Emission spectrum modeling of white LED light source using Gaussian function

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Abstract—A mathematical model for emission spectrum modeling that is simple, easy to use, understand, and apply is built and proposed. Then, the model can be applied to design an emission spectrum using LED, studying the optical and color performance of the emitted white light spectrum. This efficient method is helpful for researchers working in the solid-state lighting (SSL) field, spectrum design for light sources, and optimizing the optical and electrical performance of any specific desired light source.

Light emitting diodes have been replaced traditional light sources due to their advanced properties such as energy saving, fast response, environment friendly, and high color performance [1–3]. The white light can be generated by combining blue and yellow light. The blue light is used to excite the yellow phosphor (YAG:Ce), and the absorbed blue light is converted to longer wavelength light of yellow color. Mixing unabsorbed blue and converted yellow light will generate white light under human perception [3]. Such a white light generation's emission spectrum is illustrated in Fig. 1. In the process of white light making, designing the spectrum is essential work in the field of solid-state lighting to obtain a light source with high energy efficiency and color performance. In the design spectrum stage, the Gaussian function is helpful in the deconvolution of the spectra in analyzing the electroluminescence (EL) and photoluminescence (PL) spectra. Thus, the efficient model for designing emission spectra of light sources is always a demand in the field of SSL. Some models related to emission spectrum modeling have been reported. Ohno has developed a simulation program to analyze the possible performance of white LEDs and the problems of the CRI for Various white LED spectra of multichip type and phosphor type [4]. Jin *et al.* reported modifying a single Gauss simulation of a phosphor-coated, light-emitting diode. Then, this Gauss function-based model is used to simulate the performance of a light-emitting diode to avoid the material and time costs in packaging and testing [5]. Jin *et al.* propose a two-part Gauss simulation model to simulate a YAG:Ce phosphor-coated LED (PC-LED). This model divides the emission spectra of YAG:Ce phosphor into two parts, and they use different half spectral widths in the Gauss function to accurately simulate the spectra of YAG:Ce PC-LED [6]. Xu *et al.* reported an appropriate mathematical model to fit the monochromatic LED spectral curve for solar spectrum matching. Xu concludes that the two-dimensional density model is more suitable for simulating monochromatic LED spectral radiation than the Gaussian and Lorentz models [7]. Yang *et al.* have proposed a method of fitting the emission spectrum to detect phosphor temperature in phosphor-converted white LEDs. The model was converted from a Gaussian form to match the emission spectrum of pcW-LEDs [8]. Chen *et al.* reported an effective method for modeling and optimizing multi-LED solar spectrum synthesis with widely-tuning radiant flux output. SPD behavior at different currents was modeled under the controlled constant environmental temperature [9]. Liu has reported a Gaussian distribution model for LED Solar Spectrum Computer Simulation. This non-negative least-squares solution of the overdetermined equations based on the non-dominated sorting genetic algorithm (NSGA) to optimize the monochromatic light-emitting diode (LED) matching light source combination, replace some monochromatic LED with white LED to simulate the solar spectrum [10]. Bachouch *et al.* reported a methodological approach for simulating luminary output radiation, which is achieved by mixing light-emitting diodes (LEDs) to match any plant absorption spectrum. Various recorded narrow-band LED spectra of different colors were first characterized and fitted with a multi-Gaussian model [11]. Liu *et al.* used the double Gaussian model to describe the SPD of a single GaN chip or a single QD system. This model is applied in the spectral design of light-emitting diodes based on quantum dots for plant photosynthesis [12]. Bauer reported a method for assessing the blue-light hazard of light-emitting diodes with Gaussian functions. This can help develop pc-LEDs with a smaller blue proportion while preserving the desired light characteristics [13]. Benkner reported a theoretical emission spectrum of a monochromatic LED, which is described by the product of the density of states and carrier distribution allowed in the energy band defined by the Boltzmann distribution [14]. In general, some reported models still show a complicated mathematical form, leading to users' difficulty using them. It is a demand that requires a simple and efficient

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model for the field of LED-based light source spectrum design and solid-state lighting.

In this study, we built a model for the emission spectrum of pcW-LED light sources. The model includes two Gaussian functions for blue and yellow emission bands. The model is applied to investigate the effect of the amount of yellow light in combination with blue light on CCT, CRI, Duv, and color vector graphics (CVG). We propose a simplified process using the Gaussian function theory in modeling the emission spectrum of the pcW-LED light source. The simplified form of the Gaussian function for matching the emission spectrum will be presented. The proposed simplified form of the Gaussian function helps reduce the complexity of research related to spectrum design and LED packaging for a particular emission.

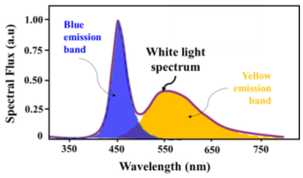

Fig. 1. White light spectrum combination from blue and yellow emission band.

For a dichromatic method-based white light source, white light can be generated by a combination between blue LED and yellow phosphor. The mathematical description for the SPD is:

$$P_{white}(\lambda) = P_{blue}(\lambda) + P_{yellow}(\lambda), \quad (1)$$

where $P_{white}(\lambda)$ is the spectral power distribution of white light. The $P_{blue}(\lambda) + P_{yellow}(\lambda)$ are SPD of blue and yellow emission bands that contribute to the SPD of white light, respectively.

The mathematical description for the $P_{blue}(\lambda) + P_{yellow}(\lambda)$ can used in the general form:

$$P(\lambda) = P_0 \exp\left[-\beta\left(\frac{\lambda - \lambda_{peak}}{\Delta E}\right)^2\right], \quad (2)$$

where β is the corrected coefficient, which changes the width of the shape of the function $P(\lambda)$, ΔE is the FWHM in nm of blue or yellow emission band, P_0 is the optical power of considered blue or yellow emission band. The value of λ is 400 to 800 nm. The wavelength interval is 2 nm., and λ_{peak} value for the blue and yellow emission bands are 450 nm and 560 nm, respectively. The ΔE value for blue and yellow emission bands are 20 nm and 100 nm, respectively. Value β is varied to match the emission bands' experiment data.

Selection of suitable β value in simulation aims to match best. Compared to the experimental emission spectrum of white light, the value of β at 2.5 for the blue and yellow bands in the simulation matches the blue and yellow bands in the experiment. This indicates that the mathematical model is trustable for modeling the emission spectrum of pcW-LEDs light source.

After confirming the trustability of the mathematical model and suitable value of β coefficient, the following simulation will be conducted. The value of β at 2.5 is used for the following simulation emission spectrum of white light with different power ratios of yellow and blue light. In detail, different power ratios of yellow light and blue light at 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2 are simulated and investigated the optical and color properties include emission spectrum, CCT, CRI, and luminous efficiency.

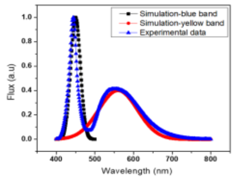

Fig. 2. Comparison to the experimental emission spectrum of white light and blue and yellow band in simulation using the value of β equal to 2.5.

Simulation emission spectrums versus different yellow/blue power ratios 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2 are shown in Fig. 3. The spectra are mainly different in the wavelength range of 480 nm to 700 nm. The valley at wavelength 480 shows a smooth curve bending, indicating that the model has described the emission curve of white light.

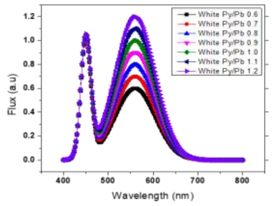

Fig. 3. Simulation emission spectrums versus differenct yellow/blue power ratio 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2.

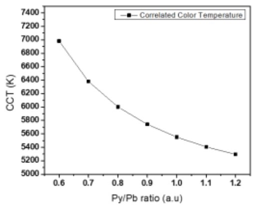

Fig. 4. CCT versus different yellow/blue power ratios.

The effect of yellow light on CCT is shown in Fig. 4. The results show that as yellow/blue power ratio 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2, the value of CCT are 6981 K, 6380 K, 6001 K, 5741 K, 5551 K, 5407 K, and 5294 K, respectively. The higher amount of yellow light to the blue light is, the lower value of CCT is. This show the inverse proportional relation between yellow light and obtained CCT value. Thus, the amount of added yellow

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light is essential for controlling and designing the CCT value for output light.

Changing of color rendering index (CRI) versus the different yellow/blue power ratios is shown in Fig. 5. The results show that as yellow/blue power ratios 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2, the values of CRI are 64, 63, 61, 60, 59, 59, and 58. These values indicated that the CRI is poor. The main reason is caused by the lack of red emission bands at wavelengths of 650 nm to 700 nm. The changing of CRI as the amount of yellow light increases shows that the CRI is still almost the same. This indicates that the CRI can not improve with increased yellow light. The CRI is possibly enhanced by adding red emission or cyan blue emission band spectrum in the spectrum. Such a high CRI light source is suitable for applications that require the high value of CRI, such as in fashion stores, museums, and display rooms. The higher CRI value of the light source will help achieve better accuracy in the reproduced color of the object as illuminated by that light source. However, a light source with a limited CRI value (e.g., 60) is suitable for applications where CRI is not the highest required factor, for example, in the case of the lamp in the bedroom. Another example is a road lamp. The lamp used for lighting roads at night corresponds to two road conditions. This lamp type includes two modes: the first mode has the output spectrums of blue (B), yellow (Y), and red (R) bands, and the second mode has output spectrums of the B and Y bands. Under road conditions with many vehicles, the red band and the B and Y bands are on, so the high CRI is obtained. However, under conditions without cars on the road, the red band is turned off to reduce energy consumption. At the same time, the B and Y are still operated to provide a level enough for bright perception.

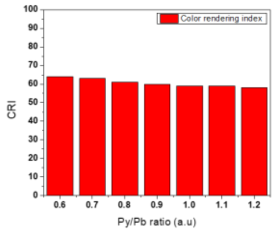

Fig. 5. Changing of CRI versus different yellow/blue power ratios.

For lighting purposes, it is often expected to have output flux the most when designing a spectrum. The changing of output luminous flux versus the different yellow/blue power ratios is shown in Fig. 6. The result indicated the linear relationship between the added amount of yellow light and the output luminous flux. The increase of luminous flux is related to the rise of the component of green light at peak wavelength at 555 nm in the designed spectrum.

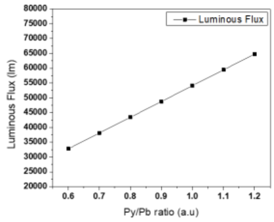

Fig. 6. Changing of Luminous Flux versus yellow/blue power ratios.

In summary, this paper is motivated by one of the difficulties caused by the complexity of the mathematical form for people who want to model the emission spectrum. The proposed model can solve this difficulty. As a result, the reader can more easily understand how to model the light source's emission spectrum using the simplified Gaussian function. In more detail, a simplified model to model the emission spectrum of pcW-LEDs light source has been built and confirmed to experiment data. This model uses Gaussian functions for blue and yellow emission bands with a suitable beta coefficient value. The value of the beta coefficient is essential for matching the experiment and the simulation emission band. The proposed model is applied to investigate the effect of the amount of yellow light in combination with blue light at different ratios of 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, and 1.2 regarding CCT, CRI, and luminous performance. The results show that the simplified form of the Gaussian function for matching the emission spectrum helps reduce the complexity of research related to spectrum design and LED packaging for a specific emission.

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