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利用相关色温和光通量优化白光 LED 光谱

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摘　要:在单颗 LED 中,以 1℃/W～30.5℃/W 范围的散热器热阻值和 0.5 W～6.5 W 范围的负载电功率作为优化变量,40 lm～460 lm 范围的光通量和 7 100 K～8 600 K 范围的色温作为目标变量,通过光-电-热理论和多重光谱模型优化白光 LED 的光谱功率分布.计算获得白光 LED 的光通量和相关色温在系统中变化时所对应的光谱功率分布,目标值与理论值的误差在 5%以内.该理论模型可为 LED 照明系统的设计提供参考.

关键词:LED;光谱分布;光通量;相关色温;散热器

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Optimization Spectrum of White Light Emitting Diodes Based on Correlated Color Temperature and Luminous Flux

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Abstract: Considering the direct current drive electrical power from 0.5 W to 6.5 W on a different heatsink and the thermal resistance from 1℃/W to 30.5℃/W as optimization variables, a series of calculations are performed in order to obtain the target variables which are the objective function of luminous flux from 40 lm to 460 lm and correlated color temperature from 7 100 K to 8 600 K. The spectral power distribution of white light-emitting diodes was optimized using a combination of the photo-electro-thermal theory and multi- spectral power distribution modeling. When the objective function is close to 5%, the optimized results of SPD is obtained. The work provides a reference for practicing LED system designers to optimization an LED system.

Key words: Light-emitting diode; Spectral power distribution; Luminous flux; Correlated color temperature; Heatsink

OCIS Codes: 300.6170; 300.6280; 300.6430

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0 Introduction

Light-Emitting Diode (LED) involves multidisciplinary subjects, including photometry, electric, and heat, which are interdependent on one another. The Photo-Electro-Thermal (PET) theory can determine the operating point of maximum light flux and also be used to set conditions of the optimum thermal design of the suitable heatsink for a given application[1-5]. The Spectral Power Distribution (SPD) is a significant characteristic of an LED that determines the color properties, which is highly dependent on the electric power and junction temperature[6-8].

The junction temperature influences luminous efficiency and dominant wavelength of LED properties. An LED chip is encapsulated in package, the junction temperature cannot be measured directly. In Ref. [9], it describes the junction temperature measurement approaches, and focuses on discussing the measurement issues. Several reports[10-11] have pointed out that the relationships of light output degradation and the junction temperature of the LED. With the increase of temperature, the luminous efficiency of LEDs will drop to about 0.2 ~ 1%[12]. Accelerated aging of experiments showed the degradation in light efficiency induced by thermal storage[13].

With increasing demand for higher power density, high-brightness LED is facing challenging thermal problems that affect optical characteristics and reliability[14-16]. The silicon-based thermoelectric device could reduce the thermal resistance of the high power LED [17]. An instrument that could measure the thermal resistance of high brightness LED quickly using electrical test method was introduced in Ref. [18], and established a standard on how to do thermal resistance measurement for LED[19].

Color perception of the LED light is also an important subject for research in LED systems. In terms of indoor applications, it is important to take into account the Correlated Color Temperature (CCT) of the illumination. It is highly pointed out that the CCT of the phosphor-coated white LED will change with the LED power[20-21].

The optimization spectrum of LED was proposed based on luminous flux and CCT. For a given heatsink, the maximum luminous flux and CCT of white LED could be determined using the proposed method. The maximum luminous flux of an LED will occur at a power level that is dependent on the thermal resistance of the heatsink. If a small heatsink with high thermal resistance, the maximum luminous flux tends to occur at a lower power. The proposed approach of the paper contributes to the white LED in different CCT and luminous flux to extract the optimum electrical power and thermal resistance of the heatsink, and select the best working conditions for white LED. The work offers an important tool for practicing LED system designers to optimize SPD of white LED system.

1 The characteristics for spectral and optical model of an LED

1.1 Multi-Spectral Power Distribution

The PET theory links the electrical, thermal, and luminous aspects of an LED system, which can explain why the maximum flux may not occur at the rated power of the LED system [1]. For a given thermal design, the theory can predict the optimal operating point at which maximum luminous flux can be achieved. The extended PET theory can predict the heat-dissipation coefficients, optical power, and internal junction temperature that cannot be easily obtained in practice [4].

The asymmetrical SPD of monochrome LED are typically modeled with a Gaussian function

$$P_{\lambda}=P_{\mathrm{opt}}\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-0.5\cdot\frac{(\lambda-\lambda_{\mathrm{peak}})^2}{\sigma^2}\right] \tag{1}$$

where P_{opt} is optical power of SPD, σ is dependent on peak wavelength λ_{peak} and FWHM $\Delta\lambda$. FWHM is full width at half maximum, which descript the spectral width of emitting light.

$$\sigma=\frac{\lambda_{\mathrm{peak}}^2\Delta E}{2hc\sqrt{2\ln 2}}=\frac{\lambda_{\mathrm{peak}}^2\left(\frac{hc}{\lambda_1}-\frac{hc}{\lambda_2}\right)}{2hc\sqrt{2\ln 2}}=\frac{\lambda_{\mathrm{peak}}^2\left(\frac{hc\Delta\lambda}{\lambda_1\lambda_2}\right)}{2hc\sqrt{2\ln 2}} \tag{2}$$

$$P_{\lambda}=\sum_{m=1}^{m=n}P_{\lambda,m} \tag{3}$$

The SPD of a white LED using yellow YAG phosphor and blue LED chip can theoretically be predicted using by multi-SPD model[6]. With the help of the multi-SPD model in Eq. (3), the SPD for following white LEDs can be constructed as reference SPD. The peak wavelength and FWHM of the spectra can be established as a function of the junction temperature using the practical measurement[6]. Due to temperature effect on the peak wavelength λ_{peak} and FWHM $\Delta\lambda$, the peak wavelength and FWHM of multi-SPD can be expressed as

$$\lambda_{\mathrm{peak},m}(T_j)=k_{\mathrm{peak},m}(T_j-T_o)+\lambda_{\mathrm{peak},m,r} \tag{4}$$

$$\Delta\lambda_m(T_j)=k_{\Delta\lambda,m}(T_j-T_0)+\Delta\lambda_{m,r} \tag{5}$$

where $\lambda_{\mathrm{peak},m}$ is the peak wavelength of m^{th} SPD, $k_{\mathrm{peak},m}$ is temperature effect on the peak wavelength of m^{th} SPD, $\lambda_{\mathrm{peak},m,r}$ is the reference peak wavelength of m^{th} SPD. $\Delta\lambda_m$ is FWHM of m^{th} SPD, $k_{\Delta\lambda,m}$ is a coefficient of the temperature effect on FWHM of m^{th} SPD, $\Delta\lambda_{m,r}$ is reference peak wavelength of m^{th} SPD, due to $P_{\mathrm{opt\text{-}g}}/P_{\mathrm{opt-phosphor}}=0.327$ and $P_{\mathrm{opt\text{-}y}}/P_{\mathrm{opt-phosphor}}=0.673$, the required parameters of Eqs. (4) and (5) can be determined, which are shown in Table 1.

Table 1 Required parameters for Eqs. (4) and (5)

$k_{peak,g}$	$k_{peak,y}$	$k_{\Delta\lambda,g}$	$k_{\Delta\lambda,y}$
−0.017	−0.034	0.017	0.035

Due to optical power variation with injection current and temperature, the optical power $P_{opt,m}$ of m^{th} SPD can be expressed as

$$P_{opt,m}(T_j, P_d) = (\alpha_m T_j + \beta_m)(\chi_m P_d + \gamma_m) \quad (6)$$

where α_m, β_m, χ_m, γ_m are the temperature and electrical power coefficients for optical power of m^{th} SPD.

The SPD of the white LED sample used blue LED chip with yellow YAG phosphor, which can theoretically be considered as the summation of three SPDs. Therefore, it can be expressed as a tricolor spectrum model in the following

$$P_\lambda(P_d, T_j) = \eta_b P_{opt\text{-}total}(P_d, T_j)\frac{1}{\sigma_b(T_j)\sqrt{2\pi}}\exp\left\{-0.5\frac{[\lambda(T_j)-\lambda_{peak-b}(T_j)]^2}{\sigma_b(T_j)^2}\right\} + \eta_g P_{opt\text{-}total}(P_d, T_j)\cdot \frac{1}{\sigma_g(T_j)\sqrt{2\pi}}\exp\left\{-0.5\frac{[\lambda(T_j)-\lambda_{peak-g}(T_j)]^2}{\sigma_g(T_j)^2}\right\} + \eta_y P_{opt\text{-}total}(P_d, T_j)\frac{1}{\sigma_y(T_j)\sqrt{2\pi}}\cdot \exp\left\{-0.5\frac{[\lambda(T_j)-\lambda_{peak-y}(T_j)]^2}{\sigma_y(T_j)^2}\right\} \quad (7)$$

where η_b、η_g、η_y are the ratios of blue, green and yellow spectra, respectively, which is related to the internal junction temperature of the LED.

Table 2 Required parameters for Eq. (7)

α_y	β_y	χ_y	γ_y	α_g	β_g	χ_g	γ_g
−0.000135	0.103	2.94	−0.27	−0.000065	0.508	4.66	−4.89

As shown in Fig. 1[6], the calculated results agree well with practical measurements. These agreements confirm the validity of the proposed Tri-color SPD modeling method.

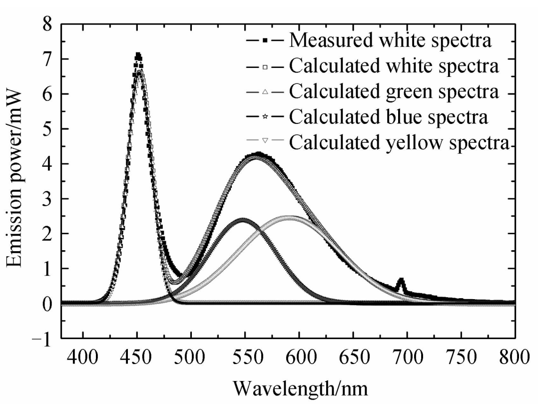

Fig. 1 Measured and calculated spectral power distributions for white LED sample at a junction temperature of 68.6℃ and a current of 0.34A

1.2 Luminous flux and correlated color temperature

The effect of the luminous flux reduction with increasing current linked to several mechanisms. The interactions of luminous flux, electrical power and junction temperature of LED can be described as

$$\Phi_v = N\cdot P_d \cdot E = NE_0\{[1+k_e(T_a - T_0)]P_d + k_e k_h(R_{jc}+NR_{hs})P_d^2\} = NE_0\{[1+k_e(T_a - T_0)]P_d + k_e(1-\frac{P_{opt\text{-}total}}{P_d})(R_{jc}+NR_{hs})P_d^2\} \quad (8)$$

where Φ_v is the luminous flux, P_d is the electrical power, T_a is the ambient temperature, R_{hs} is the thermal resistance of the heatsink, R_{jc} is the thermal resistance of the LED, k_h is the heat-dissipation coefficient of the LED, E_0 is the rated efficacy at the rated temperature T_0, and k_e is the relative rate of reduction of luminous efficacy with increasing junction temperature and can be found in the data sheet. The required parameters for Eqs. (7) and (8) are shown in Table 3, which have been verified with the use of Sharp 4.4 W LED (Model number GW5BNC15L02)[6].

Table 3 Required parameters for multi-SPD model of sharp 4.4W LED sample

$\lambda_{peak\text{-}b}$	$\lambda_{peak\text{-}g}$	$\lambda_{peak\text{-}y}$	σ_b	σ_g
452.8 nm	548.0 nm	591.0 nm	22.6 nm	62.0 nm
σ_y	T_a	R_{jc}	R_{hs}	k_h
91.9 nm	20℃	7.3℃/W	2.2℃/W	0.78

CCT has been used as a metric to describe wideband light sources, that is, characterizing the spectral properties of a white light source. In this paper, CCT model of LED with MaCamy model[22] can be expressed as

$$CCT = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \quad (9)$$

where $n = \frac{x-0.3320}{0.1858-y}$, the x and y are the chromaticity coordinates.

2 Optimization spectrum based on the target luminous flux and CCT

2.1 The control range of Luminous flux and CCT

Four sets of experiments, each with the LED mounted on a different heatsink, with thermal resistance of respectively 1℃/W, 10.5℃/W, 20.5℃/W and 30.5℃/W are performed. The ambient temperature is kept constant at 25℃ and the heatsink operates under free convection with no active temperature control. For each set of experiment, using the DC drive electrical power from 0.5 W to 6.5 W is employed. The control luminous-flux range of the LED with heatsink′s thermal resistance of 1℃/W, 10.5℃/W, 20.5℃/W and 30.5℃/W are respectively obtained from Fig. 2.

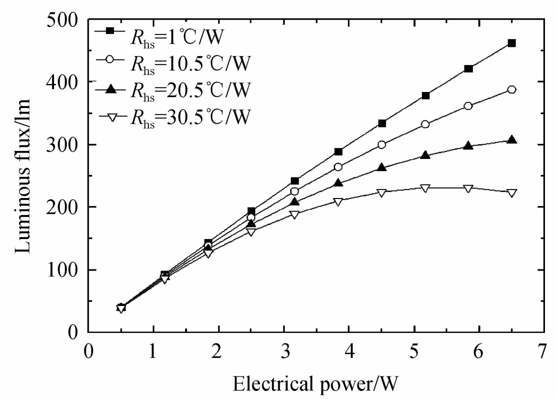

Fig. 2 Luminous flux versus electrical power for LED sample with different heatsink

Fig. 2 shows that the luminous flux of white LED decreases with increasing the heatsink thermal resistance. When electrical power is less than 2 W, the luminous flux of the LED has little difference for the same electrical power and different heatsink thermal resistance. As shown in the Fig. 2, when the thermal resistance is 30.5℃/W and electric power is about 5W, the luminous flux will reach the maximum value of 230 lm. After reaching the maximum luminous flux, Φ_v will drop with increasing P_d. When the thermal resistance R_{hs} is 1℃/W, the luminous flux can reach the maximum about 460 lm.

Following the form of Eq. (9), CCT versus electrical power for white LED with different heatsink is shown in Fig. 3.

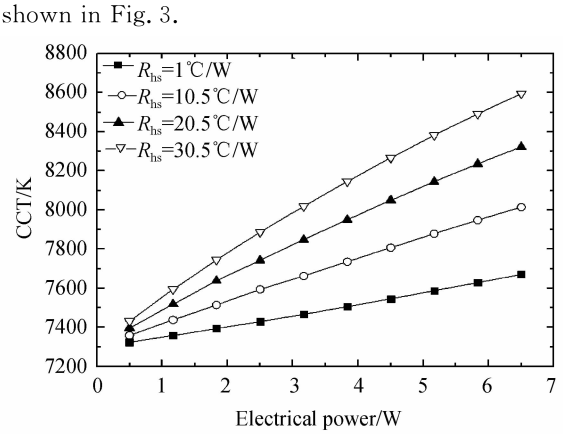

Fig. 3 CCT versus electrical power for LED sample with different heatsink

As shown in Fig. 3, the CCT increases as thermal resistance of the heatsink and the electrical power. When the electrical power of the LED mounted on given heatsink (R_{hs}=1℃/W) is 0.5W, the minimum CCT is about 7 300 K. Similarly, when the electrical power of the LED mounted on given heatsink (R_{hs}=30.5℃/W) is 6.5 W, the maximum CCT is approximate 8 600 K.

2.2 SPD characteristics of a single LED with targeted CCT and variation luminous flux

As shown in Fig. 3 the range of CCT is from 7 300 K to 8 600 K. Firstly, for a given CCT (T) and luminous flux (F), then the targeted CCT (T') and the targeted luminous flux (F') can be calculated by iterative method of electrical power and thermal resistance with the objective functions ($\left|\frac{T-T}{T}\right| \cdot 100\% \leqslant 5\%$ and $\left|\frac{F-F}{F}\right| * 100\% \leqslant 5\%$) based on Eqs. (8) and (9). It evaluates the objective function and choice a new groups for updated undetermined parameters of electrical power and thermal resistance. The variation of the undetermined parameters by optimizer is sent to a direct problem solver for building an updated objective function. When the objective function is close to 5%, the optimized results is obtained. For given CCT (T) of 7 500 K and 8 200 K, with different luminous flux, the electrical power and thermal resistance for the LED device are shown in Table 4 and 5, respectively.

Table 4 For a fixed CCT of 7 500 K, the calculated parameters for single LED sample with different luminous flux

	Error rate of CCT	Error rate of flux	Electrical power	Thermal resistance
Flux=100 lm	0.004 4	1.0000e-3	1.3 W	12℃/W
Flux=220 lm	0.012 3	5.5392e-4	3 W	7.5℃/W
Flux=320 lm	0.034 9	6.6916e-4	4.7 W	8℃/W
Flux=420 lm	0.037 6	1.2000e-3	6.2 W	4.5℃/W

Table 5 For a fixed CCT of 8200K, the calculated parameters for single LED sample with different luminous flux

	Error rate of CCT	Error rate of flux	Electrical power	Thermal resistance
Flux=200 lm	0.031 6	5.0623e-4	3.2 W	25.5℃/W
Flux=270 lm	0.011 6	5.4920e-4	4.8 W	21℃/W
Flux=350 lm	0.028 7	2.9972e-4	5.7 W	11.5℃/W
Flux=420 lm	0.034 9	2.0100e-2	6.5 W	7.5℃/W

As shown in Table 4 and 5, the electrical power increases as luminous flux when the CCT is fixed, while thermal resistance of the heatsink decreases with increasing of the luminous flux. At the heatsink′s thermal resistance of 12℃/W, electrical power is 1.3 W under luminous flux of 100 lm and CCT of 7 500 K. When the electrical power of LED with the heatsink′s thermal resistance of 4.5℃/W is 6.2 W, luminous flux increases to 420 lm and CCT keeps constant. Putting calculated the electrical power and thermal resistance of the heatsink into Eq. (7), the spectral power distribution could be obtained, as shown in Fig. 4 and 5.

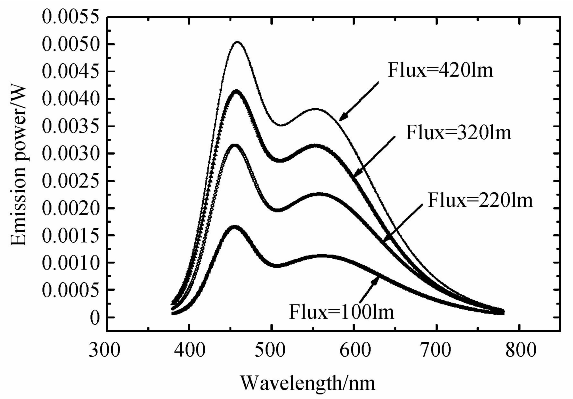

Fig. 4 Spectral power distribution of LED sample with different flux at fixed CCT of 7 500 K

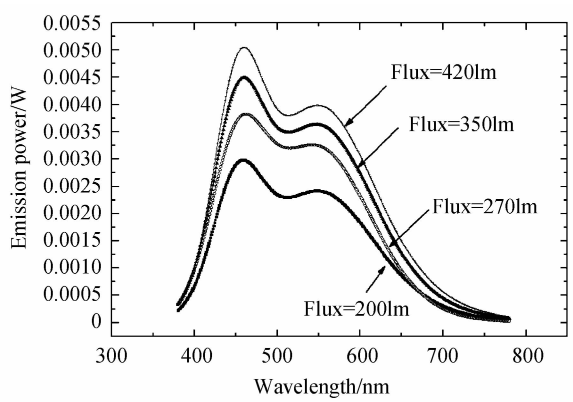

Fig. 5 Spectral power distribution of LED sample with different flux at fixed CCT of 8 200 K

2.3 SPD characteristics of a single LED with targeted luminous flux and variation CCT

As shown in Fig. 2, the controlled range of luminous flux is from 39lm to 460lm. Firstly, for a fixed luminous flux (F), then the targeted luminous flux (F') can be calculated by iterative method of electrical power with the objective function ($\left|\frac{F'-F}{F}\right| \cdot 100\% \leqslant 5\%$) by Eqs. (8) and (9), and required the error of CCT is less than 5% with the minimum error of luminous flux. For given luminous flux of 200 lm and 350 lm, with different targeted of CCT, the electrical power and thermal resistance for the LED device are shown in Table 6 and 7, respectively.

Table 6 For a fixed luminous flux of 200 lm, the calculated parameters for single LED sample with different CCT

	Error rate of CCT	Error rate of flux	Electrical power	Thermal resistance
CCT=7 300 K	0.021 0	5.0623e-4	2.6 W	2℃/W
CCT=7 600 K	0.007 5	5.0623e-4	2.8 W	12.5℃/W
CCT=7 900 K	0.002 2	5.0623e-4	3.1 W	23℃/W
CCT=8 200 K	0.031 6	5.0623e-4	3.2 W	25.5℃/W

Table 7 For a fixed luminous flux of 350lm, the calculated parameters for single LED sample with different CCT

	Error rate of CCT	Error rate of flux	Electrical power	Thermal resistance
CCT=7 500 K	0.026 9	5.8543e-4	5 W	5℃/W
CCT=7 800 K	0.021 1	2.9972e-4	5.7 W	11.5℃/W
CCT=8 000 K	0.004 4	2.9972e-4	5.7 W	11.5℃/W
CCT=8 300 K	0.021 5	8.7115e-4	6.3 W	14.5℃/W

As shown in Table 6 and 7, the electrical power and thermal resistance of the heatsink increase as CCT when the luminous flux is fixed. At the heatsink′s thermal resistance of 5℃/W, electrical power is 5W under luminous flux of 3 50 lm and CCT of 7 500 K. When the electrical power of the LED with the heatsink′s thermal resistance of 14.5℃/W is 6.3 W, CCT increases to 8 300 K and luminous flux keeps constant. Putting obtained electrical power and the thermal resistance into Eq. (7), the spectral power distribution can be obtained, as shown in Fig. 6 and 7.

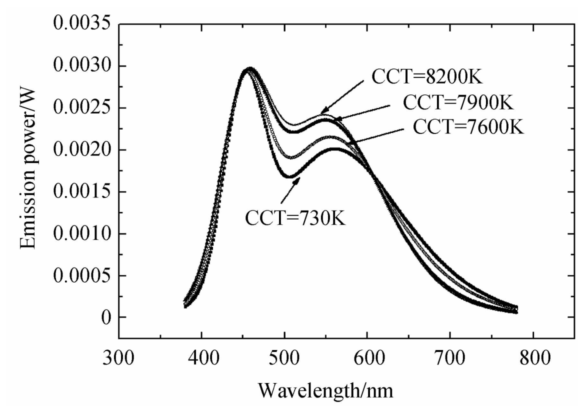

Fig. 6 Spectral power distribution for LED sample with different CCT at fixed flux of 200 lm

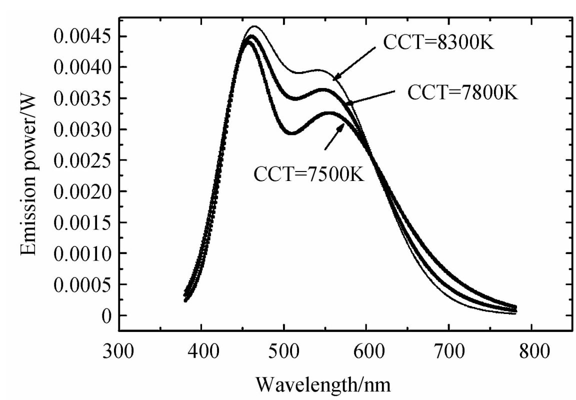

Fig. 7 Spectral power distribution for LED sample with different CCT at fixed flux of 350 lm

2.4 SPD characteristics of two LEDs with targeted CCT and variation luminous flux

The electrical power of the two LEDs mounted on a different heatsink is the same as the single LED. The controlled CCT range is from 7 327 K to 9176K. For a given CCT, the electrical power and thermal resistance can be calculated by using iterative method at different luminous flux, and the allowable error rate of flux and CCT are less than 5% and the error rate of flux is the minimum. For fixed CCT of 7 500 K, with different luminous flux, the electrical power and thermal resistance for LED devices are shown in Table 8.

Table 8 For a fixed CCT of 7500K, the calculated parameters for two LEDs with different luminous flux

	Error rate of CCT	Error rate of flux	Electrical power	Thermal resistance
Flux=100 lm	0.017 0	2.6000e-2	0.7 W	30.5℃/W
Flux=250 lm	0.013 3	5.2325e-4	1.7 W	9.5℃/W
Flux=550 lm	0.032 2	2.1971e-4	4 W	5℃/W
Flux=700 lm	0.026 9	5.5657e-4	5 W	2.5℃/W

As shown in Table 8, the electrical power increases as luminous flux when the CCT is fixed, while the thermal resistance will decrease with the increasing of the luminous flux. At the heatsink′s thermal resistance of 30.5℃/W, electrical power is 0.7 W under luminous flux of 100 lm and CCT of 7 500 K. When the electrical power of LED with the heatsink′s thermal resistance of 2.5℃/W is 5W, luminous flux increases to 700 lm and CCT keeps constant. Putting the derived electrical power and the thermal resistance in Table 8 into Eq. (7), the spectral power distribution can be obtained, as shown in Fig. 8.

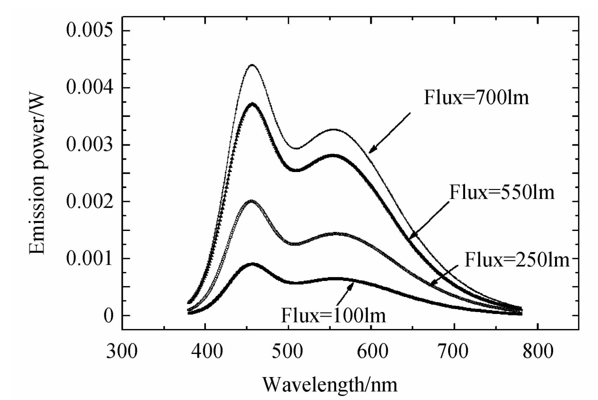

Fig. 8 Spectral power distribution for two LEDs with different flux at fixed CCT of 7 500 K

2.5 SPD characteristics of two LEDs with targeted luminous flux and variation CCT

Based on targeted luminous flux, the error rate of flux and CCT also meet the above section. If the fixed flux is 600 lm, the corresponding results in the different CCT about the error rate of CCT, error rate of flux, electrical power and thermal resistance are shown in Table 9 respectively.

As shown in Table 9, the electrical power and the thermal resistance increase as CCT when the luminous flux is fixed. At the heatsink′s thermal resistance of 3℃/W, electrical power is 4.2 W under luminous flux of 600lm and CCT of 7 400 K. When the electrical power of LED with the heatsink′s thermal resistance of 10℃/W is 5.8 W, CCT increases to 8 500 K and luminous flux keeps constant. Putting obtained electrical power and the thermal resistance in Table 9 into Eq. (7), the spectral power distribution is obtained, as shown in Fig. 9.

Table 9 For a fixed luminous flux of 600lm, the calculated parameters in different CCT for two LEDs sample

	Error rate of CCT	Error rate of flux	Electrical power	Thermal resistance
CCT=7 400 K	0.035 4	4.4000e-3	4.2 W	3℃/W
CCT=7 800 K	0.005 3	4.1753e-4	4.4 W	4.5℃/W
CCT=8 200 K	0.032 7	4.1753e-4	4.8 W	7℃/W
CCT=8 500 K	0.033 1	7.5086e-4	5.8 W	10℃/W

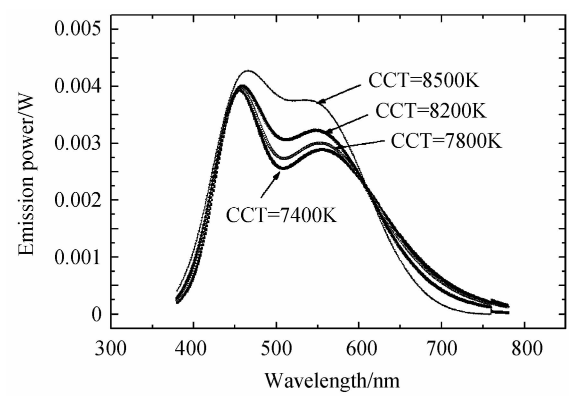

Fig. 9 Spectral power distribution for two LEDs with different CCT at fixed flux of 600 lm

3 Conclusion

The spectrum of white light-emitting diodes was characterized and modeled using a combination of the PET theory and SPD modeling. The controlled range of CCT and luminous flux could be determined by a series of electrical and optical measurements. The targeted luminous flux and CCT can be calculated by iterative method of electrical power with the objective functions. The proposed method is more effective for optimizing spectrum of white LED based on targeted luminous flux and CCT. The work shall provide a research and development tool for practicing LED system designers to predict the instantaneous variations of SPD with given luminous flux and CCT.

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