LED-based spectrally tunable light source with optimized fitting

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According to the LED spectra measured in the rated current, Gauss distribution function and asymmetric Gaussian distribution function methods are used to simulate the individual LED spectrum. Based on this mathematical model, 32 LEDs are used to synthesize arbitrary spectral distribution of the light source. Processing the spectral data with multiple linear regressions, CIE illuminant A and CIE illuminant D_{65} are simulated. The results show that for each LED, different Gauss models should be used. The simulation results are quite satisfying. However, there is a difference between the simulation results and the experimental results. The spectral evaluation indices of fitted both CIE illuminant A and CIE illuminant D_{65} do not exceed 2.5%. But in experiment, because of the changes of the peak wavelength and the FWHM caused by the current, the spectral evaluation indices of fitted CIE illuminant A and CIE illuminant D_{65} are around 5%.

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In human's production activities, spectrally tunable light sources are widely used. They are used in spectra measurement instruments, biological illumination, and environmental illumination[1−3]. Spectrally tunable light sources can produce spectra of different shapes[4]. In 2004, Bialystok University of Technology of Poland and National Institute of Standards and Technology of America first developed a spectrally tunable, integral sphere structured light source that could be used on the measurement of radiance, luminosity, and chromaticity. This light source can be used to simulate different kinds of CIE standard artificial daylight, such as D_{65}, and spectra used on the measurement of luminosity and chromaticity[5−7]. Similar researches are conducted in China as well, and similar spectrally tunable light sources are designed[8−10]. In researches above, first, LED distribution on different spectral bands are fixed, and then, each LED's output power is modified by current control, and the total spectrum of the LEDs is constructed through spectral fitting. This makes the spectrum of this structure tunable. Currently, most spectral fitting algorithms are iterative methods, which include steepest gradient method used by NIST[11] and least square method frequently used in the field of spectral research[12].

In previous researches, when selecting fitting algorithms for LEDs, the difference in spectral distribution of different LEDs is often ignored. The accuracy and consistency of spectral fitting are not high. We further research the spectral characteristics of LEDs, and use the closest fitting algorithm for each LED based on the spectral characteristics of the LED. We also propose a data processing algorithm based on multi-variable linear regression to apply spectral fitting to the spectrum, and improve the consistency between the target spectrum and the fitted spectrum.

Emission spectra of typical LEDs resemble Gauss distribution. Thus, Gauss function is often used to simulate the spectrum of single LED. Each LED's correspondent Gauss function is

$$S(\lambda)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left[\frac{-1}{2}\Big(\frac{\lambda-\lambda_{\text{peak}}}{\sigma}\Big)\right]^2, \tag{1}$$

where λ_{peak} represents the peak wavelength of the LED, and σ represents full width at half maximum (FWHM).

Because LED spectrum is not symmetric and Gauss simulated spectra often have error, asymmetric Gauss models is proposed to simulate LED spectra. Usually, the left side of the peak is simulated using Gauss distribution while the right side is simulated using Lorentz simulation, as shown in

$$S(\lambda)=\begin{cases}\dfrac{1}{\sigma\sqrt{2\pi}}\exp\left[\dfrac{-1}{2}\Big(\dfrac{\lambda-\lambda_{\text{peak}}}{\sigma}\Big)\right]^2, & \lambda<\lambda_{\text{peark}}\\ \dfrac{1}{\sigma\sqrt{2\pi}}\cdot\dfrac{\sigma^2}{4(\lambda-\lambda_{\text{peak}})^2+\sigma^2}, & \lambda\geqslant\lambda_{\text{peak}}\end{cases}, \tag{2}$$

or vice versa, as shown in

$$S(\lambda)=\begin{cases}\dfrac{1}{\sigma\sqrt{2\pi}}\cdot\dfrac{\sigma^2}{4(\lambda-\lambda_{\text{peak}})^2+\sigma^2}, & \lambda\geqslant\lambda_{\text{peak}}\\ \dfrac{1}{\sigma\sqrt{2\pi}}\exp\left[\dfrac{-1}{2}\Big(\dfrac{\lambda-\lambda_{\text{peak}}}{\sigma}\Big)\right]^2, & \lambda<\lambda_{\text{peark}}\end{cases}. \tag{3}$$

In order to evaluate the consistency between simulated spectrum and target spectrum, the evaluation index p is calculated as

$$p=\frac{\Sigma|S_{\text{T}}(\lambda)-S(\lambda)|}{\Sigma S_{\text{T}}(\lambda)}, \tag{4}$$

where $S_{\mathrm{T}}(\lambda)$ is the target spectrum and $S(\lambda)$ is the simulated spectrum. The lower p is, the better the consistency between simulated spectra and their corresponding LED spectra is.

For randomly selected red, blue, and green LEDs, mono-Gauss, left-Gauss-right-Lorentz, and left-Lorentz-right-Gauss models are used to simulate. The evaluation indices are shown in Table 1. The best simulated spectra for a random blue LED with driven current of 20 mA, simulated by the three models, are shown in Fig. 1.

As shown in Table 1, blue and green LEDs are simulated better with left-Gauss-right-Lorentz model, and red LEDs are simulated better with left-Lorentz-right-Gauss model. Figure 1 also shows that left-Gauss-right-Lorentz model provides the better simulation of blue LEDs. Therefore, there is no universally best model for all LEDs. In order to accurately simulate the LEDs, they need to be analyzed with different simulation or fitting models, and the most accurate model need to be picked for each kind of LEDs.

Compound LED spectrum fitting means fitting the acquired LED spectra into a single spectrum (the target spectrum). According to the spectrum superposition principle, the mathematical model for LED spectrum fitting is

$$S_{\mathrm{T}} = (\lambda) = \Sigma K_i \times S_i(\lambda), \tag{5}$$

where $K_i(\lambda)$ is a coefficient for ith LED that dictates its current input and $S_i(\lambda)$ is the simulated spectrum for the SPD of LED at specific driven current. The target spectrum is the closest to the fitted spectrum as

$$\Sigma|S_{\mathrm{T}}(\lambda) - K_i \times S_i(\lambda)| = \min. \tag{6}$$

For each kind of LEDs, the best fitting algorithm (Eq. (6)) is chosen, and its normalized luminous power weight, $S_n(\lambda)$ is calculated. For compound LED light sources, at any wavelength λ, we hold

$$\begin{aligned} S_{\mathrm{T}}(\lambda) =& S_1(\lambda) \times K_1 + S_2(\lambda) \times K_2 + S_2(\lambda) \times K_2 + \cdots \\ &+ S_n(\lambda) \times K_n, \end{aligned} \tag{7}$$

where n represents the LED type in the optimal solution; $S_1(\lambda)$, $S_2(\lambda)$, $S_3(\lambda)$, $\cdots$, $S_n(\lambda)$ represent the normalized intensity of the n LEDs of different peak wavelengths, at wavelength λ; K_1, K_2, K_3, $\cdots$, K_n are coefficients related to the current. For the target spectrum, we have

$$\mathbf{S_T} = \mathbf{S} \times \mathbf{K}, \tag{8}$$

$$\mathbf{S_T} = [S_{\mathrm{T}}(380) S_{\mathrm{T}}(390) S_{\mathrm{T}}(400) \cdots S_{\mathrm{T}}(780)]^{\mathrm{T}}, \tag{9}$$

$$\mathbf{S} = \begin{bmatrix} S_1(380) & S_2(380) & \cdots & S_n(380) \\ S_1(390) & S_2(390) & \cdots & S_n(390) \\ \vdots & \vdots & & \vdots \\ S_1(780) & S_2(780) & \cdots & S_n(780) \end{bmatrix}, \tag{10}$$

$$\mathbf{K} = [K_1 K_2 K_3 \cdots K_n]^{\mathrm{T}}, \tag{11}$$

where $\mathbf{S}$ is a $m \times n$ matrix representing the n recorded spectra of different LEDs (n =32) uniformly sampled by m points (m= 40, 380 nm to 780 nm in steps of 10 nm); $\mathbf{S}_{\mathrm{T}}$ indicates the $m \times 1$ vector; $\mathbf{K}$ indicates the $n \times 1$ matrix. Because $\mathbf{K}$ is a matrix of current coefficients, the values in the matrix can only be non-negative.

When fitting the spectra of compound LEDs, the accuracy of the fitting is not only affected by the accuracy of each LED's simulation, but also affected by the number of LEDs. The more LEDs and the closer the peaks, the higher fitting accuracy. However, more LEDs also mean higher cost. We selected 32 LEDs in the experiment, their peak wavelengths were 375, 385, 395, 405, 415, 420, 430, 435, 450, 460, 470, 490, 505, 535, 555, 560, 565, 570, 590, 600, 610, 625, 630, 660, 670, 690, 710, 720, 740, 750, 760, and 770 nm.

Using the method above, the simulated spectra of CIE illuminant A and CIE illuminant D_{65} are constructed[13]. The simulated spectra, compared to their corresponding actual spectra, are shown in Fig. 2.

In order to validate the fitting results, an actual spectrally tunable light source is used. Its structure is shown in Fig. 3. This light source system consists of LED cluster, integrating sphere, computer, LED current driver, and fiber spectrometer. There are 32 LEDs on the LED cluster. Each LED is controlled by LED current driver, which is controlled by the computer. This system can accurately control the current on each LED. Fiber spectrometer can monitor the output intensity and spectral distribution from the integrating sphere, and send the results to the computer. The baffle in the integrating sphere is to avoid the light of LED going into the fiber directly. The computer calculate the optimal current for each LED based on the simulated and actual spectra. Then, the current on the LEDs are modified by the system, in order to obtain the spectra similar to the target spectra.

Table 1. LED Spectral Fitting

LED	Wavelength (nm)	Mono-Gauss	p Value Left-Gauss	Right-Gauss
Blue	458	18.83%	16.84%	19.06%
Green	514	15.29%	15.24%	19.75%
Red	635	27.33%	19.76%	19.53%

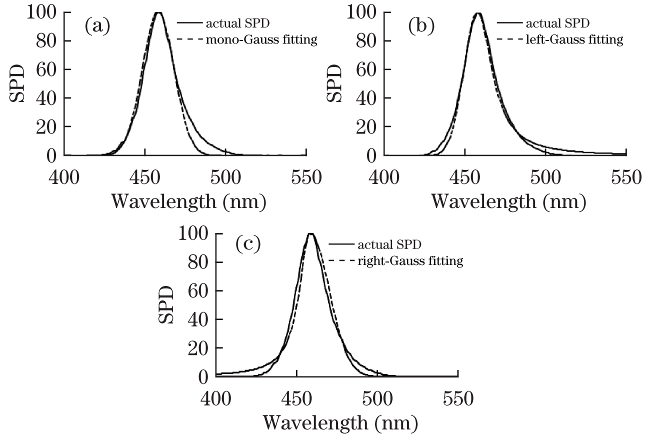

Fig. 1. Comparison of four kinds of blue LED spectral fitting method: (a) mono-Gauss fitting; (b) left-Gauss fitting; (c) right-Gauss fitting.

Using actual spectrally tunable light source, the spectra of CIE illuminant A and CIE illuminant D_{65} are validated. The spectral distributions of the two light sources are shown in Fig. 4.

When evaluating fitting spectra, evaluation indices p with both simulation and experiment are calculated, as shown in Table 2. Results show that the evaluation indices of simulated spectra of both light sources are less than 2.5%, which means the simulations accurately simulated the two light sources; on the other hand, experimental spectra of spectrally tunable light source have slightly larger error, but the error is still within 5%.

From the comparison between Figs. 2 and 4, as well as data from Table 2, even though the most accurate simulation model is selected for each LED during the simulation, the simulated spectra are still fairly different from the spectra from actual spectrally tunable light source. There are a few possible explanations. First, even if the most accurate simulation is used for each LED, the simulated spectra are different from the actual spectra. Secondly, simulation does not take the effect of current change on spectral distribution into account. In the experiment, as current increases, peak wavelength and HWFM drift, as shown in Fig. 5. Thirdly, the SPD of LED is correlated to junction temperature and ambient temperature[14].

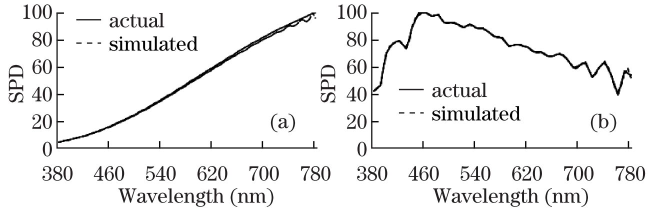

Fig. 2. Simulated spectra of (a) A light source and (b) D_{65} light source.

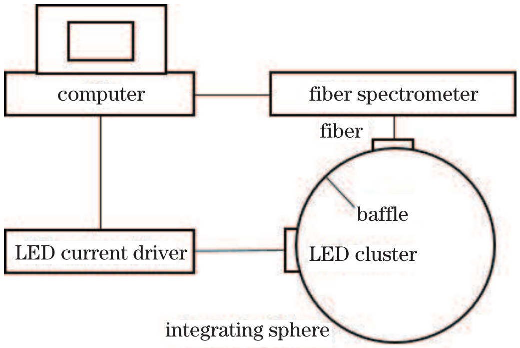

Fig. 3. Sketch of the light source structure.

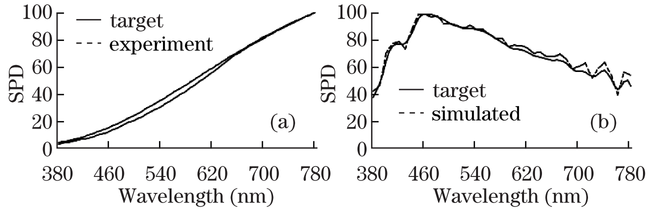

Fig. 4. Spectra of (a) A light source and (b) D_{65} light source measured in experiment.

Table 2. Spectral Fitting Evaluation

Light Source	p Value	
	Simulation	Experiment
CIE Illuminant A	2.31%	4.71%
CIE Illuminant D_{65}	0.74%	3.21%

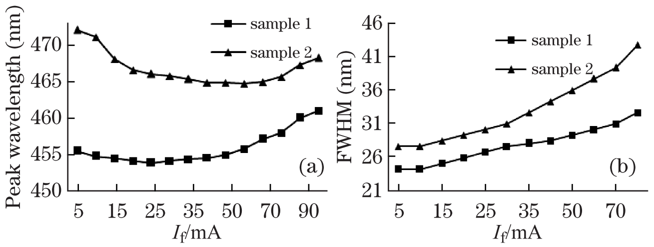

Fig. 5. (a) Peak wavelength and (b) FWHM with the change of current.

In conclusion, we chose the best performing algorithm for each LED in the simulation, and multiple LED spectra are fitted into the spectra of CIE illuminant A and CIE illuminant D_{65}. The data is processed with multivariable linear regression. Experiments show that the evaluation indices for simulated spectra are less than 2.5%, the fitting is acceptable. The actual spectra are affected by various factors, including current, peak wavelength, and FWHM. Therefore the experimental spectra are not as good as simulated spectra, but the evaluation indices are still within 5%.

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