balance of three complementary colors: yellow, red and green. The higher the CQS value, the higher the color quality. In Y structure, the value of CQS is the lowest. Generally, Y structure is advantageous to luminous flux, but containing difficulty in managing color quality if there is no addition of red and green lights components. Though there still exists the disadvantage in color quality, Y structure is beneficial for production, which means the process of manufacturing would be simpler than the other structures, and production cost could be reduced.
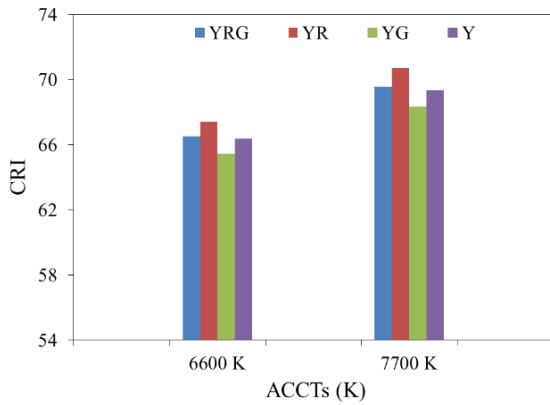
Figure 4. Color rendering indexes of phosphor configurations corresponding to ACCTs
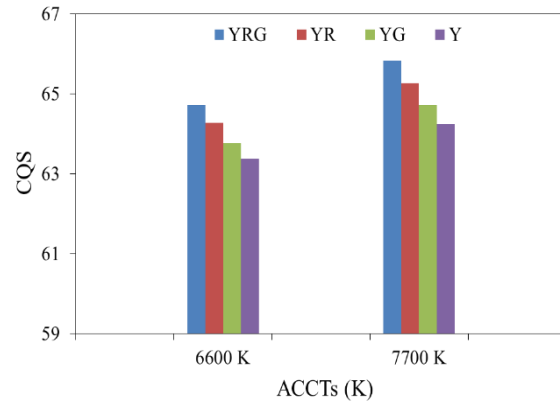
Figure 5. Color quality scale of phosphor configurations corresponding to ACCTs

Based on the results in Figure 5, it is possible to affirm that if manufacturers aim at color quality, they should choose YRG structure. However, if the color quality is better, is the luminous flux affected? To answer this question, the research team has compared the emitted luminous flux between single and double layers. In this part, the mathematical model of the transmitted blue light and converted yellow light in the double-layer phosphor structure will be presented and explained, to examine the great attained enhancement of LED efficiency from this structure. The transmitted blue light and converted yellow light for single layer remote phosphor package with the phosphor layer thickness of $2h$ are expressed as in below formulas:

$$PB_1 = PB_0 \times e^{-2\alpha_{B1}h} \tag{1}$$

$$PY_1 = \frac{1}{2}\frac{\beta_1 \times PB_0}{\alpha_{B1}-\alpha_{Y1}}(e^{-2\alpha_{Y1}h}-e^{-2\alpha_{B1}h}) \tag{2}$$

The transmitted blue light and converted yellow light for double layer remote phosphor package with the phosphor layer thickness of h are determined in following expressions:

$$PB_2 = PB_0 \times e^{-2\alpha_{B2}h} \tag{3}$$

$$PY_2 = \frac{1}{2}\frac{\beta_2 \times PB_0}{\alpha_{B2}-\alpha_{Y2}}(e^{-2\alpha_{Y2}h}-e^{-2\alpha_{B2}h}) \tag{4}$$

in these expressions above, h is the thickness of each phosphor layer. The subscript "1" and "2" are used to describe single layer and double-layer remote phosphor package. β indicates the conversion coefficient for blue light converting to yellow light. γ is the reflection coefficient of the yellow light. The intensities of blue light (PB) and yellow light (PY) are the light intensity from blue LED, presented by PB_0. α_B; α_Y are parameters describing the fractions of the energy loss of blue and yellow lights during their propagation in the phosphor layer respectively. With the double-layer phosphor structure, the lighting efficiency of pc-LEDs is promoted greatly compared to a single layer structure:

$$\frac{(PB_2+PY_2)-(PB_1+PY_1)}{PB_1+PY_1} > 0 \tag{5}$$

The Mie-theory is used in the analysis of scattering of phosphor particles. Moreover, through the following expression applied the Mie theory, the scattering cross section C_{sca} for

spherical particles can be computed. In addition, the transmitted light power can be calculated by the Lambert-Beer law:

$$I=I_0\ exp(-\mu_{ext}L) \tag{6}$$

here, I_0 is the incident light power, L is the phosphor layer thickness (mm) and μ_{ext} is known as the extinction coefficient, which can be expressed as: $\mu_{ext} = N_r.C_{ext}$, where N_r is as the number density distribution of particles (mm^{-3}). C_{ext} (mm^2) is the extinction cross-section of phosphor particles.

The expression (5) has proved that using many phosphor layers is more lucrative to luminous flux than using single layer, and this has been clearly demonstrated in Figure 6 whose results indicated that among four structures, Y structure resulted in the lowest luminous flux at any ACCT whereas, in YRG structure, the luminous reached the highest value. Therefore, according to this result, it is undeniable that in term of advantages in emitted luminous flux, YGR structure has the best result along with its highest color quality. While, with the contribution of green phosphor layer $SrBaSiO_4:Eu^{2+}$, YG structure is in the second place for its improvement in attained luminous flux. The green phosphor layer $SrBaSiO_4:Eu^{2+}$ supports the growth of green lights component and emission spectrum in the wavelength range from 500 nm to 600 nm. Obviously, in this range, YG has higher emitted intensity than both YR and Y due to its lowest concentration of $YAG:Ce^{3+}$ phosphor for remaining ACCT. At that time, YRG structure reduced the occurring scattering lights after a decrease in $YAG:Ce^{3+}$ concentration. Blue lights from LED chips are easily transmitted through $YAG:Ce^{3+}$ layer to other layers. In other words, YRG structure assists the energy of blue lights from the LED chip to be efficiently converted. Therefore, luminous flux intensity of YRG structure is highest when comparing to that of other remote phosphor layers in the same wavelength range of white lights. In consequences of this result, the luminous flux that YRG structure emits has obtained the highest value.
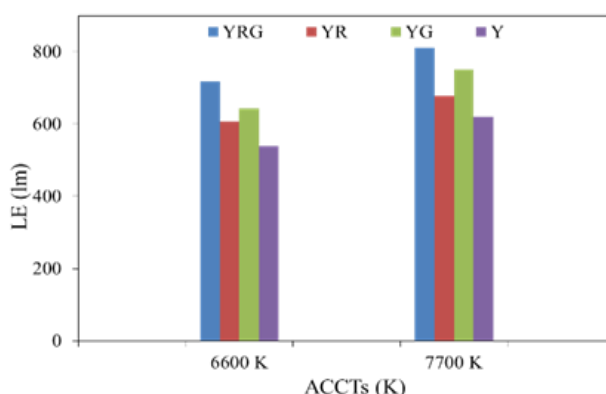

Figure 6. Luminous flux of phosphor configurations corresponding to ACCTs

In this way, YRG structure can be chosen as it is outstanding in enhancing optical characteristics of WLEDs including CQS and LE. However, when mentioning color quality issue, color uniformity can be ignored. There are many methods used to improve color quality, one of which is the usage of scattering enhancement particles such as SiO_2, $CaCO_3$,... or conformal phosphor configuration. Although the color uniformity is magnified when applying these two methods, the luminous flux value could be greatly declined. Whereas, the usage of green $SrBaSiO4:Eu^{2+}$ phosphor and red $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor increases not only scattering properties but also additional green or red lights in WLEDs to produce more white lights with better quality. Moreover, using remote phosphor structures also contributes to enhancing emitted luminous flux since the back reflection to LED chips is minimized. However, there is a need in appropriately controlling the concentration of phosphor layers to achieve the highest transmitted energy, which can be proven by the Lambert-Beer law in (6).

Described in Figure 7 is the comparison of color deviation of remote phosphor structures. The smaller the value of color deviation, the better the color uniformity. It can be seen obviously from Figure 7 that YRG structure results in the smallest color deviation, and this could be demonstrated by scattering events occurring inside the LED package before emitting white lights. The more phosphor layer in the LED package, the more occurring scattering events, and as a result, the color uniformity of WLEDs is enhanced. Obviously, if there are more occurring scattering events, it could lead to the luminous flux decrease. Nevertheless, this decrease is negligible when compared to gained benefits from minimizing the backscattering effect. Thus, YRG structure can attain the best color uniformity while having its luminous flux remained the highest value. On the contrary, Y structure presents the highest color deviation at all ACCTs.
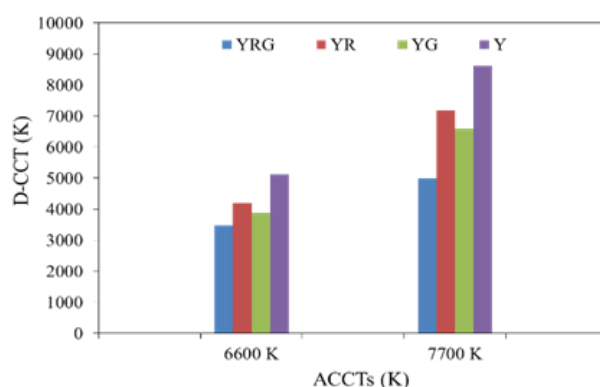

Figure 7. Corelated color temperature deviation (D-CCT) of remote phosphor configurations corresponding to ACCTs

4. Conclusion

This article demonstrates the comparison of optical efficiency of four structures Y, YG, YR and YRG at five different ACCTs. Meanwhile, the green SrBaSiO4:Eu2+ phosphor and red $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor are applied in the simulation process. Moreover, the obtained research results are examined by the Mie theory and the Lambert-Beer law. According to this, the purpose of using the green SrBaSiO4:Eu2+ phosphor layer with additional blue lights is to improve the color uniformity and emitted luminous flux. Hence, YG structure attains the better luminous flux and color uniformity than YR structure. In addition, it is possible to heighten CRI and CQS by an increase in red lights component through the red $Sr_wF_xB_yO_z:Eu^{2+}$, Sm^{2+} phosphor. As the consequence, YR structure achieves the higher CRI and CQS than YG structure. It is easy to realize that the color quality depends on the balance among three complementary colors: yellow, green and red. YRG could fulfill the management of these three colors. Besides, the reduction in backscattering of YRG layer helps the luminous flux of this configuration is considerably increased. The evidence is that the reached highest value of luminous flux is from YRG structure. Based on the results in this study, manufacturers will find it easy to select an appropriate structure for their quality enhancement of WLEDs.

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