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Study on color-tunable phosphor-coated white light-emitting diodes with high S/P ratios

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In this study, we have investigated the trade-off between the color rendering index (CRI, Ra) and the scotopic/photopic ratio (S/P) for color-tunable phosphor-coated white light-emitting diodes (LEDs) at two CRI limitations (Ra ≥ 70 and Ra ≥ 96). First, luminescent spectra measurements have been conducted to determine experimental results of Ra and S/P under various correlated color temperatures (CCTs). Then, a nonlinear programming method has been adopted for the optimization of Ra and S/P by varying spectral shapes through adjusting spectral parameters, such as peak wavelengths, full-width at half-maxima, and relative intensities. Therefore, polynomial curves of optimal S/P versus CCT at two Ra limitations have been discovered, enabling users to obtain optimal S/P under arbitrary CCTs within [2700 K, 6500 K]. In addition, a comparison study between the present work and our previous work has also been conducted at Ra = 70, and a fair agreement of optimal S/P has been observed. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). [http://dx.doi.org/10.1063/1.4945387]

I. INTRODUCTION

Solid-state lighting (SSL) devices, including light-emitting diodes (LEDs) and laser illuminants, have been demonstrated as potential replacements for white incandescent, fluorescent, and high-intensity discharge lamps due to high luminous efficacy, less energy consumption, compact size, substantially increased efficiency and longevity, less susceptibility to vibration, and spectral design flexibility.1–4 This SSL technology has significantly facilitated the development of innovative vehicle forward lighting with requirements for improved nighttime-driving safety. In general, the human eye is constructed with two types of photoreceptors, i.e., cones and rods.5 Numerous researchers have demonstrated that the latter photoreceptors in human eyes are active not only at low light levels (with a luminance level typically lower than 10−3 cd/m²), but also at interior light levels.6 White light sources with high scotopic to photopic (S/P) ratios may potentially offer equivalent perceived brightness and visual acuity at lower light levels to those attained with lamps having low S/P at higher light levels, because these rod photoreceptors appear more sensitive to the bluish white light than cone photoreceptors do.7 Adoption of high S/P lamps may offer benefits for energy-saving. In addition, good color reproduction and high luminous efficacy of radiation (LER, K) are also two significant figures of metric for white light sources. The color reproduction is commonly measured by adopting average color rendering index (CRI, or Ra)8 and the No. 9
special CRI (R9) both suggested by the Commission Internationale de l’Eclairage (CIE), or by adopting other color quality metrics like color quality scale\textsuperscript{9} provided by the American National Institute of Standards and Technology. Despite the potential energy-saving by using high S/P lamps, it is cumbersome to generate high S/P white light sources. In general, a fundamental trade-off between the Ra and the S/P ratio exists,\textsuperscript{10} leading to a challenge of producing a lamp capable of achieving high S/P and high Ra simultaneously. In reference to S/P and Ra, traditional and most current light technologies are typically limited. For example, incandescent lighting bulbs have shown a poor ratio of 1.41 despite a perfect Ra of 100.\textsuperscript{7} A SSL device including a blue InGaN chip combined with the yellow-green cerium-doped yttrium aluminum garnet (YAG:Ce\textsuperscript{3+}) phosphor (B+YG) may also exhibit S/P ranging from 1.68 to 2.38, but may provide low Ra.\textsuperscript{6} Herein, it is desirable to provide lighting sources capable of offering high S/P with high Ra at the same time. A blue InGaN chip combined with nanocrystal quantum dots (QDs) has been managed to emit blue, cyan, green, yellow, and red lights, and shown aggregated white light with the high S/P ratio in excess of 2.50.\textsuperscript{6} Under correlated color temperature (CCT) of from 2700 K to 6500 K, the theoretical maximum S/P ratio has been studied previously for both three- and four-color white LEDs (denoted as QD-LEDs) including narrow-band nanocrystal QDs and semiconductor emitters.\textsuperscript{10} In this study, considering the poor S/P and Ra of B+YG white LEDs, we investigate optimizations of three-color phosphor-coated white LEDs (B+YG+R) (including blue LED chips, yellow-green YAG:Ce\textsuperscript{3+} phosphors, and red QDs or red LEDs) on S/P ratios and Ra, and compare associated photometric and chromatic performances with those presented in previous studies.\textsuperscript{10} Not only can these LED systems be developed to reach a balance between providing the visibility and offering the comfort for drivers, but also they benefit from high Ra due to broad spectra of Ce\textsuperscript{3+}-doped YAG phosphors. Billions of LED spectral power distributions (SPDs) have been carefully optimized to determine their best visual performances.

II. EXPERIMENTS AND OPTIMIZATIONS

Prior to carrying out optimizations, we first measured SPDs of B+YG+R white LEDs. Figure 1(a) shows these white light sources including the blue LED chip, the red LED chip, the yellow-green YAG:Ce\textsuperscript{3+} phosphor plate, and the base among others.

To measure SPDs, we control each primary LED separately. After a stabilization period of more than 30 minutes, spectra of the aggregated white light, and Ra, K, S/P, and CIE 1931 color coordinates (CIE x, CIE y) have been determined by an integrating sphere (ISP-500, Instrument Systems Inc.) connected to a calibrated spectrometer (Spectro 320e, Instrument Systems Inc.). Figure 1(b) illustrates normalized scotopic and photopic luminosity functions, with the leftmost curve standing for a scotopic luminosity function, and with the rightmost curve representing a photopic luminosity function. The S/P ratio indicates how well a light source can stimulate rod photoreceptors, and can be written by the following equation,\textsuperscript{3,10}

\[
S/P = \frac{1700 \times \int_{380}^{780} S(\lambda)V'(\lambda)d\lambda}{683 \times \int_{380}^{780} S(\lambda)V(\lambda)d\lambda},
\]  

(1)

FIG. 1. (a) The schematic structure and the photograph of white LEDs. (b) Photopic and scotopic curves.
and the LER of white LEDs can be expressed as

\[ K = \frac{683 \times \int_{380}^{780} S(\lambda)V(\lambda)d\lambda}{\int_{380}^{780} S(\lambda)d\lambda}, \]  

where \( S(\lambda) \) is the SPD of a light source; \( V(\lambda) \) the normalized CIE photopic spectral luminous efficiency function; \( V'(\lambda) \) the normalized CIE scotopic spectral luminous efficiency function.

Figures 2(a)-2(d) show electroluminescence spectra with four different CCTs by adjusting the individual power supply of blue and red LED chips. For the LED sample under tests, the S/P ratio varies from 1.72 to 2.06 under four different CCTs (3174 K, 4126 K, 5194 K, and 6100 K, respectively).

As can be observed, S/P ratios are lower than 2.50, which can be treated as a upper limit value for most B+YG white LEDs and traditional white lamps. Thus, it proves significant to carry out optimization studies on high S/P ratios for these B+YG+R white LEDs based on experiments. The CRIs have also been presented in these figures.

Mathematic models for modelling the SPD in Ref. 11 based on Double Gaussian (DG) models, first proposed by Ohno and coworkers, have been used in this work. And these modified DG models are capable of accurately describing spectra of three-hump white LEDs. For the purpose of conducting optimizations, a non-linear programming software developed by our group is adopted. Optimizations are then carried out under eight representative CCTs, i.e., 2700 K, 3000 K, 3500 K, 4000 K, 4500 K, 5000 K, 5700 K, and 6500 K, respectively. In the study, the full-width at half maximum of SPDs for the blue, yellow-green, and red hump is maintained at 20 nm, 120 nm, and 20 nm, respectively, corresponding well with experimental counterparts; the CCT tolerance is set as \( \pm 10 \) K; the color distance (Duv) from the Planck locus in the CIE 1960 UCS color space smaller than 0.0054 is considered. The goal of this optimization is to obtain reasonably high S/P under the condition of \( Ra \geq Ra_o \) (the Ra threshold, here, set as 70 and 96, respectively). The high Ra threshold of 96 is set to meet high-CRI application requirements. Optimal results and relevant discussions will be presented below in detail.
TABLE I. Photometric and chromatic parameters, including CCT, Duv, peak wavelength, relative intensity, Ra, R9, K, and S/P, determined by eight representative optimal SPDs at Ra = 70.

| TCCT (K) | 2700 | 3000 | 3500 | 4000 | 4500 | 5000 | 5700 | 6500 |
|----------|------|------|------|------|------|------|------|------|
| CCT (K)  | 2701 | 3007 | 3507 | 4008 | 4504 | 5007 | 5701 | 6496 |
| Duv      | 0.0053 | 0.0032 | 0.0035 | 0.0043 | 0.0046 | 0.0017 | 0.0004 | 0.0026 |
| λB (nm)  | 484 | 484 | 481 | 482 | 480 | 477 | 475 | 473 |
| λY (nm)  | 569 | 562 | 561 | 555 | 556 | 552 | 542 | 540 |
| λR (nm)  | 630 | 620 | 622 | 624 | 627 | 630 | 629 | 628 |
| H₆ (%)   | 30.1 | 36.6 | 43.2 | 45.1 | 50.0 | 50.6 | 50.0 | 53.5 |
| H₇ (%)   | 13.7 | 14.1 | 14.7 | 15.3 | 15.5 | 14.8 | 15.3 | 15.1 |
| H₈ (%)   | 56.2 | 49.3 | 42.1 | 39.6 | 34.5 | 34.6 | 34.7 | 31.4 |
| Ra       | 70 | 70 | 70 | 70 | 70 | 70 | 70 | 70 |
| R9       | 28 | 90 | 75 | 59 | 46 | 16 | 4 | 5 |
| K        | 293 | 317 | 308 | 307 | 297 | 285 | 282 | 276 |
| S/P      | 1.78 | 1.94 | 2.15 | 2.32 | 2.47 | 2.60 | 2.76 | 2.89 |

*TCCT is the target CCT.

### III. DISCUSSIONS

Tables I and II list photometric and chromatic parameters of white LEDs, including CCT, Ra, K, S/P, Duv, peak wavelengths, relative intensities, for representative optimal SPDs at Ra = 70 and Ra = 96 under eight CCTs. As can be clearly observed, while Ra = 70 for B+YG+R white light sources, the highest S/P varies from 1.78 to 2.89 for optimal SPDs under eight CCTs. But at Ra = 96, these values change from 1.32 to 2.40 under eight CCTs. Optimal peak wavelengths and relative intensities have also been revealed in these tables, enabling the community to produce high S/P phosphor-coated white light sources under different Ra conditions. For example, at Ra = 70, 470-485 nm, 540-570 nm, and 620-630 nm for blue, yellow-green, and red peak wavelengths, respectively, are much more suitable for achieving high S/P color-tunable white light sources. Simultaneously, when the CCT value is larger than 5000 K, S/P > 2.50 is noticed for this type of white LEDs, and all K for optimal SPDs are larger than 270 lumen per watt (lm/W). In addition, a comparison between values of S/P for these white LEDs, and those for three- and four-hump QD-LEDs in our previous work has also been performed, as shown in Table III. These S/P values for B+YG+R white LEDs agree fairly well with those of three- and four-hump QD-LEDs. Figure 3 shows the optimal S/P ratio ([S/P]ₘ) versus CCT at Ra = 70 and Ra = 96. As CCT increases, S/P increases, too. Polynomial trends (with coefficients of determination, R², larger than 0.99, indicating excellent fittings) can be clearly observed, and these trends can be expressed as,

TABLE II. Photometric and chromatic parameters, including CCT, Duv, peak wavelength, relative intensity, Ra, R9, K, and S/P, determined by eight representative optimal SPDs at Ra = 96.

| TCCT (K) | 2700 | 3000 | 3500 | 4000 | 4500 | 5000 | 5700 | 6500 |
|----------|------|------|------|------|------|------|------|------|
| CCT (K)  | 2705 | 3006 | 3492 | 4003 | 4507 | 4995 | 5702 | 6505 |
| Duv      | 0.0049 | 0.0053 | 0.0022 | 0.0032 | 0.0054 | 0.0032 | 0.0002 | 0.003 |
| λB (nm)  | 464 | 463 | 464 | 459 | 458 | 455 | 451 | 456 |
| λY (nm)  | 573 | 568 | 564 | 558 | 555 | 544 | 540 | 540 |
| λR (nm)  | 630 | 628 | 629 | 629 | 627 | 623 | 623 | 626 |
| H₆ (%)   | 20.7 | 25.6 | 31.4 | 35.6 | 41.8 | 40.5 | 43.5 | 48.6 |
| H₇ (%)   | 23.2 | 23.3 | 24.3 | 23.8 | 22.8 | 22.3 | 23.5 | 22.9 |
| H₈ (%)   | 56.1 | 51.1 | 44.3 | 40.6 | 35.4 | 37.2 | 33.0 | 28.6 |
| Ra       | 96 | 96 | 96 | 96 | 96 | 96 | 96 | 96 |
| R9       | 96 | 96 | 96 | 95 | 95 | 95 | 92 | 96 |
| K        | 325 | 330 | 330 | 325 | 319 | 317 | 313 | 305 |
| S/P      | 1.32 | 1.47 | 1.65 | 1.80 | 1.95 | 2.11 | 2.22 | 2.40 |
TABLE III. S/P ratios for B+YG+R and QDs at Ra = 70.

| TCCT (K) | 2700 | 3000 | 3500 | 4000 | 4500 | 5000 | 5700 | 6500 |
|----------|------|------|------|------|------|------|------|------|
| B+YG+R   | 1.78 | 1.94 | 2.15 | 2.32 | 2.47 | 2.6  | 2.76 | 2.89 |
| QDs (3-color) | 1.71 | 1.86 | 2.08 | 2.27 | 2.41 | 2.56 | 2.72 | 2.85 |
| QDs (4-color) | 1.83 | 1.99 | 2.19 | 2.36 | 2.50 | 2.64 | 2.80 | 2.92 |

FIG. 3. S/P ratio versus CCT at Ra = 70 and 96.

\[
[S/P]_M = a \times CCT^2 + b \times CCT + c, \tag{3}
\]

where \(a\), \(b\), and \(c\) are three coefficients determined as: a) for \(Ra = 70\), \(-4.518 \times 10^{-8}\) K\(^{-2}\), \(7.017 \times 10^{-4}\) K\(^{-1}\), and 0.232, respectively; b) for \(Ra = 96\), \(-3.365 \times 10^{-8}\) K\(^{-2}\), \(5.866 \times 10^{-4}\) K\(^{-1}\), and \(-0.005\), respectively. Therefore, the highest S/P at different Ra thresholds for arbitrary CCTs in the range of [2700 K, 6500 K] can be readily obtained through the equation above without requiring complicated computations.

Furthermore, we also study the wavelength-dependent and the intensity-dependent characteristics of S/P ratios. Figure 4 plots S/P ratio versus (a) wavelength shift (5 nm) and (b) relative intensity variation at CCT = 5000 K. It is clear that the S/P ratio responds most sensitively to the blue intensity and the yellow-green wavelength among three components, indicating the significance of the yellow-green wavelength and the blue intensity on achieving high S/P light sources.

FIG. 4. The S/P ratio versus (a) the wavelength shift and (b) the intensity shift at CCT = 5000 K.

IV. CONCLUSION

In this work, the trade-off between S/P ratio and CRI for wide-band phosphor-coated white LEDs has been carried out. Under eight CCTs, optimal S/P values of 1.78-2.89 and 1.32-2.40 have
been achieved at Ra = 70 and Ra = 96, respectively. A comparison between our work and previous studies has also been conducted at Ra = 70. The proposed study provides guidelines for achieving energy-saving white LEDs via combining blue LEDs, traditional wide-band phosphors (such as YAG:Ce$^{3+}$), and red LEDs or red QDs.

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