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Blue light hazard performance comparison of phosphor-converted LED sources with red quantum dots and red phosphor

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In this study, the blue light hazard performances of phosphor converted-light-emitting diodes (pc-LEDs) with red phosphor and red quantum dots (QDs) were compared and analyzed by spectral optimization, which boosts the minimum attainable blue light hazard efficiency of radiation (BLHER) at high values of color rendering index (CRI) and luminous efficacy of radiation (LER) when the correlated color temperature (CCT) value changes from 1800 to 7800 K. It is found that the minimal BLHER value increases with the increase in the CCT value, and the minimal BLHER values of the two spectral models are nearly the same. Note that the QDs' model has advantages at CCT coverage under the same constraints of CRI and LER. Then, the relationships between minimal BLHER, CRI, CCT, and LER of pc-LEDs with QDs' model were analyzed. It is found that the minimal BLHER values are nearly the same when the CRI value changes from 50 to 90. Therefore, the influence of CRI on minimal BLHER is insignificant. Minimal BLHER increases with the increase in the LER value from 240 to 360 lm/W. *Published by AIP Publishing.*
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I. INTRODUCTION

Compared with the traditional light sources, white phosphor-converted LEDs (pc-LEDs) exhibit admirable advantages of high luminous efficiency, long lifetime, and eco-friendliness.[1,2] Therefore, in the past two decades, white pc-LEDs have been widely used in road illumination and outdoor illumination.[3–5] However, due to the lack of red color components, conventional pc-LEDs with shortcomings of low color performance cannot meet the high color performance requirements of indoor illumination.[6,7] By combining with red phosphor, color performances of pc-LED could be improved.[8] Recently, instead of red phosphor, red quantum dots (QDs) with advantages of narrow emission spectra and tunable emission wavelengths have been proven more suitable to improve the color performances of pc-LEDs.[9] Although the pc-LEDs with red phosphor or red QDs exhibit high color performance, they are facing hidden blue light hazard risk, which has been proven bringing damages to human's retinal,[10–12] physical health,[13] and psychological health.[14,15] Since humans are spending more and more time indoors and in front of the screens, hidden blue light hazard risk of LEDs has been a key factor that prevents LEDs from applying in indoor illumination widely. Since the full widths at half maximum (FWHMs) of red phosphor component and red QDs components are different,[16,17] pc-LEDs with red phosphor and red QDs have different spectral power distribution (SPD) models. With equal color performances and energy saving performances, which kind of the LED models exhibits better potential in blue light hazard performance have not been studied so far. More importantly, the relationships between the blue light hazard performances, color performances, and energy saving performances have not been systematically analyzed.

In this work, blue light hazard performances of pc-LEDs with red phosphor and red QDs were compared and analyzed by spectral optimization, which boosts the minimum attainable blue light hazard efficiency of radiation (BLHER) at high values of color rendering index (CRI) and luminous efficacy of radiation (LER) when the correlated color temperature (CCT) value changes from 1800 to 7800 K by varying the parameter matrix in the corresponding SPD models. Then, the relationships between minimal BLHER, CRI, CCT, and LER of pc-LED with QDs SPD model were analyzed.

II. SPECTRAL MODEL AND OPTIMIZATION METHOD

A. Spectral model

Our spectral model of white LEDs consists of blue chips (narrowband radiation), yellow phosphors (broadband radiation), and red phosphor (broadband radiation), or QDs (narrowband radiation). The relative SPD of white LEDs, $S_W(\lambda)$, is given by

$$S_W(\lambda) = p_b S(\lambda, \lambda_b, \Delta\lambda_b) + p_y S(\lambda, \lambda_y, \Delta\lambda_y) + p_r S(\lambda, \lambda_r, \Delta\lambda_r), \tag{1}$$

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where $S(\lambda, \lambda_b, \Delta\lambda_b)$, $S(\lambda, \lambda_y, \Delta\lambda_y)$, and $S(\lambda, \lambda_r, \Delta\lambda_r)$ refer to the relative SPDs of blue chips, yellow phosphors, and red phosphors or QDs; λ_b, λ_y, and λ_r refer to the peak wavelengths of the blue, yellow, and red color components; $\Delta\lambda_b$, $\Delta\lambda_y$, and $\Delta\lambda_r$ refer to the FWHMs of the three color components; and p_b, p_y, and p_r designate the proportions of the relative spectra of the three color components, respectively. The above spectral parameters, including peak wavelengths, FWHMs, and proportions, comprise a 3×3-dimensional parameter matrix. The three color components' radiation can be described as a modified Gaussian distribution.[18] The FWHMs of blue chip vary from 20 to 50 nm,[19] the FWHMs of green and red phosphors vary from 80 to 120 nm,[20,21] and the FWHMs of red QDs component vary from 20 to 50 nm.[17] The wavelengths for each color component vary from 380 to 500 nm for blue, 500 to 600 nm for yellow, and 600 to 780 nm for red. Here, we used two spectral models. In order to distinguish the two models easily, we named the SPD model of LED with red QDs as QDs' model and the SPD model of LED with red phosphor as phosphor model.

B. Spectral optimization method

The blue light hazard efficiency of radiation (BLHER), which is defined as the ratio of blue light hazard quantity to the corresponding radiometric quantity, is a vital index for assessing the blue light hazard of light sources. It can be expressed as[22]

$$BLHER = \frac{\sum_{\lambda} S(\lambda)B(\lambda)\Delta\lambda}{\sum_{\lambda} S(\lambda)\Delta\lambda}, \tag{2}$$

where $S(\lambda)$ is the SPD of the light source, $B(\lambda)$ is the blue light hazard spectral weighting function, and $\Delta\lambda$ is the wavelength interval (5 nm in this work).

Optimizing spectra with the lowest blue light hazard, high color performance, and high energy saving performance is a complex nonlinear programming (NLP) problem. The simulated annealing algorithm (SAA) is proved for having advantages of a high probability to obtain the global optimum, automatic calculation, and less computing time for complex NLP problems.[23,24] The penalty function approach is generic and applicable to many types of constraints.[25,26] Therefore, we adopted a SAA with penalty functions to realize the spectral optimization for QDs' model and red phosphor model, respectively.

The spectral optimization method boosts the minimum attainable BLHER at high values of CRI and LER and at various CCTs by varying the parameter matrix in the SPD model. In addition, it is important that the chromaticity difference from the Planckian locus on the CIE 1960 uv chromaticity diagram (D_{uv}) be smaller than 0.0054 for various CCTs.[9,27] Therefore, we minimize the BLHER under the constraints of CRI, LER, CCT, and D_{uv} simultaneously. The spectral optimization problem can be described as

$$\begin{cases} \text{Minimize: BLHER} \\ \text{Constraints:}\ R_a \geq R_{as},\ LER \geq LER_s,\ D_{uv} \leq 0.0054, \dfrac{|CCT - CCT_{tar}|}{CCT_{tar}} \leq 0.02, \end{cases} \tag{3}$$

where BLHER is the direct optimization goal and R_{as} and LER_s are the optimization constraints referring to the general CRI (R_a) and the luminous efficacy of radiation (LER), respectively. Here, CCT_{tar}, the designated value of CCT, varies from 1800 to 7800 K at an interval of 300 K. In our optimization, the constraint of deviation between the actual CCT and CCT_{tar} is less than 2%.

III. RESULTS AND DISCUSSION

A. Comparison of QDs' model and phosphor model

First, R_{as} value is assigned as 90. The values of LER are assigned as 330 and 300 lm/W, respectively. By conducting numerous simulations, the optimal spectral parameters of each color component and their performances with $R_a \geq 90$ and LER $\geq$ 330 lm/W for minimal BLHER have been obtained. Figure 1(a) shows the minimal BLHER values of the QDs' model and the phosphor model. Data at some CCTs in the figure are missed because the optimal spectra could not meet the constraints of $R_a \geq 90$ and LER $\geq$ 330 lm/W at the designated CCTs.

Optimal spectra with minimal BLHER can be obtained at the CCTs of 2684, 2946, 3227, 3528, 3825, and 4129 K, by varying the parameters of phosphor model, while minimal BLHER values can be obtained when the CCT value changes from 1770 to 5899 K by varying the parameters of QDs' model. The blue light hazard function is dominated by the blue light emission peak of between 400 and 500 nm,[22] and the CCT value increases with the increase in the blue light emission;[25,28] therefore, it is expected that there is an almost linear relation between CCT and BLHER. It is shown that the minimal BLHER value increases with the increase in the CCT value in Fig. 1(a).

In addition, the minimal BLHER values of the two spectral models are nearly the same when the CCT value changes from 2700 to 4100 K. The blue light hazard function is dominated by the blue light emission; therefore, it can be expected that the impact on BLHER is small from red light, no matter it comes from red phosphor model or QD model. Note that the CCT coverage of QDs' model is wider than that of phosphor model. The difference comes from different FWHMs of red phosphors and red QDs in the SPD model described in formula (1). Therefore, it is possible to fabricate low blue

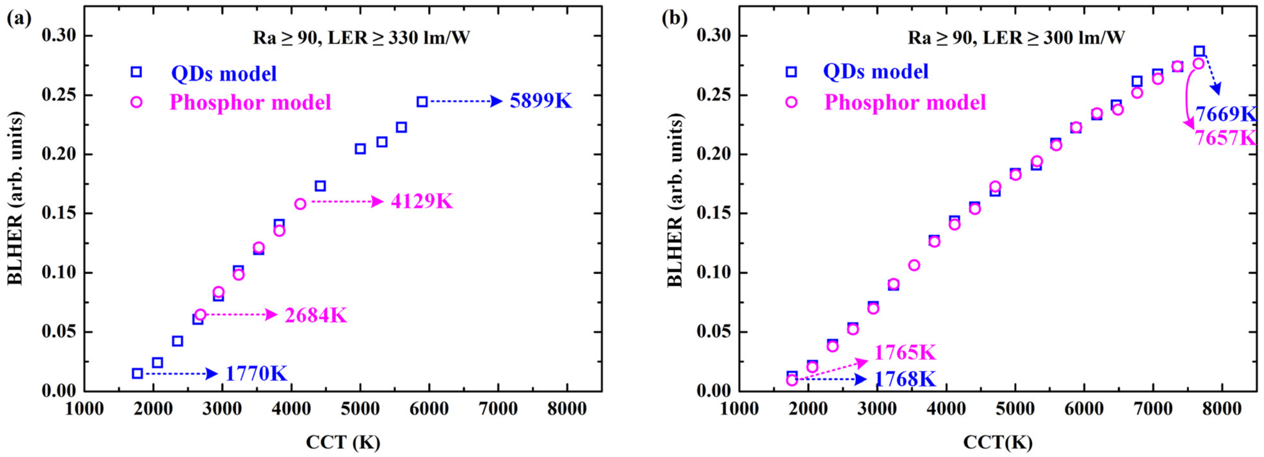

FIG. 1. Optimization results for (a) BLHER values under the constraints of $R_a \geq 90$ and LER$\geq$ 330 lm/W and (b) BLHER values under the constraints of $R_a \geq 90$ and LER$\geq$ 300 lm/W.

light hazard and high CRI and LER values with wider CCT coverage by QDs' model than phosphor model.

Figure 1(b) shows the minimal BLHER values with $R_a \geq 90$ and LER $\geq$ 300 lm/W of the QDs' model and the phosphor model. The minimal BLHER values of the two spectral models are nearly the same when the CCT value changes from 1765 to 7657 K. Comparing Figs. 1(a) and 1(b), it is found that the CCT coverage can be extend approximately low to 1800 K and high to 7800 K by decreasing the LER constraint.

Figure 2 shows the minimal BLHER values with $R_a \geq 70$ and LER $\geq$ 330 lm/W, at designated CCTs from 1800 to 7800 K of the QDs' model and the phosphor model. Minimal BLHER values can be obtained when the CCT value changes from 1766 to 7431 K by varying the parameters of QDs' model, and when the CCT value changes from 2059 to 5300 K by varying the parameters of phosphor model. The CCT coverage under the constraint of $R_a \geq 70$ is wider than that under the constraint of $R_a \geq 90$. Subsequently, the CCT coverage increases with the decrease in the CRI value.

Therefore, it is concluded that the CCT coverage of QDs' model is wider than that of phosphor model from Figs. 1 and 2. It is apparent that QDs' model has advantages at CCT coverage under the same constraints of CRI and LER. Thus, it is advised to fabricate low blue light hazard and high CRI and LER with wide CCT tunable range by the pc-LED with red QDs.

Further, based on the optimization results, we chose pc-LEDs with red QDs to fabricate two actual LEDs with high CCT and low CCT, separately. By our optimization proposed in formula (3), spectral parameters including peak wavelengths, FWHMs, and proportions can be obtained.[27] Then, we chose phosphors and QDs with the above spectral parameters for fabrication. By adjusting the amounts of phosphors and QDs alternatively, the LEDs with optimized SPDs were fabricated. Figure 3 shows that two SPDs with high CRI ($R_a = 90$), high LER (325 lm/W) at CCT = 2648 K and R_a = 90, LER = 301 lm/W at CCT = 6723 K were obtained. The peak wavelengths are 455 nm, 570 nm, and 635 nm at CCT = 2648 K, and 455 nm, 525 nm, and 610 nm at CCT = 6723 K, respectively. The BLHER value at CCT = 2468 K is low to 0.063, which is nearly the same as the simulation results shown in Fig. 1(a) (BLHER = 0.061 at CCT = 2468 K). Also, the BLHER value at CCT = 6723 K is 0.278, which is

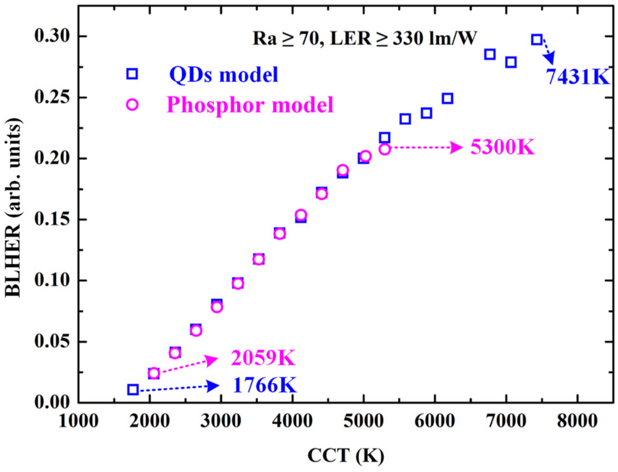

FIG. 2. Optimization results for minimal BLHER values under the constraints of $R_a \geq 70$ and LER $\geq$ 330 lm/W.

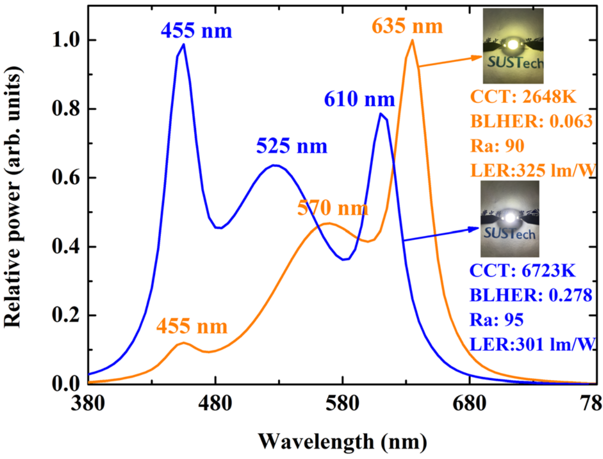

FIG. 3. SPDs of pc-LEDs with red QDs at CCT = 2648 K and CCT = 6723 K.

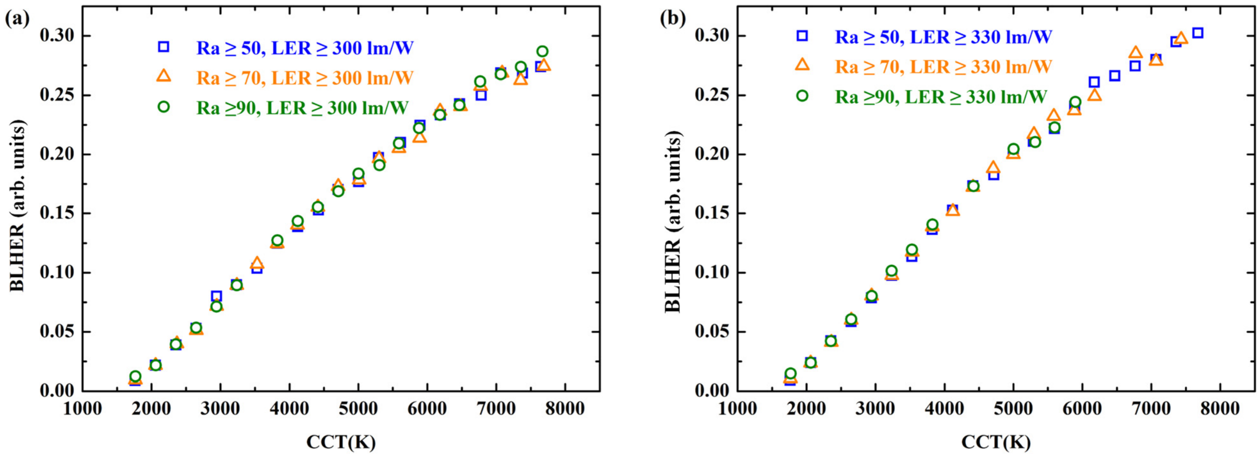

FIG. 4. The minimal BLHER value varies with the increase in the R_a value from 50 to 90 when the CCT value changes from 1800 to 7800 K under (a) LER = 300 lm/W and (b) LER = 330 lm/W.

nearly the same as the simulation results shown in Fig. 1(b) (BLHER = 0.261 at CCT = 6767 K).

B. Relationships between BLHER, CRI, and LER

In this section, the relationships between BLHER, CRI, and LER of QDs' model are analyzed. Figure 4 shows the minimal BLHER value varies with the increase in the R_a value from 50 to 90 when CCT value changes from 1800 to 7800 K. It is found that minimal BLHERs are nearly the same when the CRI value changes from 50 to 90. Therefore, the influence of CRI on minimal BLHER is insignificant.

Figure 5(a) shows that the minimal BLHER value varies with the increase in the LER value from 240 to 360 lm/W, $R_a \geq 70$ lm/W, when the CCT value changes from 1800 to 7800 K. It is shown that BLHER increases with the increase in the LER value. The discipline can be explained as follows. LER is calculated by the integration of the photopic vision function and the SPD,[29] and BLHER is calculated by the integration of the blue light hazard function and the SPD.[22] The two functions have a wavelength range cross from 430 to 550 nm (including blue light and yellow light). Therefore, for increasing LER value, the spectral power among the wavelength range cross, as well as the enhanced BLHER, could be increased.

The influence of LER on minimal BLHER is significant. In addition, optimized spectra with minimal BLHER and $R_a \geq 70$ can be obtained when the CCT value changes from 1765 to 5590 K with LER ≥ 360 lm/W by varying the parameters of QDs' model. While optimized spectra can be obtained when the CCT value changes from 1768 to 7646 K with LER ≥ 240 lm/W. Thus, the CCT coverage increases with the decrease in the LER value.

In addition, the relationship tendency between BLHER, LER, and CCT with $R_a \geq 90$ shown in Fig. 5(b) is similar with that shown in Fig. 5(a). In conclusion, minimal BLHER value increases with the increase in the LER value. Thus, under different CRI and LER requirements, we could obtain the minimal BLHER values at different CCTs. The discipline can be used to guide fabricating minimal BLHER for pc-LED with red QDs at desired CCTs.

IV. CONCLUSIONS

The spectral optimization method boosts the minimum attainable BLHER at high values of CRI and LER and at

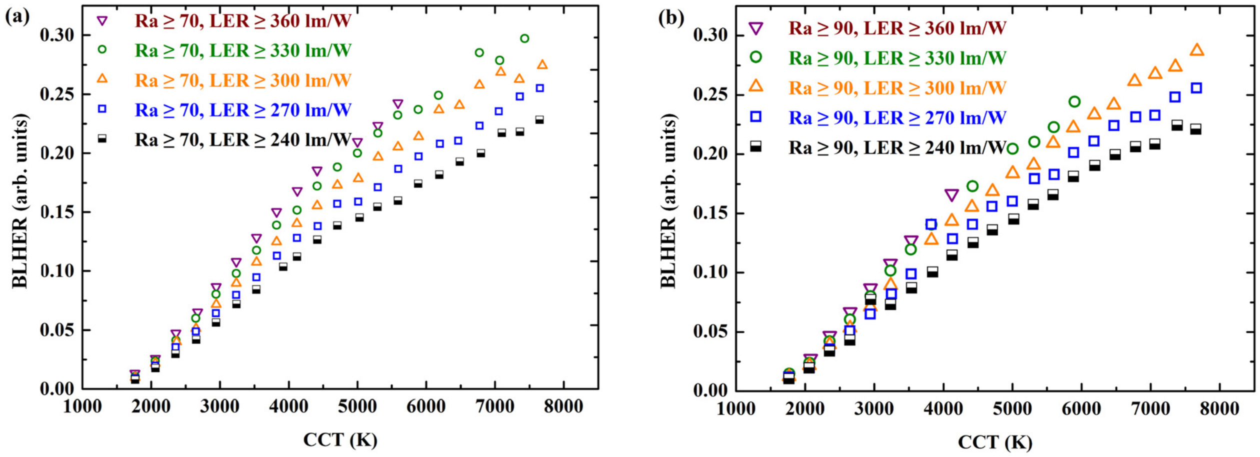

FIG. 5. Minimal BLHER value varies with the increase in the LER value from 240 to 360 lm/W when the CCT value changes from 1800 to 7800 K for (a) $R_a \geq 70$ lm/W and (b) $R_a \geq 90$.

various CCTs by varying the parameter matrix in the QDs SPD model and phosphor SPD model, respectively. Then, the relationships between BLHER, CRI, and LER of QDs' model are systematically analyzed. It is found that the minimal BLHER value increases with the increase in the CCT value of the two models, and the minimal BLHER of the two spectral models are nearly the same. Note that the QDs' model has advantages at CCT coverage under the same constraints of CRI and LER. Thus, it is advised to obtain low blue light hazard and high CRI and LER with wide CCT tunable range by the pc-LED with red QDs. It is also found that minimal BLHERs are nearly the same when the CRI value changes from 50 to 90. Therefore, the influence of CRI on minimal BLHER is insignificant. While, the minimal BLHER value increases with the increase in the LER value from 240 to 360 lm/W. Thus, under different CRI and LER requirements, we could obtain the minimal BLHER values at different CCTs. The discipline can be used to guide fabricating minimal BLHER for pc-LED with red QDs at desired CCTs.

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