Luminous and Melanopic Efficiency Performance of Phosphor-Converted LEDs with Tunable Spectral Characteristics

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Abstract: In this work, we investigated the luminous and melanopic efficiency of the radiation (LER/MER) performances of phosphor-converted LEDs (PC LEDs) with tunable spectral characteristics, namely peak wavelength, full width at half maximum (FWHM), and emission intensity. We constructed theoretical PC LED spectra based on the characteristics extracted from the database of IES TM-30-15, analyzed the relations between LER/MER and different spectral characteristics, and proposed spectral composition strategies at various correlated color temperatures (CCTs). Results showed that both MER and LER are linear with the FWHM of phosphor within the peak wavelength range in practical use, but the change in values by tuning emission intensity varies with spectral compositions. Hence, different spectral characteristics should be considered comprehensively. We further explored the trade-off between luminous and melanopic efficiency. Lowering the FWHM of phosphor and the intensity distribution of the blue LED can obtain higher LER and low circadian effect at lower CCT. As CCT increases, considering color rendering and the increase in the blue intensity distribution, besides reducing FWHM, tuning the peak wavelength close to the peak wavelength of V(λ) helps to reduce the circadian effect. These investigations provide optimization strategies for ideal melanopic and luminous performance of PC LED light sources.

Keywords: tunable spectrum composition; circadian rhythm; FWHM; peak wavelength

1. Introduction

The spectral power distribution of a light source determines both the photometric and colorimetric properties. For example, a high-pressure sodium lamp is rich in the long-wavelength visible light part and thus has high luminous efficiency and low correlated color temperature (CCT); three-band fluorescent lamps have tunable red, green, and blue spectral intensities and thus have tunable luminous efficiencies and CCTs. LEDs, which mainly cover two types (chip-emitting and phosphor-converted LEDs), have their own spectral characteristics. These might lead to new performances.

There are different spectral models for LEDs. As a mixed light source, the spectra of LEDs are usually decomposed into independent “Bell-shape” sections. For chip-emitting LEDs, the Gaussian function model [1] is the most widely used distribution in fitting. Considering the asymmetry in the phosphor-converted spectra, researchers propose a series of modifications, such as a multiple Gaussian function model [2], an asymmetric to sigmoidal function model [3], and an asymmetric Gaussian function model [4–6]. The spectra of LEDs are thus constructed with several spectral characteristics, which are peak wavelength, FWHM, emission intensity, and the asymmetric degree of the shape.

Tunable spectral characteristics of LEDs lead to tunable performance. Color rendering properties and luminous efficacy vary with the peak wavelengths and FWHMs of the spectra, both in a
chip-emitting and a phosphor-converted LED (PC LED) [1,6–8]. Researchers have put forward trade-off strategies by boosting the LER with high color rendering properties [9,10], whereas the study of melatonin suppression has revealed the impacts of spectral composition on human circadian rhythms [11–13], suggesting the inadequacy of traditional assessments of luminous efficacy and color rendering. Possible solutions to circadian lighting design were thus developed with RGBW LEDs [14,15], based on the circadian action curve $C(\lambda)$ and circadian stimulus model [16,17]. On the other hand, studies also adopted the melanopic spectral efficiency function $M(\lambda)$ in circadian lighting evaluation [12,18]. Since the blue light hazard has been proven to be related to circadian rhythm, some research focused on the melatonin suppression effect at different short wavelengths, illumination intensities, and correlated color temperatures [19]. PC LEDs have been widely applied in practical use, but there are fewer studies on spectral optimization in circadian lighting for this type compared with RGB LEDs. Currently, spectral optimization work mainly focuses on synthesizing several specific monochromatic spectra and then selecting the optimal multi-channel combination under a series of lighting requirements. Hence, it is beneficial to work out their impacts on human circadian rhythms and corresponding spectral tuning strategies in daily use. More studies with respect to particular spectral characteristics and spectral construction are required for further spectral optimization and detailed spectral composition guidance.

In this study, we focused on how different spectral characteristics simultaneously affect the luminous and melanopic efficiencies of PC LEDs, including peak wavelength, FWHM, and emission intensity. We found that the effect of each characteristic on LED performance varies with the spectral combination and should be considered comprehensively. Both MER and LER are linear with the FWHM of phosphor within the peak wavelength range in practical use. The maximum of LER at each FWHM corresponds to a similar peak wavelength. The change in values by tuning emission intensity varies with spectral compositions. Based on the investigated variation of MER and LER with tunable spectral characteristics, we provided feasible spectral composition guidance for PC LED performances, which contributes to the luminous and circadian performance optimization and evaluation from the perspective of spectral construction.

2. Methods

2.1. Constructions of PC LED Spectra

Blue-pumped LED exciting yellow phosphor is the most widely used type in commercial PC LEDs nowadays, and thus was selected in the modeling process. We adopted a Gaussian function [1] in Equation (1) and an asymmetric Gaussian function [6] in Equation (2) to calculate the spectral power distributions (SPDs) of a blue LED and phosphor, respectively. The spectrum of the PC LED can then be synthesized by a linear combination of these two functions. The adopted model was based on the measurement of a large number of commercial PC LEDs, which were fabricated with a YAG: Ce$^{3+}$ phosphor pumped with a blue-emitting LED.

$$S_1 = A_1 \exp\left(-4 \ln 2 \frac{(\lambda_i - \lambda_1)^2}{\Delta \lambda_1^2}\right)$$  \hspace{1cm} (1)

$$S_2 = A_2 \exp\left(-4 \ln 2 \frac{(\lambda_i - \lambda_2)^2}{\Delta \lambda_2 (1 + AF \cdot \text{sign}(\lambda_i - \lambda_2))}\right)$$  \hspace{1cm} (2)

where $S_1$ and $S_2$ refer to the spectra of the blue LED and phosphor, respectively; $A_1$ and $A_2$ refer to the intensities of the spectrum; $\lambda_i$ refers to the wavelength band from 380 to 780 nm; $\lambda$ and $\Delta \lambda$ refer to the peak wavelength and FWHM of the spectrum, respectively; and the subscripts 1 and 2 refer to the blue LED and phosphor, respectively. The index AF is the factor that reflects the asymmetric shape of the Gaussian function, which is recommended to be 0.3 [6].
2.2. Luminous and Melanopic Properties of PC LEDs

We selected LER in Equation (3) and MER in Equation (4) to analyze their correlations with spectral characteristics.

\[
LER = \frac{K_m \int_{380}^{780} P(\lambda)V(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)d\lambda}
\]

(3)

\[
MER = \frac{K_z \int_{380}^{780} P(\lambda)M(\lambda)d\lambda}{\int_{380}^{780} P(\lambda)d\lambda}
\]

(4)

where \(P(\lambda)\) refers to SPDs; and \(V(\lambda)\) and \(M(\lambda)\) refer to the photopic vision sensitivity curve and melanopic sensitivity curve [12], respectively, with the efficacy peaks of \(K_m\) (683 lm/W) at 555 nm and \(K_z\) (832 blm/W) at 490 nm, respectively, as shown in Figure 1.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** The normalized spectra of photopic vision sensitivity \(V(\lambda)\) and melanopic efficiency \(M(\lambda)\).

We conducted an investigation into dozens of PC LEDs in practice and analyzed their spectral characteristics. This information was used to help construct theoretical PC LED spectra for the luminous and melanopic efficiency performance study.

3. Results

3.1. Investigated Practical PC LEDs and Extracted Spectral Characteristics

A total of 119 relative spectral power distributions of commercial PC LEDs provided in the database of IES TM-30-15 were adopted, from which the spectral characteristics were extracted, as shown in Figure 2. The spectral compositions in practice were divided into two groups according to whether the emission intensity ratio of blue LED to phosphor (B:Y ratio) was greater than 1. Under these two conditions, B:Y ratios range from 1:0.44 to 1:0.97, and from 0.33:1 to 0.99:1, respectively. We found that the mean peak wavelength (\(\lambda_1\), 449.67 ± 4.81 nm and 450.95 ± 4.19 nm) and FWHM (\(\Delta\lambda_1\), 23.91 ± 2.92 nm and 26.11 ± 4.02 nm) of blue LEDs are concentrated. However, the mean peak wavelength and FWHM of phosphor (\(\lambda_2\) and \(\Delta\lambda_2\)) differ greatly with the B:Y ratio. For PC LEDs of B:Y ratio > 1, \(\lambda_2\) and \(\Delta\lambda_2\) are 563.49 and 133.84 nm, respectively; for PC LEDs of B:Y ratio < 1, \(\lambda_2\) and \(\Delta\lambda_2\) are 604.08 and 149.27 nm, respectively, as shown in Figure 2. In addition, the asymmetric factor seems to be slightly different. Based on the extracted spectral characteristics above, we focused on the peak wavelength and FWHM of phosphor as well as the emission intensity ratio, since they are more adjustable in practical applications.
In the subsequent spectral construction process, we constructed a series of spectra with Equations (1) and (2). MER and LER were then obtained with Equations (3) and (4). We analyzed the impacts of peak wavelength and FWHM of phosphor on MER and LER at a specific range of blue:yellow emission intensity ratios, as shown in Figure 3. Given that the practical spectrum of the blue LED exerts limited impacts outside of its small range of change, the peak wavelength and FWHM were fixed at 450 and 25 nm, respectively. We mainly adjusted the spectra of phosphor, in which the FWHMs varied from 100 to 200 nm. Different ranges of peak wavelengths were set according to a B:Y ratio > 1 or not. The B:Y ratio of the solid lines with square markers in Figure 3a,b is 1:0.7, and in Figure 3c,d corresponds to 0.6:1, with the peak wavelength ranging from 520 to 600 nm and from 520 to 620 nm, respectively. In addition, the filled area of light color in Figure 3a–d shows an influence from the variation of B:Y ratio, with the range of 1:(0.6–0.9) and (0.3–0.9):1, respectively. Compared with the practical spectra, the two asymmetric factors were set at 0.3 and −0.05.

Figure 3 reveals the variation trends of MER and LER with tunable spectral characteristics. There are similar variation trends for MER and LER at different B:Y ratios, which are approximately linear with Δλ₂, especially at λ₂ below 600 nm. Figure 3a,c reveals that tuning λ₂ is the most effective way to make a significant change in MER. With the increase in λ₂, MER firstly decreases with Δλ₂, and then turns to slightly increasing with it. The variation caused by Δλ₂ is quite limited at λ₂ above 560 nm. Moreover, adjusting the B:Y ratio hardly has an effect on MER, especially at the shorter part of λ₂, but has a slight effect on the values of LER. In Figure 3b,d, LER linearly decreases with Δλ₂ at λ₂ below 600 nm. The subplots in Figure 3b,d indicate that no matter what the Δλ₂ is, LER always peaks at λ₂ of 545 nm with a B:Y ratio of more than 1, and varies to λ₂ of 560 nm with a B:Y ratio less than 1, which forms a nearly symmetric distribution. Furthermore, LER has the greatest range of variation on these two axes as well. In brief, in most cases, the impact of each parameter varies with the spectral composition. Hence, the effects of different spectral characteristics on LED performance should be considered comprehensively. Generally, spectral composition strategies for light sources with high luminous efficiency and appropriate circadian effect are desirable. The investigation above can then develop different combinations of spectral characteristics for specific lighting requirements.
Spectral Composition Strategies with Tunable Spectral Characteristics

3.3. Spectral Composition Strategies with Tunable Spectral Characteristics

We constructed a series of spectra at the range of CCT from 3000 to 7000 K in both cases of B:Y ratio. McCamy’s formula [20] was adopted to calculate CCT, where x and y refer to the chromaticity coordinates in the CIE 1931 chromaticity diagram. The color rendering index \( R_a \) is also calculated using the calculator proposed in the database of IES TM-30-15.

\[
\text{CCT} = -449 \cdot n^3 + 3525 \cdot n^2 - 6823 \cdot n + 5520.33, \quad \text{where } n = \frac{x - 0.3320}{y - 0.1858}
\]  

(5)

Figure 4a,b shows the spectra under the LER-maximizing strategy. The spectral characteristics corresponding to the spectra in Figure 4a,b are listed in Table 1.
The values of the spectral characteristics reveal that to maximize LER, $\Delta \lambda_2$ approximately reaches the minimum we set (100 nm) at various CCTs. The increase in CCT mainly depends on the variation of $\lambda_2$ towards a short wavelength. As for the B:Y ratio, it tends to minimize the distribution of the blue LED. These results suggest that a low intensity ratio of blue LED and the FWHM of phosphor are beneficial for LER. Under the LER-maximizing strategy, LER reaches a peak of 390.0 lm/W at 6000 K for B:Y Ratio > 1, whereas the values of LER are all over 410 lm/W for B:Y ratio < 1. Reducing the blue light distribution is more likely to obtain a higher LER at each CCT, of which high LER and low MER make it a better strategy in low circadian effect lighting at CCT below 4000 K. However, the color rendering index $R_a$ in this case decreases sharply at a higher CCT due to the excessive reduction of blue intensity. Therefore, different combinations of spectral characteristics correspond to tunable LED performance even at the same CCT.

Figure 5 shows LER and MER with different B:Y ratios at various CCTs under the LER-maximizing strategy (the blue and red solid lines with solid square markers) and the MER-maximizing strategy (the blue and red solid lines with hollow square markers), respectively. It reveals that the values of MER are quite close under these two strategies, and both increase with CCT. Furthermore, in both Figure 5a,b, MER under the LER-maximizing strategy almost overlaps with the maximum MER at a higher CCT, no matter what the intensity of blue light is. This suggests that a decrease in MER necessarily leads to a decrease in LER. Hence, we further explored the trade-off between MER and LER in circadian lighting and the corresponding spectral composition, which is discussed in the next section.
In various scenes, which requires a strategy is almost maximum simultaneously, and LER under the latter strategy, maximizing MER can change in MER to decrease. Hence, we adopted MER under the former strategy is almost maximum simultaneously, and LER under the latter strategy to decrease.

The International Well Building Institute [21] recommends Equivalent Melanopic Lux (EML) for circadian lighting evaluation by setting a threshold in various scenes, which requires no more than 50 EML in nocturnal lighting. In this standard, only the melanopic curve is taken into consideration to quantify the circadian effect of light, whereas there are five kinds of equivalent α-opic illuminance for five photoreceptors, and all of them are proven to have impacts on rhythm [12,17]. Nevertheless, EML is still instructive in circadian lighting for its relationship between melanopic sensitivity and light. The equation of EML is as follows, where $E_e(\lambda)$ refers to the SPD of a light source, and $N_\alpha(\lambda)$ refers to the spectral sensitivity curve of melanopsin.

$$EML = 72983.25 \int E_e(\lambda)N_\alpha(\lambda) \, d\lambda \propto \frac{MER}{LER} \Phi_e$$  \hspace{1cm} (6)

On the right side of Equation (6), EML is proportional to the product of eye-level photopic illuminance $\Phi_e$ and MER/LER. Considering the results in Section 3.3, for light sources with fixed photopic flux, neither simply maximizing LER nor minimizing MER can efficiently reduce EML, since MER under the former strategy is almost maximum simultaneously, and LER under the latter strategy is particularly low. For the lighting scenes requiring sufficient EML, maximizing MER can obtain both high MER and relatively low LER at lower CCT, but improving EML at higher CCT tends to rely more on the decrease in LER, because the values of MER do not change much when LER continues to decrease. Hence, we adopted MER/LER as values of interest and calculated the maximum and minimum, respectively, as shown in Figure 6a. For light sources with fixed photopic illuminance, the change in MER/LER can represent the variation of EML. The figure reveals that both the minimum and maximum MER/LER increase along with CCT, but the maximum MER/LER at each CCT has much lower LER, which suggests that high LER plays an important role in low circadian effect. Furthermore, the results over 5000 K show that minimizing MER/LER accompanies the reduction of LER. The key to spectral composition is the trade-off between luminous efficiency and low circadian effect under the limit of color rendering.
The variation of CCT at minimum MER/LER mainly depends on the phosphor, which is also close to the peak wavelength of $\lambda_{2}$. Within the limit of color rendering, when CCT is over 5000 K, due to the limitation of color rendering, the distribution of blue intensity which sheds new light on convenient property evaluation and spectral composition for PC LEDs phosphor exert different impacts on the luminous and melanopic performance, and the trade-off in low circadian effect lighting design. The investigations are summarized as follows:

We restrained LER at over 330 lm/W and color rendering index Ra at over 60. Figure 6b shows the spectra of MER/LER we eventually chose following the principle of minimum, and the corresponding spectral characteristics are listed in Table 2.

Table 2. Spectral characteristics with minimum MER/LER from 3000 to 7000 K.

| CCT (K) | $\lambda_{2}$ (nm) | $\Delta\lambda_{2}$ (nm) | B:Y ratio | MER (blm/W) | LER (lm/W) | MER/LER | Ra |
|--------|-------------------|--------------------------|------------|-------------|-----------|--------|----|
| 3000   | 588               | 100                      | 0.3:1      | 140.91      | 414.23    | 0.34   | 60 |
| 4000   | 572               | 109                      | 0.32:1     | 214.41      | 430.75    | 0.50   | 60 |
| 5000   | 550               | 105                      | 1:0.98     | 243.06      | 386.73    | 0.63   | 60 |
| 6000   | 548               | 100                      | 1:0.68     | 269.32      | 363.99    | 0.74   | 61 |
| 7000   | 550               | 102                      | 1:0.5      | 278.10      | 332.24    | 0.84   | 66 |

Compared with the spectral characteristics under the LER-maximizing strategy listed in Table 1, all the values of $\Delta\lambda_{2}$ at various CCTs still approach the minimum we set (100 nm). The spectral characteristics at CCT from 3000 to 4000 K are similar to those with maximum LER, which suggests that for light sources within this range of CCT, it might be a viable option to reduce circadian effect. When CCT is over 5000 K, due to the limitation of color rendering, the distribution of blue intensity should be improved. Among the spectral characteristics, the values of $\lambda_{2}$ are quite close and approach the maximum of the axis (545 nm), which is also close to the peak wavelength of the photopic sensitivity curve (555 nm). The variation of CCT at minimum MER/LER mainly depends on the intensity ratio of phosphor. These results indicate that a narrow FWHM of phosphor is expected for both luminous efficiency and low circadian effect. Within the limit of color rendering, the trade-off between them at a higher CCT depends more on tuning the intensity distribution of blue LED and phosphor than the peak wavelength, which suggests the comprehensive effects of tuning spectral characteristics for various lighting requirements.

5. Conclusions

This study investigates luminous and melanopic performance with tunable spectral characteristics, which sheds new light on convenient property evaluation and spectral composition for PC LEDs in practice. The peak wavelength and FWHM of phosphor and the intensity ratio of blue LED to phosphor exert different impacts on the luminous and melanopic performance, and the trade-off in low circadian effect lighting design. The investigations are summarized as follows:

![Figure 6. (a) Maximum and minimum MER/LER as functions of CCT; (b) spectra with minimum MER/LER from 3000 to 7000 K, of which LER is restrained at over 330 lm/W and Ra at over 60.](image-url)
1. Both MER and LER are approximately linear with the FWHM of phosphor within the peak wavelength range of phosphor in practical use. LER linearly decreases with the FWHM of phosphor, whereas MER linearly decreases only at shorter peak wavelengths. Adjusting the intensity ratio of the blue LED has less impact on LER and MER than the other two characteristics do, especially at the shorter peak wavelength of phosphor. Therefore, a single characteristic can play a different role in different spectral combinations.

2. LER reaches the maximum at a peak wavelength of phosphor of 545 nm for B:Y ratio > 1 and 560 nm for B:Y ratio > 1, respectively. Nevertheless, when maximizing LER at each CCT, the variation of CCT relies more on the change in the peak wavelength of phosphor. Lowering the FWHM of phosphor and the intensity distribution of the blue LED mainly helps to obtain higher LER at each CCT. However, the excessive reduction of blue light intensity is accompanied by a decline in color rendering.

3. The values of MER under LER-maximizing and MER-maximizing strategies are quite close and both increase with CCT, which suggests that a decrease in MER necessarily leads to a decrease in LER, especially at higher CCTs. Hence, neither simply maximizing LER nor minimizing MER in spectrum tuning can efficiently reduce the circadian effect.

4. Different optimization strategies correspond to various combinations of spectral characteristics, even at the same CCT. The spectral composition of maximizing LER with lower blue LED contribution is viable only at lower CCTs. As CCT increases, it is confronted with the trade-off between luminous efficiency, circadian effect, and color rendering. In this case, improving the blue light intensity is more appropriate for less loss of color rendering. Meanwhile, tuning the peak wavelength of phosphor close to the peak of LER and decreasing the FWHM of phosphor may still be a solution to help maintain luminous efficiency and lower the circadian effect, though the loss of LER is inevitable in the trade-off at higher CCTs.

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