光学学报

红/绿/蓝/暖白4色LED白光温度光谱优化方法

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摘要 研究了一个基于高斯模型和双高斯模型的温度变化光谱模型，并基于脉冲宽度调制（PWM）调光的红/绿/蓝/暖白（R/G/B/WW）4色LED混合白光进行了实验验证。结果表明，在20～90 ℃温度范围内，当相关色温为3000、5000、6500 K时，光源参数（照度、显色指数、相关色温、蓝光危害因子和节律因子）的最大相对误差为3.79%。基于该模型，采用自适应差分进化（JADE）算法获取R/G/B/WW发光二极管在不同温度下的补偿占空比，并建立光谱优化模型以消除温度对光源光谱及其光源参数的影响。结果表明，优化补偿后的光谱与初始温度光谱基本一致，光源参数最大相对误差为2.62%。

关键词 光谱学；光谱优化模型；发光二极管；温度；脉冲宽度调制；自适应差分算法
中图分类号 TN383；TU113 **文献标志码** A **DOI**：10.3788/AOS221760

1 引 言

发光二极管（LED）光源具有光效高、光色可调、响应速度快和寿命长等优点，被广泛应用在室内外照明、显示和背光等领域中[1-3]。在LED光源工作过程中，温度的变化会对其发射光谱和能量效率产生影响。丁天平等[4]研究了温度对功率型LED光谱特性产生的影响，并得出了LED性能随温度的变化关系。唐燕如等[5]研究了温度对LED发光性能的影响，结果发现温度变化会影响发射光谱，进而影响其发光性能。已有的研究主要采用不同的散热结构减少温度对LED发光效率和性能的影响[6-7]。Llenas等[8]为降低温度对光源光谱的影响设计了一个闭环负反馈系统。周湘艳等[9]基于视觉和非视觉效应研究了RGBY 4色LED光源温度光谱补偿方法。照明用白光LED多采用蓝光激发钇铝石榴石荧光粉来获得，存在色温范围单一、显色性差的缺点。多基色LED合成白光可实现亮度、色温的动态调节，具有较高的显色性和光照品质。田会娟等[10-11]提出了基于脉冲宽度调制（PWM）调光的多基色LED高显色性白光优化模型，但未考虑光源模块热效应对LED混合白光光学参数的影响。本文在该工作基础上，研究了温度对红/绿/蓝/暖白（R/G/B/WW）4色LED光谱的影响，并获得了随温度变化的光谱模型。针对温度对视觉与非视觉效应的影响，采用自适应差分进化（JADE）算法建立了一种基于温度与占空比的4色LED光谱优化模型，并通过实验对该模型进行了验证。

2 温度光谱模型

实验采用R/G/B/WW 4色LED 2颗串联组成光源模块。实验装置包括微控制器（MCU）、R/G/B/WW LED光源、积分球、HASS-2000光谱辐射计和CL-200温控仪等，如图1所示：MCU以特定的红、绿、蓝和暖白占空比（D_R、D_G、D_B和D_{WW}）产生4个不同的PWM信号，实现多基色LED混光[12-13]；积分球和HASS-2000光谱辐射计用于测量R/G/B/WW光源模块中各单色LED的光谱功率分布（SPD），以及混合光的光通量、相关色温和显色指数等；CL-200温控仪控制实验过程中LED温度的变化。本实验设置的初始温度为20 ℃，所采用的温度范围为20～90 ℃（热沉温度），温度间隔为10 ℃，实验的误差范围为−0.1～0.1 ℃。在测试中，R/G/B/WW 4色LED的输出电流为350 mA，驱动电压为6 V。

当占空比为1时，通过实验测得温度在20～90 ℃范围内，间隔为10 ℃的各个单色LED光源的8组光谱功率分布曲线。采用高斯模型、高斯-洛伦兹模型和双高斯模型拟合不同温度下的LED光源光谱[9]，相应的光谱功率分布可以表示为

$$P_{\text{Gaussian}}(\lambda)=\frac{A_1}{\Delta\lambda\sqrt{\frac{\pi}{4\ln 2}}}\exp\left[\frac{-4\ln 2(\lambda-\lambda_P)^2}{(\Delta\lambda)^2}\right], \quad (1)$$

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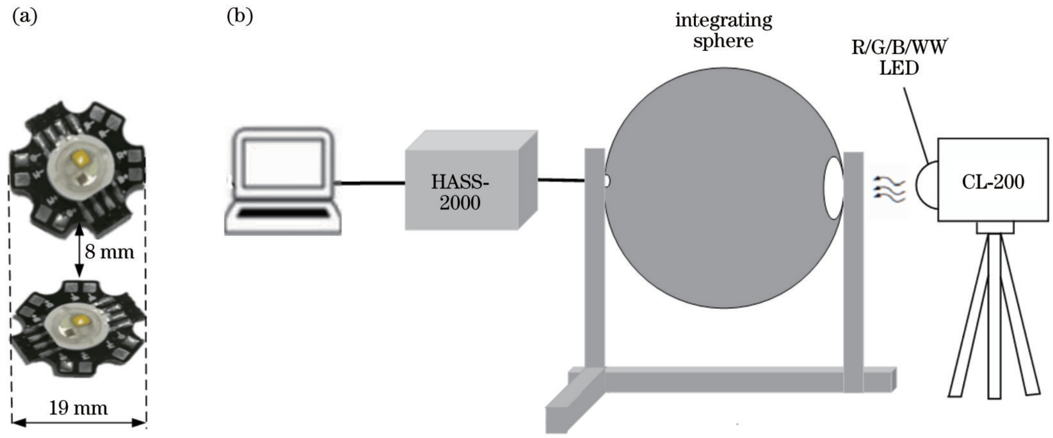

图 1 光源结构和实验装置的示意图。(a)光源结构;(b)实验装置

Fig. 1 Schematic diagram of light source and experimental setup. (a) Light source; (b) experimental setup

$$P_{\text{Gauss-Lorentz}}(\lambda)=\begin{cases}\dfrac{A_1}{\Delta\lambda\sqrt{\dfrac{\pi}{4\ln 2}}}\exp\left[\dfrac{-4\ln 2(\lambda-\lambda_{\mathrm{P}})^2}{(\Delta\lambda)^2}\right], & \lambda\leqslant\lambda_{\mathrm{P}}\\ \dfrac{2A_2}{\pi}\left[\dfrac{\Delta\lambda}{4(\lambda-\lambda_{\mathrm{P}})^2+(\Delta\lambda)^2}\right], & \lambda>\lambda_{\mathrm{P}}\end{cases},\tag{2}$$

$$P_{\text{Bigaussian}}(\lambda)=\begin{cases}A_3\exp\left[0.5\left(\dfrac{\lambda-\lambda_{\mathrm{P}}}{\Delta\lambda_1}\right)^2\right], & \lambda\leqslant\lambda_{\mathrm{P}}\\ A_3\exp\left[0.5\left(\dfrac{\lambda-\lambda_{\mathrm{P}}}{\Delta\lambda_2}\right)^2\right], & \lambda>\lambda_{\mathrm{P}}\end{cases},\tag{3}$$

式中:λ_{P}为光谱功率分布的峰值波长;$\Delta\lambda$为光谱功率分布的峰值半峰全宽。$\Delta\lambda_1=\lambda_{\mathrm{P}}-\lambda_1$为左半峰全宽,其中$\lambda_1$为光谱峰值左半峰全宽所对应的波长;$\Delta\lambda_2=\lambda_2-\lambda_{\mathrm{P}}$为右半峰全宽,其中$\lambda_2$为光谱峰值右半峰全宽所对应的波长,且$\lambda_2>\lambda_1$;$A_1$、$A_2$和$A_3$分别对应三种不同模型的面积。根据多基色混光方法[14],考虑温度时合成白光的光谱功率分布可以表示为

$$P(\lambda,T)=D_1P_1(\lambda,T)+D_2P_2(\lambda,T)+\cdots+D_nP_n(\lambda,T),\tag{4}$$

式中:D_n为第n种光源的占空比;$P_n(\lambda,T)$为第n种光源在温度T时的光谱功率分布。

图 2 为 R/G/B/WW 4 种单色光源在不同温度下的测试光谱。如图 2 所示,各色 LED 光源的光谱峰值强度、半峰全宽和峰值波长会随温度的变化而变化。温度的不断升高使单色 LED 光源的光谱峰值产生一定的衰减,且光谱发生红移[4]。同时,发现红光受温度的影响最大,暖白光 LED 受温度的影响最小。

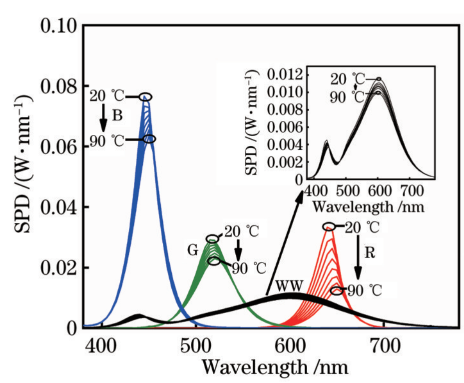

图 2 R/G/B/WW LED 光源的温度光谱功率分布图

Fig. 2 Spectral power distribution of R/G/B/WW LED light source at different temperatures

选用 3 种不同光谱拟合模型分别对不同温度下红光、绿光、蓝光和白光 LED 的光源光谱功率分布进行拟合,平均拟合系数如表 1 所示。

根据表 1,红光、绿光和蓝光 LED 采用式(1)所示的高斯模型进行拟合最佳。暖白光 LED 光谱特性采用分段拟合,第一处波峰采用高斯模型,第二处波峰则采用式(3)的双高斯模型。由此可得,R、G、B 和 WW LED 光源拟合光谱参数与温度T之间的关系为

表 1 R/G/B/WW 4 色 LED 光源 3 种模型的拟合系数表

Table1 Fitting coefficients of three models of R/G/B/WW four-color LED light source

Model	R	G	B	Part I in WW	Part II in WW
Gaussian model	0.985	0.994	0.992	0.988	0.991
Gauss-Lorentz model	0.970	0.988	0.984	0.972	0.986
Bigaussian model	0.972	0.991	0.989	0.992	0.996

$$\begin{cases} A_{1,\mathrm{R}} = -0.00869 \cdot T + 1.2080 \\ \lambda_{\mathrm{P,R}} = 0.11902 \cdot T + 636.02 \\ \Delta\lambda_{\mathrm{R}} = 0.04966 \cdot T + 33.8884 \end{cases}, \quad (5)$$

$$\begin{cases} A_{1,\mathrm{G}} = -0.00246 \cdot T + 1.2884 \\ \lambda_{\mathrm{P,G}} = 0.04344 \cdot T + 515.02 \\ \Delta\lambda_{\mathrm{G}} = 0.04799 \cdot T + 46.8905 \end{cases}, \quad (6)$$

$$\begin{cases} A_{1,\mathrm{B}} = -0.00207 \cdot T + 2.3459 \\ \lambda_{\mathrm{P,B}} = 0.03408 \cdot T + 445.998 \\ \Delta\lambda_{\mathrm{B}} = 0.06024 \cdot T + 32.4074 \end{cases}, \quad (7)$$

$$\begin{cases} A_{1,\mathrm{WW}} = -0.0001737 \cdot T + 0.1633 \\ \lambda_{\mathrm{P,WW}} = 0.08273 \cdot T + 437.4289 \\ \Delta\lambda_{\mathrm{WW}} = 0.07599 \cdot T + 38.6793 \\ A_{3,\mathrm{WW}} = -1.87476 \cdot T \times 10^{-5} + 0.01214 \\ \lambda_{\mathrm{P,WW2}} = 0.04103 \cdot T + 605.1288 \\ \Delta\lambda_{1,\mathrm{WW}} = 0.01812 \cdot T + 68.9773 \\ \Delta\lambda_{2,\mathrm{WW}} = -0.02612 \cdot T + 55.0058 \end{cases}, \quad (8)$$

其中红、绿、蓝和暖白光LED的光谱拟合参数分别对应于下标为R、G、B和WW，且相关系数为$R^2 \geqslant 0.9852$。

3　温度光谱优化方法与实验分析

根据式(4)～(8)可得到R/G/B/WW LED光源在不同温度下的光谱功率分布。基于已有工作可实现3000～7000 K相关色温范围内R/G/B/WW 4色LED白光调节[13]。将初始温度设置为20 ℃，沿黑体轨迹取目标色温值分别为3000、5000、6500 K，可得显色指数的变化趋势如图3所示。

选取合成白光光谱的显色指数分别为92.9、93.3和91.4。根据温度光谱模型，计算温度为20、60、90 ℃下的光谱功率分布。从拟合效果上可以看出，随温度变化的光谱功率分布曲线的模型计算结果与测试结果基本相同，如图4所示。

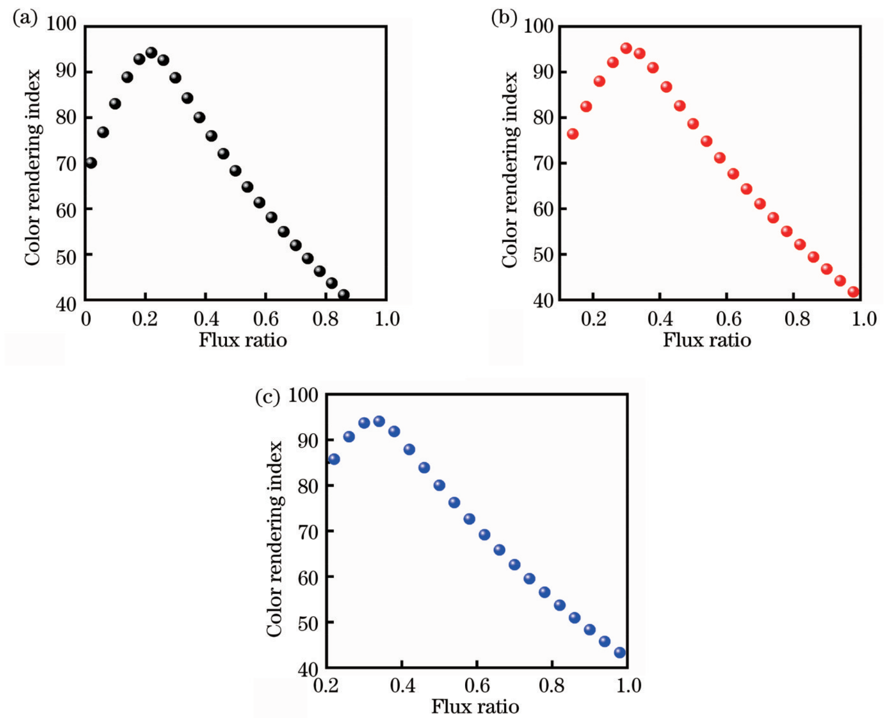

图3　不同相关色温下合成白光的显色指数。(a) 3000 K；(b) 5000 K；(c) 6500 K

Fig. 3　Color rendering index of mixed white light at different correlated color temperatures. (a) 3000 K; (b) 5000 K; (c) 6500 K

根据温度光谱模型可计算得到不同温度下的照度E_{V}、显色指数Ra、相关色温T_{C}、蓝光危害因子η_{B}和节律因子C_{AF}[15]等考虑视觉/非视觉效应的光源参数，并与实测光源参数进行了对比，如表2所示。

表2　3000 K、5000 K和6500 K相关色温下实测与模型光源参数值的对比误差

Table 2　Comparison errors between experimental and model light source parameter values under correlated color temperatures of 3000 K, 5000 K and 6500 K

Correlated color temperature /K	Error in T_{C} /%	Error in E_{V} /%	Error in Ra /%	Error in C_{AF} /%	Error in η_{B} /%
3000	3.79 (70 ℃)	1.45 (20 ℃)	3.25 (30 ℃)	2.92(30 ℃)	2.94 (80 ℃)
5000	2.67 (70 ℃)	1.38 (40 ℃)	2.10 (20 ℃)	2.77 (90 ℃)	3.66 (90 ℃)
6500	1.56 (90 ℃)	1.14 (40 ℃)	2.66 (80 ℃)	3.34 (70 ℃)	2.52 (90 ℃)

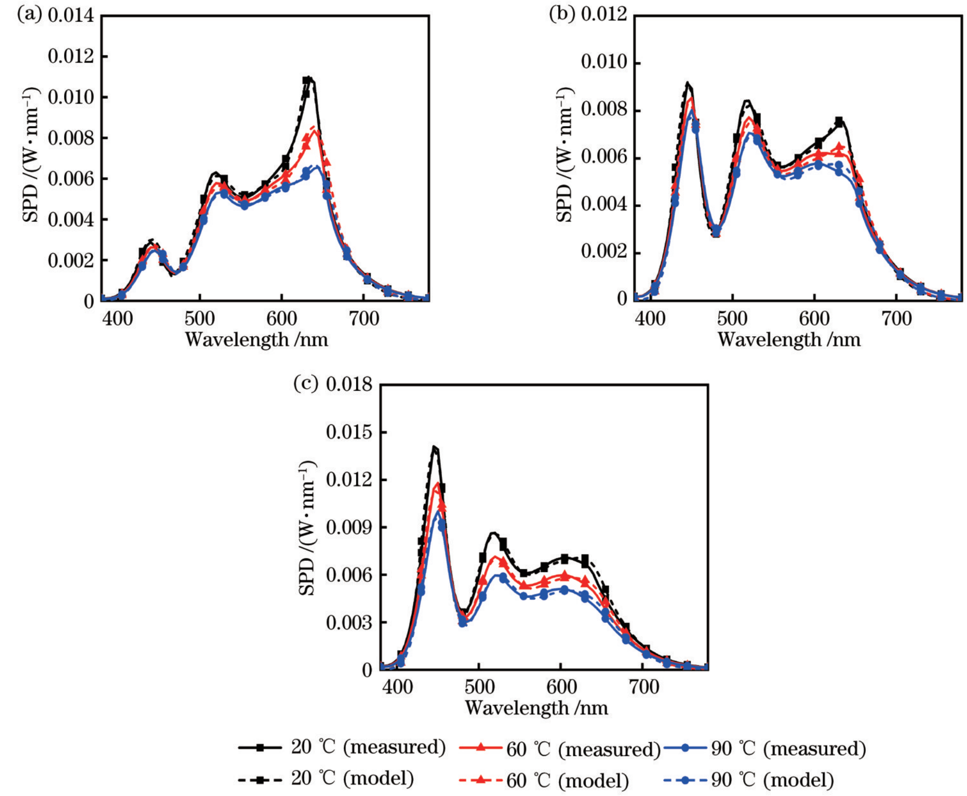

图 4 不同相关色温下模型计算与测试结果对比。(a) 3000 K；(b) 5000 K；(c) 6500 K

Fig. 4 Comparison between measured and model calculated results under different correlated color temperatures. (a) 3000 K; (b) 5000 K; (c) 6500 K

由表 2 可以看出，3 种光源的模型参数值与实测参数值之间的最大误差为 3.79%，色品差(ΔC)均小于 5.4×10^{-3}。

此外，从图 5 中可以看到，随着温度的升高，T_{C}、C_{AF} 和 η_B 值基本呈线性增加，E_{V} 值呈线性衰减。当温度升到 90 ℃时：与初始值相比，色温为 3000 K 的光源的 E_{V} 下降了 15.5%，T_{C} 上升了 11.9%，C_{AF} 和 η_{B} 分别上升了 10.6% 和 7.1%；色温为 5000 K 光源的 E_{V} 下降了 11.8%，T_{C} 上升了 11.8%，C_{AF} 和 η_{B} 值分别上升了 10.5% 和 9.7%；色温为 6500 K 光源的 E_{V} 下降了 10.9%，T_{C} 上升了 10.0%，C_{AF} 和 η_{B} 分别上升了 9.1% 和 8.3%。

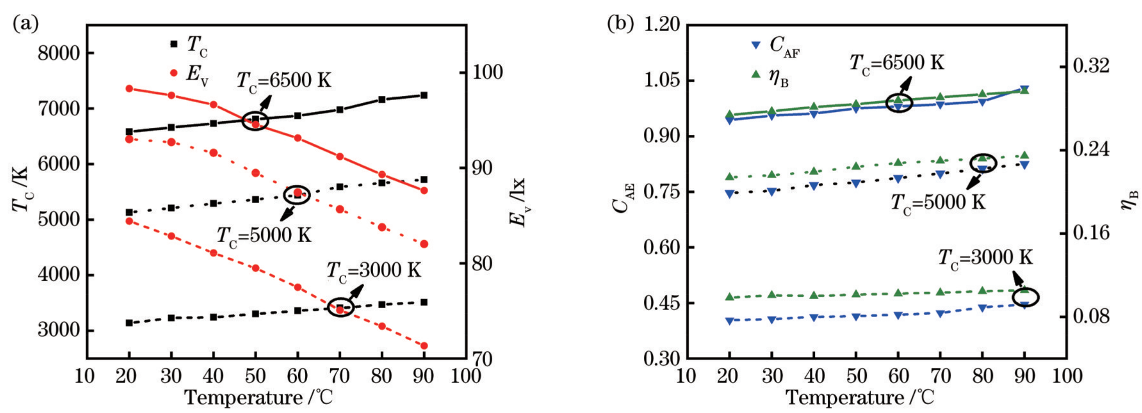

图 5 3000 K、5000 K 和 6500 K 相关色温下光源的测试参数。(a) T_{C} 和 E_{V}；(b) C_{AF} 和 η_{B}

Fig. 5 Measured parameter of light source under correlated color temperatures of 3000 K, 5000 K and 6500 K. (a) T_{C} and E_{V}; (b) C_{AF} and η_{B}

针对温度升高导致的光源光谱及其参数变化，采用 JADE 算法[16]调整各通道的占空比，对光源光谱和相关参数进行优化。当光源色温为 3000、5000、6500 K 时，通过 JADE 算法得到的不同温度下的补偿占空比与温度存在一定的线性关系，采用 Origin 9.0 对其进行线性拟合，得到热沉温度 T 与各补偿占空比 D_{R}、D_{G}、D_{B}、D_{WW} 的函数关系，相关系数为 $R^2\geqslant0.9818$。相应的公式为

$$\begin{cases} D_{\mathrm{R},3000}=0.10183+0.00329\cdot T \\ D_{\mathrm{G},3000}=0.11454+0.000248\cdot T \\ D_{\mathrm{B},3000}=0.0089+4.89\times10^{-4}\cdot T \\ D_{\mathrm{WW},3000}=0.49346+0.00121\cdot T \end{cases}, \tag{9}$$

$$\begin{cases} D_{\mathrm{R},5000}=0.05298+7.34\times10^{-4}\cdot T \\ D_{\mathrm{G},5000}=0.17937+2.52\times10^{-4}\cdot T \\ D_{\mathrm{B},5000}=0.00863+1.77\times10^{-4}\cdot T \\ D_{\mathrm{WW},5000}=0.51442+0.00121\cdot T \end{cases}, \tag{10}$$

$$\begin{cases} D_{\mathrm{R},6500}=0.02952+2.14\times10^{-5}\cdot T \\ D_{\mathrm{G},6500}=0.1849+2.38\times10^{-4}\cdot T \\ D_{\mathrm{B},6500}=0.14458+2.66\times10^{-4}\cdot T \\ D_{\mathrm{WW},6500}=0.54594+0.00142\cdot T \end{cases}, \tag{11}$$

通过式(9)~(11)可计算4色LED混合白光光源色温为3000、5000、6500 K时不同温度下的补偿占空比，并对补偿后的光谱及其参数进行了实验验证。经测试得到补偿后不同温度下的光谱功率分布，并与初始温度下的光谱进行对比，如图6所示。可以发现，经过补偿后的光谱功率分布与初始温度的光谱功率分布基本一致。

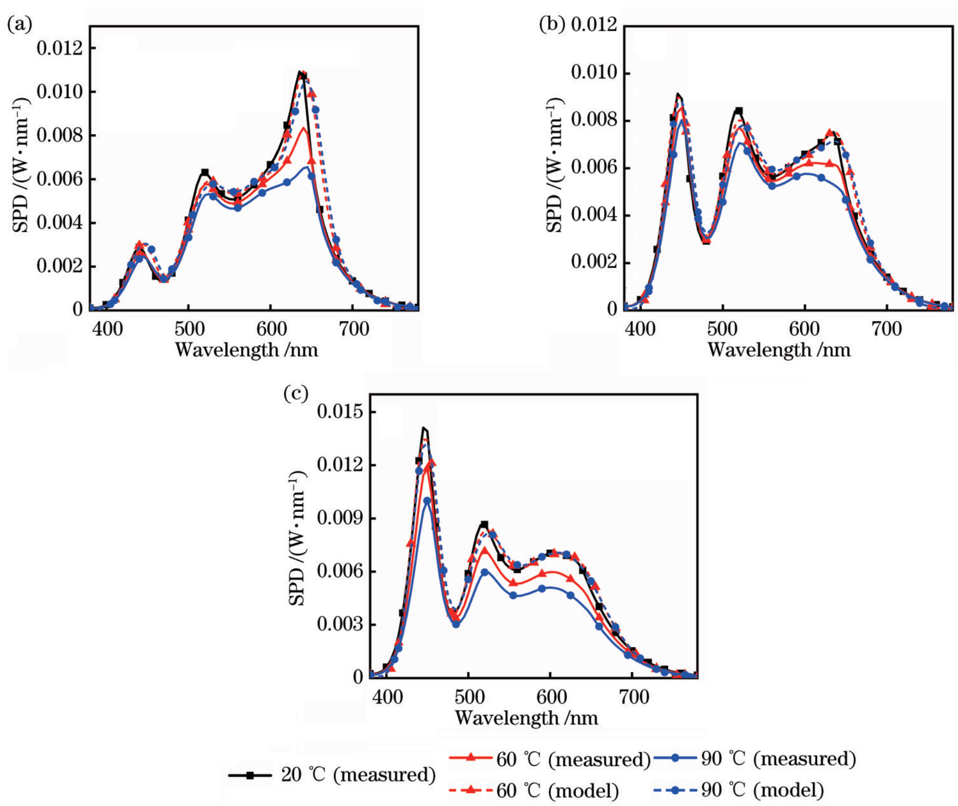

图6 不同相关色温下测试光谱与补偿模型光谱对比。(a) 3000 K；(b) 5000 K；(c) 6500 K

Fig. 6 Comparison between measured and compensation model spectra under different correlated color temperatures. (a) 3000 K; (b) 5000 K; (c) 6500 K

对初始温度的光源参数与补偿后不同温度下的光源参数进行了误差分析。由表3可知，在上述3种光源下，补偿后的光源参数 T_{C}、E_{V}、C_{AF} 和 η_{B} 随温度的变化保持基本稳定：与初始温度的相关色温相比，补偿后3种光源的平均误差分别为0.83%、0.63%和0.63%；照度值也得到了相应的增加，与初始温度照度的平均误差分别为1.46%、0.52%和0.86%；C_{AF} 值与初始温度时的平均误差分别为1.78%、0.66%和1.05%；η_{B} 值与初始温度时的平均误差分别为1.72%、2.03%和0.34%；光源参数最大误差为2.62%。

4 总　　结

根据PWM调光技术，利用JADE算法研究了混合白光LED随温度变化的光谱优化方法。由温度光谱模型获得了R/G/B/WW混合白光LED在不同温度下的光谱，基于该模型，根据JADE算法补偿结果建立的光谱优化模型可有效调节不同温度下的光源光谱。经优化补偿后，在设定的不同光源色温下初始温度的光谱数据与不同温度下的补偿光谱数据基本一致，光源参数的最大相对误差为2.62%。该方法在一定程度上可解决因温度变化引起的多基色LED光色变化问题，为健康照明系统的优化设计提供了参考。在后续工作中，需进一步研究获取LED芯片实时结温的方法，并构建一个反馈控制系统，实现温度变化时光源参数的动态补偿。

表3 补偿后不同相关色温和温度下测试参数与初始温度参数的相对误差

Table 3 Relative errors between measured values and set values at different correlated color temperatures and temperatures after compensation

Correlated color temperature /K	Set T /℃	Measured T_C /K	Relative error of T_C /%	Measured E_V /lx	Relative error of E_V /%	Measured C_{AF}	Relative error of C_{AF} /%	Measured η_B	Relative error of η_B /%
3000	30	3109	0.98	83.99	0.51	0.4101	1.74	0.1001	1.62
	40	3119	0.66	83.55	1.03	0.4102	1.76	0.1002	1.73
	50	3131	0.26	83.51	1.07	0.4101	1.74	0.1003	1.83
	60	3140	0.12	83.18	1.47	0.4104	1.81	0.1001	1.62
	70	3164	0.79	82.91	1.79	0.4103	1.79	0.1002	1.73
	80	3175	1.12	82.74	1.99	0.4102	1.76	0.1002	1.73
	90	3199	1.91	82.43	2.35	0.4105	1.84	0.1003	1.83
5000	30	5098	0.42	92.90	0.13	0.7422	0.63	0.2169	1.40
	40	5112	0.09	92.70	0.40	0.7449	0.28	0.2173	1.59
	50	5128	0.22	92.00	1.07	0.7478	0.12	0.2178	1.82
	60	5145	0.41	92.70	0.38	0.7502	0.44	0.2184	2.10
	70	5154	0.69	92.10	1.06	0.7531	0.83	0.2187	2.24
	80	5169	1.09	92.50	0.53	0.7546	1.03	0.2192	2.47
	90	5189	1.48	92.90	0.06	0.7563	1.26	0.2195	2.62
6500	30	6517	0.99	99.70	1.36	0.9315	1.31	0.2718	0.80
	40	6526	0.85	99.30	0.98	0.9316	1.30	0.2724	0.58
	50	6554	0.43	98.60	0.30	0.9314	1.32	0.2729	0.40
	60	6571	0.18	97.60	0.75	0.9337	1.08	0.2734	0.22
	70	6596	0.21	98.80	0.42	0.9345	0.99	0.2737	0.11
	80	6627	0.68	97.50	0.85	0.9367	0.76	0.2741	0.04
	90	6653	1.07	97.00	1.34	0.9386	0.56	0.2746	0.22

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Temperature Spectrum Optimization of Mixed White LED Cluster Comprising Red/Green/Blue/Warm White LED

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Abstract

Objective Light emitting diode (LED) features high luminous efficiency, adjustable luminance and color temperature, fast response, and long life, and it is widely applied in various fields. During the operation of LED light sources, the temperature change exerts an impact on its emission spectrum and energy efficiency. In previous studies, the designs of heat dissipation structures are mainly adopted to reduce the impact of temperature on LED luminous efficiency and performance. Some researchers have also employed other methods to study the impact. A closed-loop negative feedback system is designed to reduce the influence of temperature on the spectrum of the light source, and the temperature spectrum compensation method of RGBY four-color LED light source is proposed based on visual and non-visual effects. The white LED for lighting is mostly obtained by blue excited yttrium aluminum garnet phosphor. However, its color temperature cannot be adjusted and color rendering is poor. A mixed white LED cluster can achieve dynamic adjustment of color temperature and high color rendering index. Therefore, the optimization method of multi-channel LED white light with tunable color temperature and high color rendering index has been extensively studied. However, the influence of the thermal effect on the optical parameters of a mixed white LED is rarely considered. Thus, this paper studies the impact of temperature on the spectrum of red/green/blue/warm-white (R/G/B/WW) four-color LED and obtains the spectral model with temperature change. Additionally, the spectral optimization model of R/G/B/WW LED mixed white light is built by the adaptive differential evolution (JADE) algorithm based on the temperature and duty ratio, and it is verified through experiments.

Methods The experimental setup mainly consists of microcontroller (MCU), R/G/B/WW LED light source, integrating sphere, HASS-2000 spectral radiometer, and CL-200 temperature control device. Two R/G/B/WW four-color LED clusters are connected in series. The MCU can generate four different pulse width modulation (PWM) signals with specific duty ratios (D_R, D_G, D_B and D_{WW}) to achieve four-color LED mixed white light. The HASS-2000 spectral analysis system is adopted to measure the spectral power distribution (SPD) of each LED in the R/G/B/WW LED clusters, and the parameters of mixed white light including the luminous flux, color rendering index, and correlated color temperature. The stability of LED temperature is controlled by the CL-200 temperature control device. The temperature range is from 20 ℃ to 90 ℃ with error margin of ±0.1 ℃, and the temperature interval is 10 ℃. In addition, the driving output current of the R/G/B/WW four-color LED clusters is 350 mA and the driving voltage is 6 V. Eight groups of spectral power distribution curves of each monochrome LED light source with temperature between 20 ℃ and 90 ℃ and the interval of 10 ℃ are measured by experiments when the duty ratio is 1. Three modes of Gaussian, Gauss-Lorentz, and Bigaussian are utilized to study the temperature spectral model of LED light source respectively. Additionally, the spectral model changing with temperature can be obtained.

Results and Discussions The four-color LED mixed white light with color temperatures of 3000 K, 5000 K, and 6500 K is employed to verify the accuracy of the temperature spectrum model (Fig. 3). Based on the temperature spectral model, the SPDs at temperatures of 20 ℃, 60 ℃, and 90 ℃ are calculated, respectively. The results show that the SPD of the model with temperature change is approximately the same as the measured results (Fig. 4). According to the temperature spectrum model, the parameters of light source containing illuminance (E_V), color rendering index (Ra), correlation color temperature (T_C), blue light hazard factor (η_B), circadian action factor (C_{AF}), and considering visual/non-visual effects can be calculated at different temperatures. Meanwhile, the calculation results are compared with the measured parameters of the light source at different temperatures (Table 2). The maximum deviation between the model parameters and measured parameters in the three LED light sources is 3.79%, and the chromaticity difference is less than 5.4×10^{-3}. The light source spectrum and parameter values can change with the rising temperature (Fig. 5). Finally, the JADE algorithm is adopted to acquire the single channel duty ratio to optimize the light source spectrum and related parameters. At the above three LED light sources, the optimization duty ratio obtained by the JADE algorithm shows a linear relationship with the temperature. Based on the optimization model, the SPDs and parameter values of light source at different temperatures after optimization can be obtained. The optimized SPD is approximately the same as the light source spectrum at the initial temperature (Fig. 6), and the maximum relative error of the parameter values is 2.62% (Table 3).

Conclusions In this paper, according to PWM dimming technology, the JADE algorithm is leveraged to study the spectrum optimization of R/G/B/WW LED mixed white cluster with temperature change. According to the temperature spectral model, the R/G/B/WW LED mixed white spectra changing with temperature are obtained. Based on the obtained mixed white light spectra at different temperatures, the spectral optimization model that can effectively adjust the spectrum of the light source at different temperatures is built in accordance with the compensation results of the JADE algorithm. After compensation, the measured spectra are basically consistent with those of the optimization model, and the maximum relative error of LED light source parameter values is 2.62%. This method can compensate for parameters of light source caused by temperature, and guide the optimal design of health lighting system. In future studies, the method of obtaining real-time junction temperature of LED chips should be further explored, and the feedback control system should be constructed to realize the dynamical compensation of the light source parameters.

Key words spectroscopy; spectral optimization model; light-emitting diode; temperature; pulse width modulation; adaptive differential evolution algorithm