Design, optimization, and photometric analysis of white light spectrum generated by RGB LEDs using MATLAB

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Abstract—We have applied MATLAB software to simulate the emission spectra and optimize the parameters in the simulated spectrum to obtain the highest similarity level between simulation and experimental spectra. Also, we have developed algorithms to determine the quantities of the white light spectrum, including correlated color temperature, output lumen, CIE-chromaticity coordinates, tristimulus values, and luminous efficiency of radiation. The optical model and developed photometric calculation algorithm were applied to study the effect of red light on the output white light properties. The result obtained indicates that MATLAB (version R2017b) is a helpful tool in the spectrum design of white light.

Light emitting diodes (LEDs) as white light sources have an essential role in many applications of human life due to their advantages (e.g., low power consumption, environmentally friendly due to without containing mercury, vivid color, fast response, broad color gamut) compared to the traditional white light source. White light can be created by covering a yellow phosphor on the top of a blue LED chip with a suitable amount. Also, white light is generated by mixing there or many individual LEDs [1-3]. In general, no matter what method is used for generating white light, the well-controlled optical properties and photometric characteristics of output light are always considered essential requirements to have the highest lighting quality [4,5]. Much attention has been paid to the optical properties and photometric characteristics of the output light, and they have been shown in many reported articles. Some proposed solutions have focussed on improving color rendering performance, optical uniformity property, and blue light hazard efficiency when mixing the red (R), green (G), and blue (B) LEDs [6,7], modeling the white light spectrum by mixing blue and yellow light [8], and for asymmetrical emission spectrum curves of luminescent material [9].

Spectrum design is an essential work in the field of solid-state lighting to obtain a light source with high energy efficiency and color performance. When mixing the R, G, and B LEDs, the color performance and optical properties of generated white light are sensitive to the power ratio of blue, green, and red light. Spectrum design is not only useful in general LED lighting technology but also applicable in the spectrum design of light sources for solar cell illumination in the laboratory. In detail, solar-simulator equipment is fabricated from a combination of different types of LEDs to generate a spectrum highly correlated to the solar spectrum. Under this equipment's illumination, the solar cell's efficiency can be studied effectively. To our best knowledge, the development of an efficient model for spectrum design and photometric calculation of LEDs-based white light using MATLAB software and verification with normalized cross-correlation algorithms is still not available. Thus, there is a demand for such a research topic.

Firstly, the optical model for RGB LEDs based white light generation is developed. The mathematical model for describing each component spectrum of blue, green, and red emission bands can be expressed as:

$$P(\lambda) = P\exp\left[-\beta\left(\frac{\lambda-\lambda_{peak}}{\Delta E}\right)\right], \qquad (1)$$

where P is the height of the emission band, beta is the shape correcting factor, λ_{peak} is the value of the peak emission band, and ΔE is the value of FWHM of the emission band. For the RGB LED-based white light generation method, white light can be generated by combining blue, green, and red LEDs. Thus, the mathematical description for the spectral power distribution (SPD) of RGB LEDs-based white light is:

$$P_{white}(\lambda) = P_{blue}(\lambda) + P_{green}(\lambda) + P_{red}(\lambda), \qquad (2)$$

where $P_{white}(\lambda)$ is the SPD of generated white light, $P_{blue}(\lambda)$, $P_{green}(\lambda)$, and $P_{red}(\lambda)$ are the SPD of blue, green, and red light that contribute to that white light, respectively. From the experiment data, the radiation peaks (peak) for the red, green, and blue diodes are 630 nm, 520 nm, and 450 nm, respectively. The value of ΔE for the red, green, and blue emission bands are 16 nm, 30 nm, and 20 nm, respectively. The simulation is described as follows. Replacing the known parameters (emission peak λ_{peak}, and ΔE value) of each band in Eq. (1), assume one any value of β (e.g., β=1.5), lets the value of wavelengths λ changes in the visible light regions (e.g., wavelengths λ changes from 400 nm to 780 nm, and the

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wavelength interval is 1 nm). Using Eq. (2), the emission band of white light generated by combining blue, green, and red LEDs is simulated. The process is repeated for other values of β constants. After validating the accuracy of the optical model, this model is applied to continue to calculate the photometric parameter of white light by incorporating the theory of color science [1]. Let X, Y, and Z be the tristimulus values that give the stimulation (i.e., power) of each of the three primary red, green, and blue lights needed to match the color of P(λ). Values of X, Y, and Z indicate red, green, and blue colors of the spectrum P(λ), respectively:

$$X = \int_{\lambda} \bar{x}(\lambda) P(\lambda) d\lambda, \quad (3)$$

$$Y = \int_{\lambda} \bar{y}(\lambda) P(\lambda) d\lambda, \quad (4)$$

$$Z = \int_{\lambda} \bar{z}(\lambda) P(\lambda) d\lambda, \quad (5)$$

where are color-matching functions. Just three variables can describe the color of any light source.

The luminous flux, Φ_{lum}, is obtained from the radiometric light power using the equation:

$$\Phi_{lum} = 683 \int_{\lambda} V(\lambda) P(\lambda) d\lambda, \quad (6)$$

where V(λ) is the luminous efficiency function or eye sensitivity function. P(λ) is spectral power distribution (W/nm). The constant 683 (lm/W) is the maximum luminous efficiency value for the monochromatic light at a wavelength of 555 nm in the photopic (daytime) vision.

The optical power (P) emitted by a light source is then given by:

$$P = \int_{\lambda} P(\lambda) d\lambda, \quad (7)$$

The luminous efficacy (η_v) of optical radiation (also called the luminosity function or luminous efficiency of radiation), measured in units of lumens per watt of optical power, is the conversion efficiency from optical power to luminous flux. The luminous efficacy is defined as:

$$\eta_v = \frac{\Phi_{lum}}{P} = \frac{683 \int_{\lambda} V(\lambda) P(\lambda) d\lambda}{\int_{\lambda} P(\lambda) d\lambda}. \quad (8)$$

Light causes color perception in human eyes. Colors are described with x and y chromaticity coordinates from CIE1931 color space. The relation of x and y chromaticity coordinates to tristimulus values are described as follows:

$$x = \frac{X}{X + Y + Z}, \quad (9)$$

$$y = \frac{Y}{X + Y + Z}, \quad (10)$$

Once the *x* and *y* chromaticity coordinates are defined, the correlated color temperature (CCT) values are calculated by the McCamy approximation formula, which is expressed [10,11] as follows:

$$\mathrm{CCT} = -449 \cdot n^3 + 3525 \cdot n^2 - 6823.3 \cdot n + 5520.33, \quad (11)$$

where n is calculated by the formula as follows:

$$n = \frac{x - 0.3320}{0.1858 - y}. \quad (12)$$

Based on these theories, the RGB-based white light spectrum is generated and compared to the experimental spectrum. The similarity between simulated spectra and experimental spectrum is quantitively defined by the normalized cross-correlation (NCC) [9,12]. Many simulated spectra at different beta values have been compared to the experimental spectrum. Some results of this comparison are shown in Fig. 1. As shown in Figs. 1 (a)-(d), the beta value change leads to a corresponding change in the NCC value. Based on the behavior of NCC according to beta, as shown in Fig. 2, The suitable beta value for matching the simulation and experimental spectrum can be selected at 2.5.

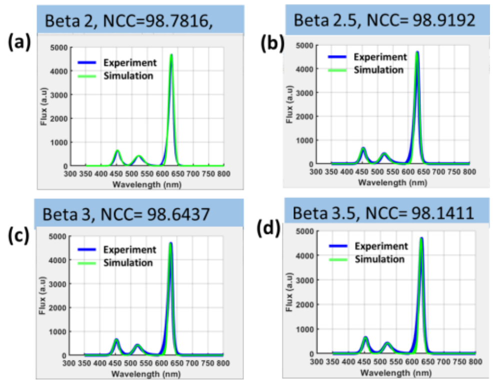

Fig. 1. The change of NCC value corresponding to β values.

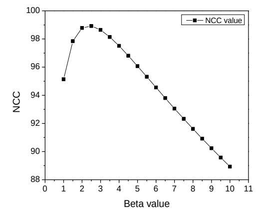

Fig. 2. The behavior of NCC according to β.

As an illustration of this research application, the developed model is applied to study the effect of red light on the output white light properties. The power ratio of blue and green light is kept constant with a ratio of 1:1. The red light is changed from 0 to 9.5 with each increased interval of 0.5. The effect of red-light contribution to the CCT value is shown in Fig. 3. The addition of red light will cause a decrease in the value of CCT. This change of CCT versus red light variation has indicated that the CCT value of output light can be controlled by adding more red light into a constant amount of blue and green light. For example, in spectrum design for lighting applications, if the power ratio of blue light and green light is 1:1, adding the red light power higher than 4, white light with CCT less than 7000K can be generated. The added red-light power can be controlled to make different types of white light, such as cool white, neutral white, and warm white, respectively. The general ratio of Blue:Green:Red light to generate the white light when changing the red light can be generalized as 1:1:r, where the r value is larger than 4. Figure 4 shows the effect of red-light power on the moving of chromaticity coordinates of the output white light. With increasing red light, the chromaticity coordinate is moved to the red-light region of the color space. Based on this information, it can control the color quality of output light to satisfy requirement standards. Figure 5 shows the effect of red-light power on the luminous efficiency of radiation (LER) of the output light. With the increase of red light from 0 to 9.5 by an increase interval of 0.5, the value of LER decreases gradually from 289, 281, 274, 269, 264, 259, 255, 252, 248, 245, 243, 240, 238, 236, 234, 232, 231, 229, 228, and 226 (lm/W), respectively. As comparing to LER value 289 (lm/W) of the case without adding red light, the percentage of decrease of LER value when increase of red light from 0.5 to 9.5 by increase interval of 0.5 are 2.8%, 5.2%, 6.9%, 8.7%, 10.4%, 11.8%, 12.8%, 14.2%, 15.2%, 15.9%, 17.0%, 17.6%, 18.3%, 19.0%, 19.7%, 20.1%, 20.8%, 21.1%, and 21.8%, respectively. In general, adding red light to the overall emission spectrum will decrease the output light property, CCT, and LER values. However, the significant change can be controlled by defining the amount of added red light.

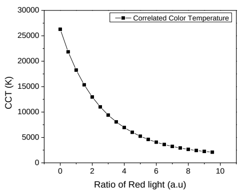

Fig. 3. Effect of red-light power on CCT change of the output light.

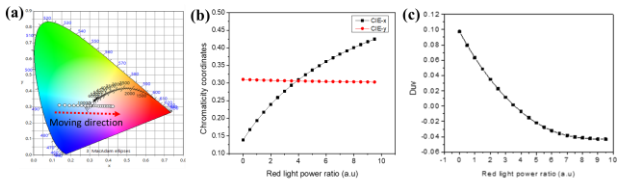

Fig. 4. (a) Effect of red light power on moving of chromaticity coordinates, (b) corresponding value (x,y), and (c) distance of each point from the Planckian locus.

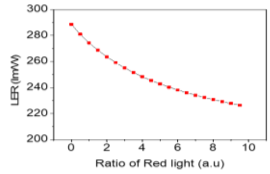

Fig. 5. Effect of red light power on change of luminous efficiency of radiation of the output light.

In summary, we proposed and successfully demonstrated an efficient model for spectrum design and photometric calculation of LEDs-based white light using MATLAB software (version R2017b). The emission spectrum can be modeled using Gaussian functions; MATLAB software is used to simulate the emission spectrum. An optimized process of beta parameters was performed to obtain the simulated spectrum, which shows the highest similarity level between simulation and experimental data. This developed model is then applied to study the effect of red light on the output white light. Based on the theory of color science, photometry, and programming tools of MATLAB, we have successfully developed the algorithms to determine the quantities of white light spectrum including CCT, output lumen, CIE-chromaticity coordinates, tristimulus X, Y, Z, luminous efficacy of radiation. Adding red light can reduce CCT in warm white and reddish light, as well as reduce LER. The proposed solution is not only valuable for general LED lighting technology but also in the spectrum design of the light sources for solar cell illumination in the laboratory. Furthermore, it indicates that MATLAB is a helpful tool for studying the properties of light sources.

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