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Study of Spectrum Modeling, Optical and Colorimetric Properties of Blue Laser Diodes-Based Phosphor Converted White Light

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A B S T R A C T

We reported the development of spectrum modeling for white light generation which is contributed by blue and yellow light emission bands. Blue light originates from blue laser diodes while yellow light is converted from yellow phosphor under blue light excitation. Mathematical modeling for the spectrum of generated white light is developed from Gaussian functions. The emission spectra for white light combined with blue and yellow light at different Blue and yellow light ratios are studied. The colorimetric and photometric values of the white light spectrum are calculated based on the color science and photometry theories. The spectrum modeling is applied to study the color and optical properties of different CCTs from 3609 K to 7671 K. The parameters include Output luminous flux, correlated color temperature, chromaticity coordinates, and Duv. These are defined to provide a recipe to make the white light with the highest quality possible according to the reference standard (e.g. ANSI).

1. INTRODUCTION

Light-emitting diode-based solid-state lighting has been widely used and famous thanks to many advantages such as energy saving, super brightness, environmentally friendly, and long life span [1-4]. However, when operating it at a higher injection current, the output flux decreases significantly, leading to a new technical problem named “efficiency droop” [5]. To overcome these challenges, the pumping light source is selected to replace the LED with laser diodes [6-8]. As a result, the efficiency droop phenomenon is no longer a problem when blue lasers are utilized to excite yellow phosphors to make white light. Related to the field of laser lighting, where the laser diode is utilized as an excitation source for phosphor, many studies have reported [9-15]. Cantore et. al.

reported that a high-power blue GaN-based LD coupled with a single crystal Ce-doped yttrium aluminum garnet (YAG: Ce) sample was investigated for white light illumination applications. Under CW operation, a single phosphor-converted LD (pcLD) die produced a peak luminous efficacy of 86.7 lm/W at 1.4 A and 4.24 V and a peak luminous flux of 1100 lm at 3.0 A and 4.85 V with a luminous efficacy of 75.6 lm/W [9]. Wu et al. studied a laser-diode-based white lighting module fabricated via spectral component optimization, which can achieve both high luminous flux and high color rendering index (CRI). In this work, the laser module is constituted by blue laser diodes (LDs) that excite YAG:Ce-Al_2O_3 and red LDs that can compensate for the lack of red spectrum to improve the CRI of the light source. The module has a high luminous flux of 1102 lm and a high CRI of 77.8 [7]. Tang et. al. reported a Laser-driven white light with tunable low-colour temperature based on novel ZrO_2-doped $(Gd,Lu)_2O_3$:Eu red-emitting transparent ceramics. Under the excitation of 465 nm laser light, the $(Gd,Lu)_2O_3$:Eu/ YAG:Ce ceramic converter could generate ideal white light at various low colour temperatures, effectively making up for the deficiency of the low colour rendering index and high colour temperature caused by the lack of red light components in the solid-state lighting [10]. Ye et. al. reported that color quality and blue light hazard were investigated by comparing 465 nm laser-excited phosphor materials and traditional 452 nm laser-excited phosphor materials respectively. Phosphor-converted laser-based illuminant (pc-LBI) consisting of 465-nm and 635-nm LDs (LBI-465) has a color rendering index (CRI) of 88.7, which was 8.2% higher than that of pc-LBI consisting of 452-nm and 635-nm LDs (LBI-452), and the correlated color temperature (CCT) in the range of 2200 K to 5000 K [11]. Sang et. al. have designed and fabricated a novel composite structure ceramic including a 1.0 × 1.0 mm^2 Al_2O_3-YAG:Ce ceramic and a φ=16.0 mm transparent YAG ceramic for the transmissive configuration in laser lighting. When pumped by blue laser from 0~60 W mm2, all the samples exhibited no luminous saturation phenomenon, and the 10.0 wt.% Al_2O_3-YAG:Ce/YAG composite ceramic with a thickness of 0.3 mm maintained white light with a luminous efficacy over 200 lm/W [12]. Liu et. al. studied a barcode-structured YAG:Ce/YAG:Ce,Mn ceramic phosphors for variable CCT and high CRI LED/LD lighting. Changing the blue power from 0.52 W to 2.60 W, the CCT of the laser lighting source with the encapsulation of optimized YAG:Ce/ YAG:Ce,Mn ceramic phosphors ranged from 3928 K to 5895 K, while the CRI always maintained above 80 [13]. Lee et. al. studied the impact mechanisms of laser speckles on the quality of phosphor-converted white light. This research provides valuable data and practical guidelines for designing laser-excited phosphor illumination systems to optimize color spatial uniformity [8]. Nguyen et. al. developed an optical model for green phosphor pumped by ultraviolet (UV) laser. The model is applied to study the effect of green light on the optical properties of the output spectrum. The higher the power ratio of green/UV is, the higher the output luminous flux is. The amount of green light is an important factor in controlling the output lumen of the overall spectrum through controlling the amount of green light [14]. In general, the research on optical modeling for laser lighting applications is still a knowledge gap that needs to be filled further.

In this study, we developed a spectrum modeling for estimating the property of white light that gennerated by combination of yellow phosphor and blue laser diodes excitation source. The principle of Blue laser-based white light generation is presented. The emission band of blue and yellow light is studied. The mathematical model is defined to simulate white light spectrums corresponding to different power ratios of blue and yellow light. The photometric properties of warm-to-cool white light are investigated and discussed.

2. PRINCIPLE FOR BLUE LASER BASED WHITE LIGHT GENERATION AND OPTICAL MODELING

The principle for Blue laser-based white light generation is similar to the case using Blue LED to excite the yellow phosphor as shown in Fig. 1. The yellow phosphor is mixed with polymer gel (e.g. silicone gel or epoxy gel) to make a phosphor plate. Blue laser diodes emit blue light to excite yellow phosphor plates. When blue light shines on the yellow phosphor plate, there are three parts of interaction between blue light and yellow phosphor. A portion of blue light scatters backward. A portion is absorbed and a portion is transmitted without absorption. In the case of the blue light that is absorbed by the yellow phosphor, almost (e.g. 90%) of the absorbed blue light is converted into yellow light. The output yellow light and unabsorbed blue light are mixed which can cause the white light feeling under human eyes' perceptions.

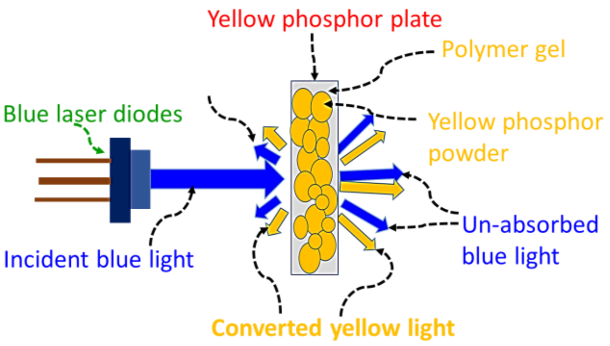

Fig. 1. Illustration the Blue laser based white light genneration.

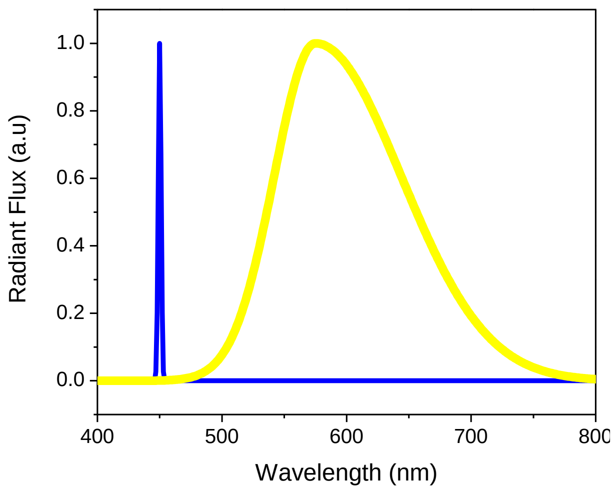

Fig. 2. Simulation emission spectrum of the blue emission band and yellow band.

For the blue laser-based phosphor-converted white light generation method, white light can be generated by combining unabsorbed blue and converted yellow light. The mathematical description for the spectral power distribution (SPD) of pcW-LED is

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

Where *Pwhite(λ)* is the SPD of generated white light. *Pblue(λ)*,and *Pyellow(λ)* are the SPD of blue and yellow light that contributese to that white light spectrum. The mathematical description for each component spectrum *Pblue(λ)*, *Pyellow(λ)* can be used as follows [15-17]:

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

Where beta β is corrected coeficient, λ *peak is the peak emission wavelength of emission band,* ΔE is the FWHM in nanometers (nm) units, and P is the optical power of LED in watts (W) units. Based on the mathematical model described in equation (2), the emission spectra of the blue and yellow bands are done as shown in Fig. 2. The emission band of blue laser diodes is narrow with a peak emission wavelength of 450 nm. The yellow phosphor shows a broader emission band in the wavelength region 470 nm to 760 nm.

3. APPLICATION OF SPECTRUM MODELING TO STUDY THE PHOTOMETRIC PROPERTY OF WARM TO COOL WHITE LIGHT

After making sure the trustale of modeling, the spectrum model is applied to study the photometric property of warm to cool white light. Ase on the parameters, the different white light spectra corresponds to different B/Y power ratios is simulated as shown in Fig. 3. In this study, the B/Y is mimulasted as 0.5 to 32 with changed interval of 0.5. based on the photometry and color science theories, the value of these parameters (including the output luminous flux in lumen, correlated color temperature, chromaticity coordinates, chromaticity difference from Planckian locus-Duv) are calculated.

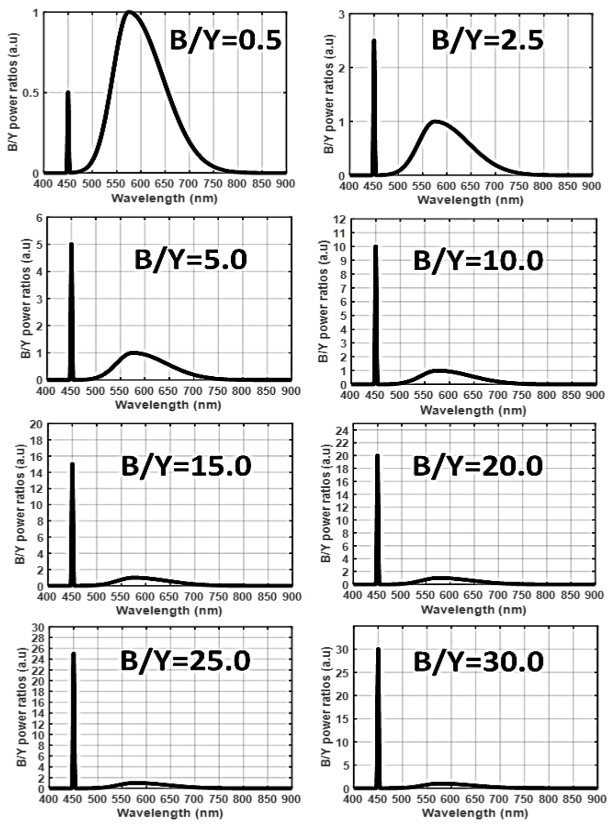

Fig. 3. White light spectra coresponds to different B/Y power ratios.

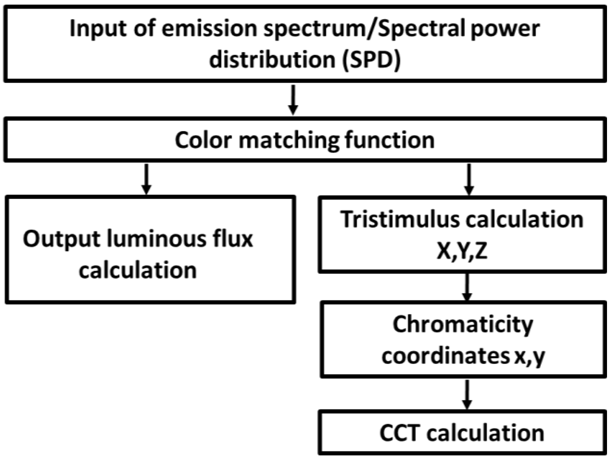

Fig. 4. Algorithm in photometric parameter calculation.

Fig. 4 shows the algorithm in calculation these parameter. The calculated result of photometric/colorimetric property are presented in next sections. Figure 5 shows the changing of output luminous flux of the white light spectrum corresponding to different B/Y power ratios. Fig. 6. Shows the effect of B/Y power ratios on chromaticity property of the white light.

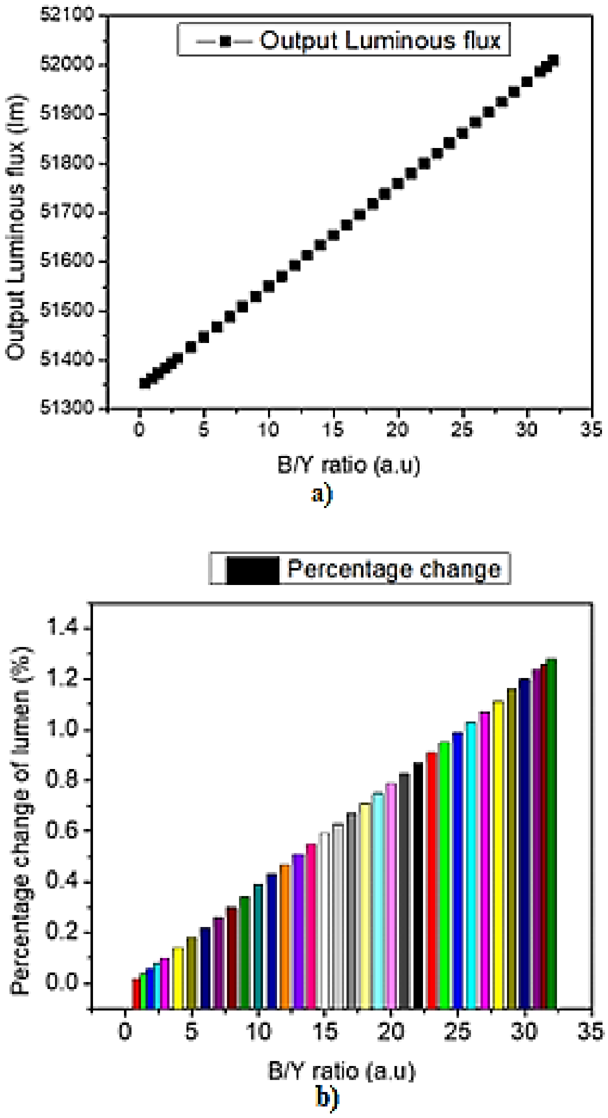

Fig. 5. (a) Changing of output luminous flux of the white light spectrum corresponding to different B/Y power ratios. (b) Percentage change of output luminous flux.

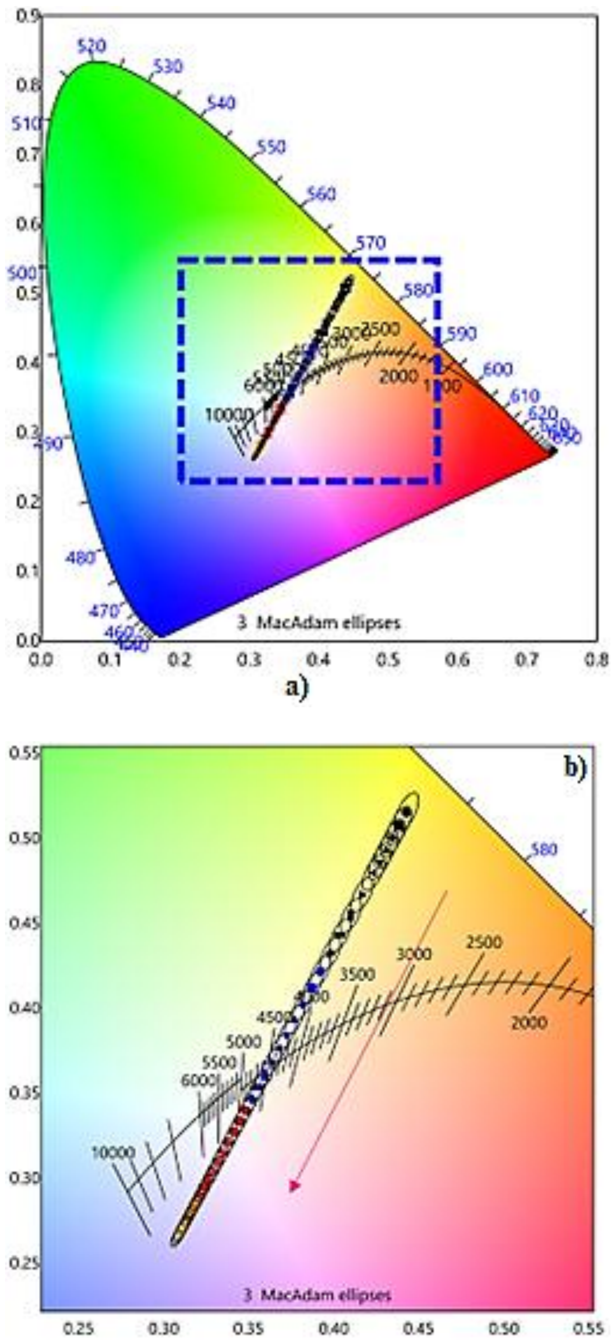

Fig. 6. (a) Changing of chromaticity property of the white light spectrum corresponding to different B/Y power ratios. (b) enlarged part of dash light rectangle in figure 6 (a).

Although the changing is as a function of the incrasing of blue light power ratios, the percentage of increasing luminous flux is not sigificant (less than 1.5%). This results is realated to small luminous effiicacy of Blue radiation.

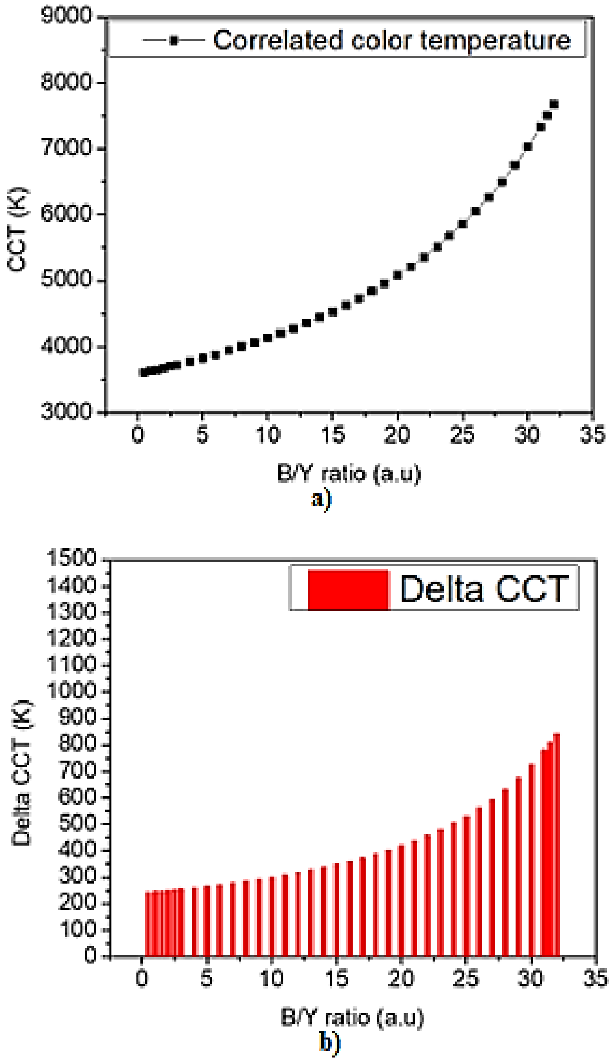

Fig. 7. (a) Changing of CCT of the white light spectrum corresponding to different B/Y power ratios, and (b) corresponded delta CCT.

For each CCT value, it is expected that the chromaticity difference from Planckian locus-Duv is as small so that meet the standard. The changing of Duv value versus the B/Y power ratios is shown in Fig. 8. It can see that the more B/Y power ratios, the farther of color point to the Plankian curve is. However, the chromaticity difference from Planckian locus-Duv for B/Y power ratios from 0.5 to 31.5 is still lesser than 0.004. it indicated that the quality of white light is still good and sasitfy the standard. Figure 9 shows the changing of CRI of the white light spectrum corresponding to different B/Y light power ratios. For convenient estimate the CRI behavior, the CRI values of white light at different B/Y light power ratios of 0.5, 5.0, 10.0, 15.0, 20.0, 25.0, and 30.0 are investigated. The obtained CRI values are 59, 62, 65, 70, 75, 77, and 70. It can see that the CRI of white light at B/Y light power ratios of 0.5, 5.0, 10.0 are poor. However, CRI values is more better for cases B/Y light power ratios 15.0, 20.0, 25.0, and 30.0. The obtained CRI is good to use in light application.

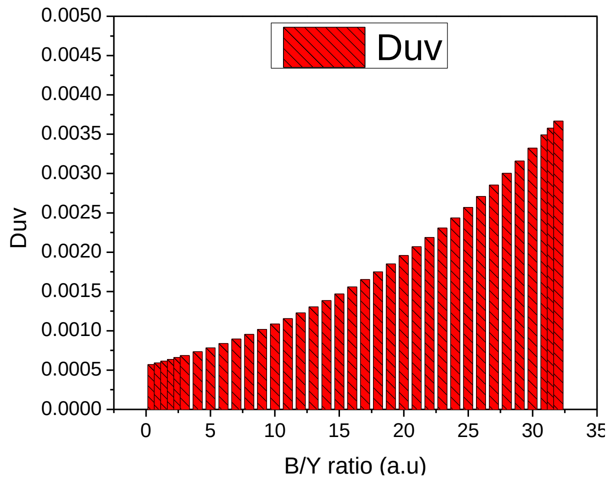

Fig. 8. The changing of chromaticity difference from Planckian locus-Duv value versus the B/Y power ratios.

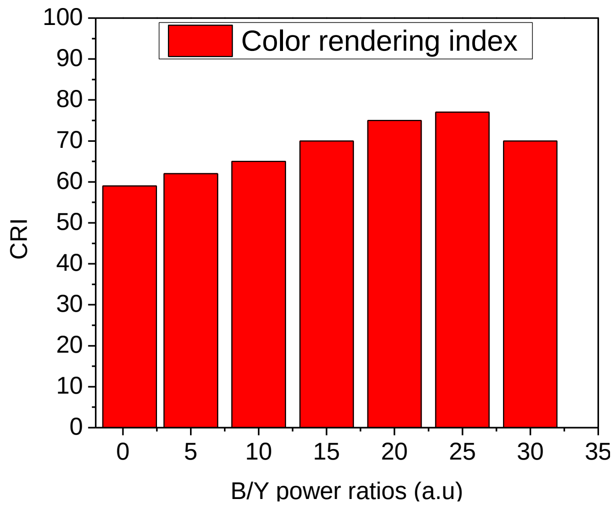

Fig. 9. Changing of CRI of the white light spectrum corresponding to different B/Y power ratios.

4. CONCLUSION

We reported the development of spectrum modeling for white light generation which is contributed by blue and yellow light emission bands. Blue light originates from blue laser diodes while yellow light is converted from yellow phosphor under blue light excitation.

Mathematical modeling for the spectrum of generated white light is developed from Gaussian functions. The emission spectra for white light combined with blue and yellow light at different Blue and yellow light ratios are studied. The colorimetric and photometric values of the white light spectrum are calculated based on the color science and photometry theories.

The spectrum modeling is applied to study the color and optical properties of white light combined with blue and yellow light at different Blue and yellow light ratios from 0.5 to 31.5. Although the change of output luminous flux is a function of the increasing blue light power ratios, the percentage of increasing luminous flux is not significant (e.g. less than 1.5%). The changing of CCT versus the changing of B/Y power ratios in the white light spectrum. The effect of increased blue light content on the CCT shows that the larger the amount of blue light, the higher the value of CCT is. The range of CCT is from 3609 K to 7671 K in this investigation. The behavior of CCT versus B/Y power ratios indicates that the blue light content is the main factor in increasing the CCT value of white light. With increasing B/Y power ratios, the color point coordinates overcome the region of high CCT values and then tend to move to the blue light regions. The CRI values of white light at different B/Y light power ratios of 0.5, 5.0, 10.0, 15.0, 20.0, 25.0, and 30.0 are investigated. The obtained CRI values are 59, 62, 65, 70, 75, 77, and 70. The parameters including output luminous flux, correlated color temperature, chromaticity coordinates, and Duv for each B/Y ratio are defined clearly. These results are important in providing a recipe to make the white light with the highest quality possible according to the reference standard (e.g. ANSI).

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