Current Optics and Photonics
Vol. 4, No. 3, June 2020, pp. 247-252

ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2020.4.3.247

Improving CRI and Scotopic-to-Photopic Ratio Simultaneously by Spectral Combinations of CCT-tunable LED Lighting Composed of Multi-chip LEDs

Jong-Oh Kim, Hyeong-Seob Jo, and Uh-Chan Ryu*

Interdisciplinary Program of LED and Solid-State Lighting Engineering, Pukyong National University, Busan 48547, Korea

(Received March 4, 2020 : revised April 6, 2020 : accepted April 18, 2020)

Important determinants for selecting outdoor lighting are the color-rendering index (CRI) and scotopic-to-photopic (S/P) ratio of the lighting units. The higher the S/P ratio, the better energy savings and visual performance. In this study, CCT-tunable LED lighting units were optimized and fabricated by spectral combination of red, green, blue, and yellow LEDs. The measured results for RGB LEDs provided S/P ratios of 1.55~2.58 and those of RGBY LEDs gave 1.46~2.46 to the correlated color temperatures (CCTs) ranging from 2700 K to 6500 K, with CRI values of over 80 at the same time.

Keywords : Scotopic to photopic ratio, Color rendering index, Multi-chip LED lighting
OCIS codes : (230.3670) Light-emitting diodes; (330.1715) Color, rendering and metamerism; (220.2945) Illumination design

I. INTRODUCTION

Important parameters for determining outdoor lighting are the color-rendering index (CRI) and scotopic-to-photopic (S/P) ratio of the lighting units. CRI is a parameter evaluating the reproduction of colors of objects under artificial lightings. S/P ratio is an indicator of lighting efficiency in nighttime situations [1-3]. A lighting unit with higher S/P ratio provides more benefits in energy savings and visual performance. In general, CRI and S/P ratio are in a trade-off relationship, and thus it is difficult to achieve white lighting with maximized CRI and S/P ratio at the same time [4-10]. Several studies were carried out to maximize S/P ratios with CRI values over 70 by combining red, green, blue, and white LEDs (RGBW-LEDs), mixing quantum dot RGB (QD-LED) or RGBY (QD-RGBY) LED spectra, and adding a single-wavelength LED to a phosphor converted LED [4-6].

However, the special CRI values (R_9-R_{14}), color quality scale (CQS, Q_a), color gamut (R_g), and color fidelity (R_f), which have been recently emphasized for evaluating LED lighting [11, 12], were found to be too degraded for use in commercial lighting, as shown in Fig. 1, which represents the color-rendering properties calculated from the previous results [4, 6]. Therefore, to produce an LED lighting unit with highest S/P ratio and acceptable CRI at the same time, optimization of these parameters should be fulfilled by also considering R_9-R_{14}, Q_a, R_f, R_g, etc. In this paper, values of the S/P ratio according to CRIs, including general CRI (R_a) and special CRI (R_i), for CCT-tunable LED lighting units composed of RGB 3-chip and RGBY 4-chip LEDs were optimized through simulation. Optimized LED lighting units were fabricated based on the simulation results and their optical properties, such as S/P ratio, CRIs, CQS, color gamut, color fidelity, and luminous efficacy of radiation (*LER*), were measured.

II. METHODS

A simulation program was composed using the Matlab software to calculate optical properties, such as CCT, CRIs, S/P ratio, etc., based on the calculation formulas defined in the International and the Korean standards [11-13]. The

*Corresponding author: ucryu@pknu.ac.kr, ORCID 0000-0003-2371-0358
Color versions of one or more of the figures in this paper are available online.

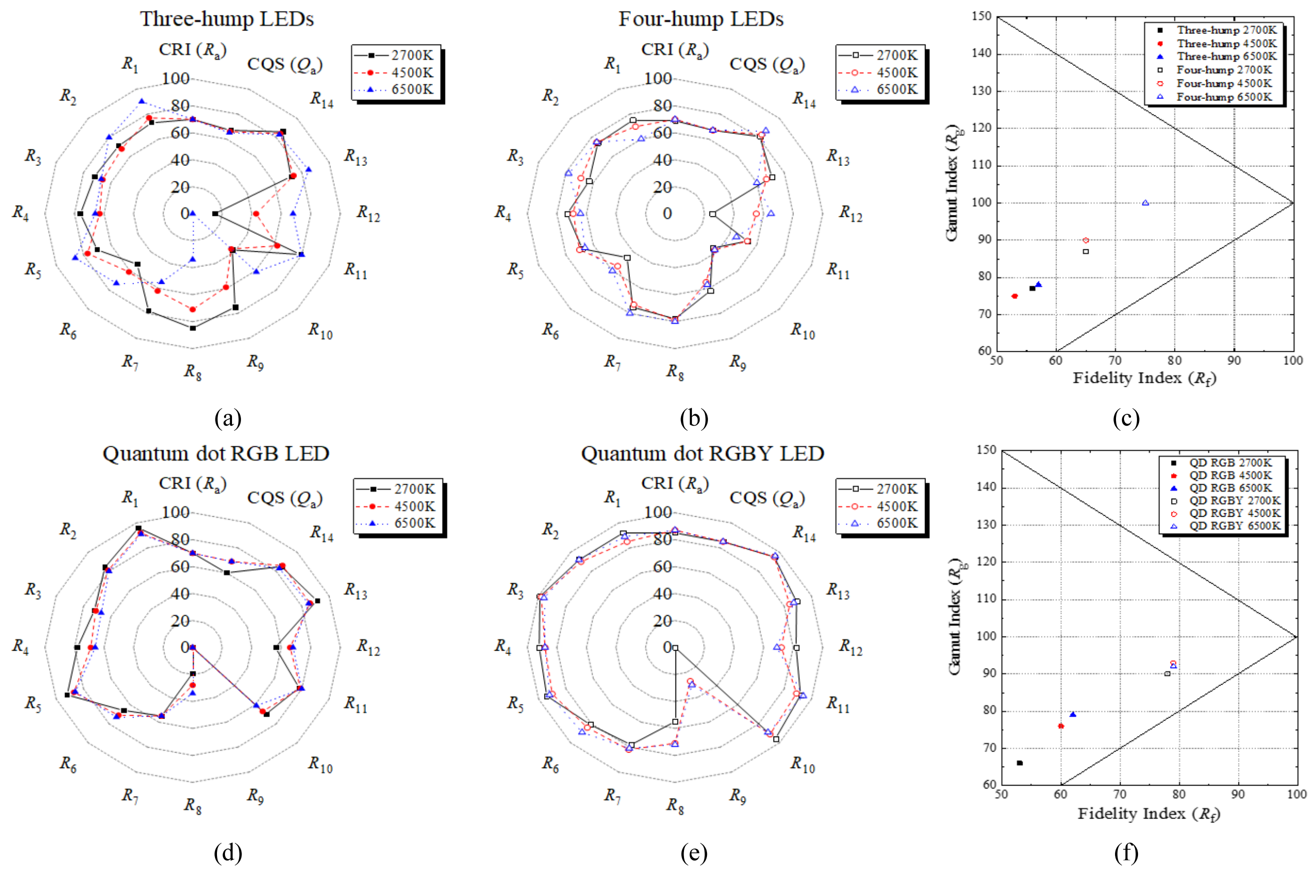


FIG. 1. Color-rendering properties from the previous results [4, 6]: (a) R_1-R_{14} and Q_a of three-hump LEDs, (b) R_1-R_{14} and Q_a of four-hump LEDs, (c) R_f and R_g of three-hump and four-hump LEDs, (d) R_1-R_{14} and Q_a of a QD-RGB LED, (e) R_1-R_{14} and Q_a of a QD-RGBY LED, and (f) R_f and R_g of a QD-RGB and a QD-RGBY LED.

program was verified in two ways: by comparing the simulated results to the measured ones, and by paralleling the simulated results with those from the OSRAM Color Calculator 6.03 and the IES TM-30-15 Basic Calculation Tool version 1.02 [13-15]. The method for tuning CCTs and evaluating S/P ratio along with CRIs for RGB LEDs is to move and scale every wavelength of the LED, summarized as follows:

① Set the peak wavelength of the blue LED at 450 nm, green at 500 nm, and red at 620 nm, with full width at half maximum (FWHM) of 30 nm, by fixing CCT at 2700 K.
② Shift the peak wavelength of the blue from 450 nm to 480 nm in 5-nm intervals, repeating procedure ①.
③ Shift the peak wavelength of the green from 500 nm to 560 nm in 5-nm intervals, repeating procedures ① and ②.
④ Shift the peak wavelength of the red from 620 nm to 660 nm in 5-nm intervals, repeating procedures ①~③.
⑤ Repeat ①~④ for CCTs of 3000 K, 3500 K, 4000 K, 4500 K, 5000 K, 5700 K, and 6500 K. Meanwhile, the CCT variation was restricted within $D_{uv} \pm 0.005$ (distance from the Planckian locus on CIE 1960 (u, v) coordinates).

The process for RGBY LEDs is almost the same as above, except for adding a procedure for the yellow LED. The FWHM of each spectrum varied from 0% to 50%, 100%, 150%, and 200%.

III. RESULTS

3.1. Simulation Results for RGB and RGBY LEDs

Values of the S/P ratio were calculated according to R_a values in four ranges: (a) 1~25, (b) 25~50, (c) 50~75, and (d) 75~100 for CCTs of 2700 K, 3000 K, 3500 K, 4000 K, 4500 K, 5000 K, 5700 K, and 6500 K. The largest S/P ratios at the CCTs by tuning the RGB LEDs were averaged as follows: 2.93, 3.04, 3.23, 3.30, 3.57, 3.78, 3.97, and 4.31 for R_a of (a) 1~25; 2.63, 2.69, 2.76, 2.98, 3.07, 3.27, 3.51 and 3.76 for R_a of (b) 25~50; 2.16, 2.34, 2.46, 2.63, 2.73, 2.90, 3.05 and 3.43 for R_a of (c) 50~75; and 1.73, 1.89, 2.05, 2.19, 2.34, 2.47, 2.64 for R_a of (d) 75~100 [16]. The largest S/P ratios at the CCTs by tuning the RGBY LEDs were averaged as follows: 3.11, 3.21, 3.35, 3.47, 3.61, 3.75, 4.00, and 4.28 for R_a of (a) 1~25; 2.79, 2.91, 3.11, 3.14, 3.30, 3.47, 3.74 and 4.01 for R_a of (b) 25~50; 2.29, 2.42, 2.65, 2.87, 3.06, 3.26, 3.45 and 3.68 for R_a of

(c) 50~75; 1.81, 1.86, 2.04, 2.22, 2.40, 2.56, 2.79, and 2.99 for R_a of (d) 75~100. As the CCT increases, the average and maximum values of the S/P ratio grow at the same time [16]. Among the above simulation results, root-mean-square values (R_{rms}) were calculated [17] for the reference of 100 for the CRI properties, and optimized spectra were selected, having the lowest R_{rms} and the highest S/P ratio at the same time. During the calculation, LED spectra below 80 in CRI (R_a) or Q_a and 250 lm/W in *LER* were excluded. The information for the optimized RGB or RGBY LED spectra was provided to an LED-chip supplier. The peak wavelengths were 460 nm, 530 nm, and 630 nm for the RGB LEDs respectively, and a yellow LED of 590 nm was added to the RGB LEDs for the RGBY LEDs. The FWHMs of the LEDs were in the range of 30~60 nm.

3.2. Measured Results for CCT-tunable Multichip LED Lighting Units

A CCT-tunable LED lighting unit composed to yield the optimized RGB or RGBY LED spectra was fabricated and

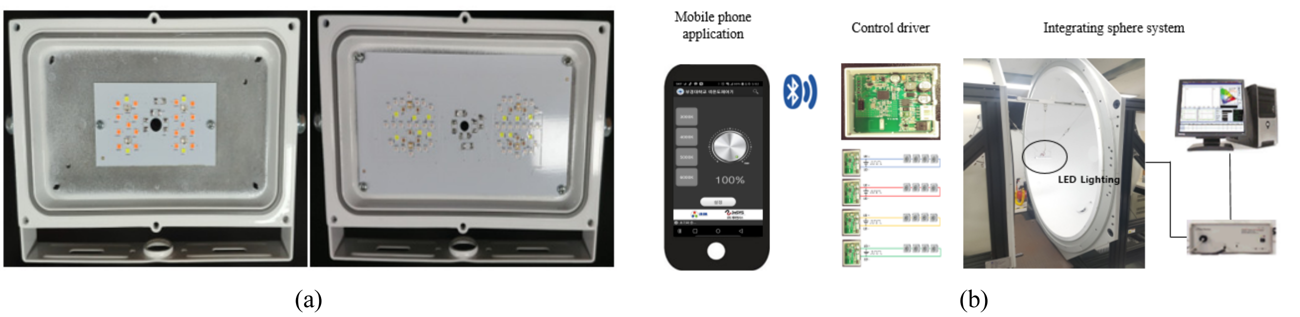


FIG. 2. Fabricated LED lighting units and measurement system: (a) fabricated lighting units of RGB (left) and RGBY LEDs (right), and (b) the integrating-sphere system.

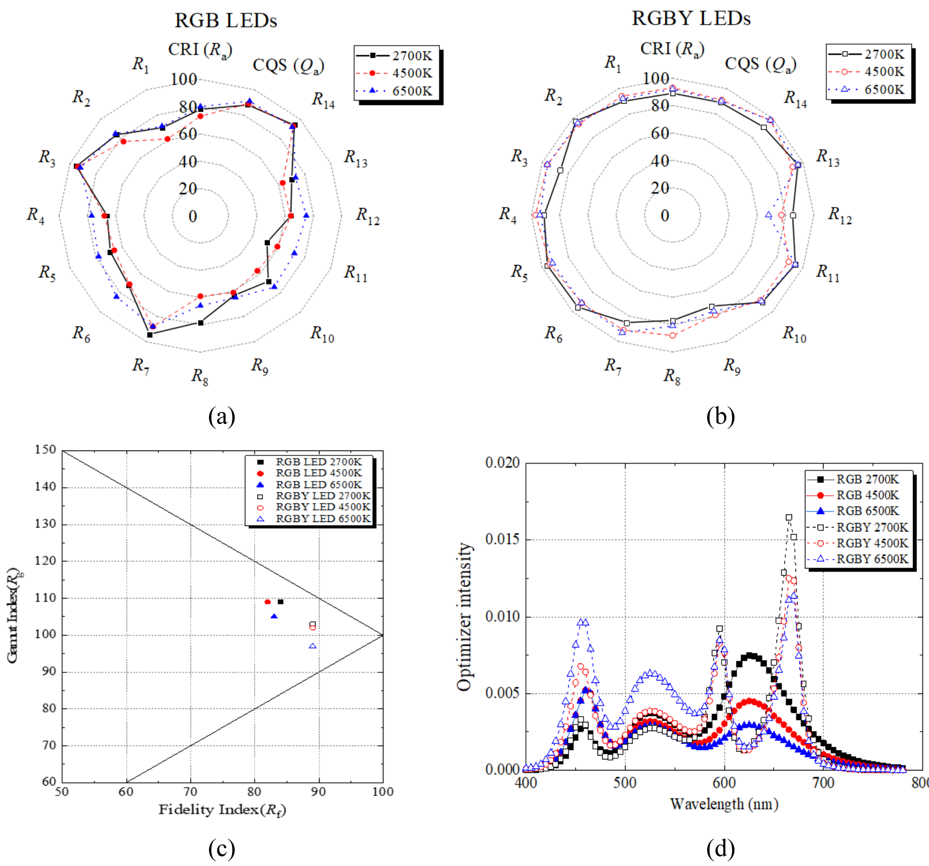


FIG. 3. Comparison of the measured results for the RGB and RGBY LED lighting units, according to their CCTs: (a) S/P ratios with CRI values over 80 for the RGB LEDs, (b) S/P ratios with CRI above go for the RGBY LEDs, (c) R_f and R_g of the LEDs, and (d) optimized spectra of the LEDs.

operated by a pulse-width-modulation (PWM) power supply, controlled by a mobile-phone application to set the CCTs. Figure 2 shows the fabricated LED lighting units (a) and how they are set in an integrating-sphere system to measure their optical properties (b). The fabricated LED lighting units were tested in the sphere system in comparison to certified standard reference lighting supplied by the Korea Research Institute of Standards and Science (KRISS), per the guidelines in [18].

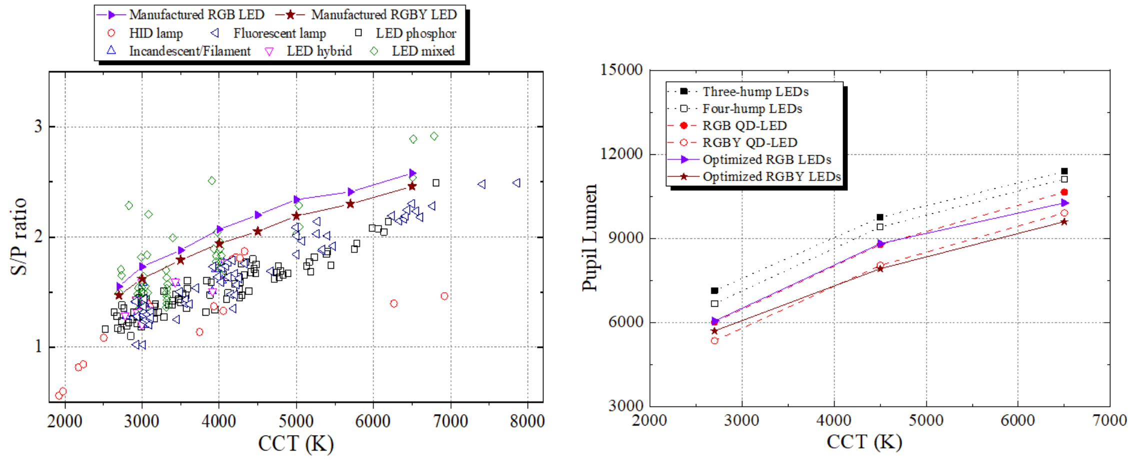
Figure 3 shows the measured results for the RGB and the RGBY LED lighting units: (a) and (b) show R_i along with Q_a for the RGB and RGBY LEDs, respectively; (c) shows R_f and R_g for the RGB and RGBY LEDs; and (d) presents the spectral distributions of the RGB LEDs (solid symbols) and RGBY LEDs (hollow symbols). In the case of the optimized RGB LEDs, when changing the CCTs the S/P ratios were decreased by 0.3 compared to those of the three-hump LEDs, and were equivalent to those of the RGB QD-LEDs. On the contrary, R_8, R_9, and R_{12} dramatically increased to more than 60.

In the case of the optimized RGBY LEDs, S/P ratios during tuning to the CCT were smaller by 0.25 than those of the four-hump LEDs, and larger by 0.1 than those of the QD-RGBY LEDs. On the other hand, R_9 increased to at least 72, R_{10} to 88, and R_{12} to 89. Furthermore, for the RGB LEDs R_f and R_g values were improved to at least 82, and to 99 for the RGBY LEDs, as plotted in (c). The measured spectra for the fabricated RGB and RGBY LED lighting units are shown in (d). The detailed measured results for the optimized lighting units and the calculated results by other groups [4, 6] are summarized in Table 1, for comparison.

Figure 4(a) describes the S/P ratios during the CCT changes of the fabricated LED lighting units in this study, along with the calculated S/P ratios from the library of the IES TM-15-30 [19]. The S/P ratios, plotted as separate symbols, were calculated from the 297 spectra of the road-lighting units included in the library (hollow symbols) [19]. The symbols for the fabricated LED lighting units, linked by straight lines, indicate that the CCTs were tuned from 2700 K to 6500 K. The S/P ratios are plotted as solid purple right-pointing triangles for the RGB and solid brown stars for the RGBY LED lighting units. To compare the results from the previous studies [4, 6], pupil lumens were calculated per the guidelines in [20] and are shown in Fig. 4(b). For convenience, pupil lumens were compared only at the CCTs of 2700 K, 4500 K, and 6500 K. Those for the RGB LED lighting at the CCTs were smaller by 18.1%, 10.6%, and 13.2% than those for the three-hump LEDs, and larger by 0.6%, 0.4%, and lower by 5.8% than those for the RGB QD-LEDs, respectively. Those for the RGBY were decreased by 17.1%, 18.7%, and 15.9 % compared to those for the four-hump LEDs, and increased by 6.2% and lowered by 1.5% and 3.3% compard to those for the RGBY QD-LEDs, respectively. Even though the S/P ratio values and the resulting pupil

TABLE 1. Comparison of the results from previous studies and for the optimized RGB or RGBY LED lighting units [4, 6]

Item	CCT (K)	R_a	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_f	R_g	Q_a	S/P ratio	*LER* (lm/W)
Three hump LEDs [4]	2700	70	75	38	79	15	72	86	56	77	67	1.83	322
	4500	70	59	37	62	43	74	84	53	75	66	2.5	306
	6500	70	0	61	80	68	85	83	57	78	65	2.92	285
Four hump LEDs [4]	2700	69	62	36	53	25	71	81	65	87	67	1.71	335
	4500	70	55	38	53	55	67	83	65	90	67	2.41	323
	6500	70	57	38	45	65	60	87	75	100	67	2.85	238
RGB QD-LED [6]	2700	70	0	70	78	56	91	85	53	66	60	1.54	385
	4500	70	0	67	79	66	86	86	60	76	69	2.25	337
	6500	70	0	61	80	68	85	83	62	79	69	2.73	317
RGBY QD-LED [6]	2700	85	0	96	92	82	89	95	78	90	85	1.37	365
	4500	87	27	91	89	72	84	95	79	93	85	2.06	346
	6500	87	30	89	94	69	87	96	79	92	85	2.54	325
Optimized RGB LEDs	2700	80	63	68	51	64	70	94	84	109	88	1.55	260
	4500	78	61	57	59	64	63	93	82	109	89	2.26	248
	6500	82	65	74	72	75	73	92	83	105	91	2.58	254
Optimized RGBY LEDs	2700	89	72	90	94	94	96	91	89	103	89	1.46	259
	4500	93	79	88	89	89	92	98	89	102	91	2.03	251
	6500	92	76	98	94	94	96	98	89	99	90	2.46	267



(a) (b)

FIG. 4. Comparison of the S/P ratios and the resulting pupil lumens: (a) the S/P ratios from the fabricated lighting units during the CCT tuning along with those from the 297 spectra of the lighting units included in the library of the IES TM-30-15 [14]; and (b) the resulting pupil lumens from the S/P ratios of this study.

lumens were degraded compared to the previous results [4, 6], most of the CRI values were upgraded significantly during the CCT tuning.

IV. CONCLUSION

Well-known parameters for evaluating indoor lighting are light efficacy (in lm/W), CRI, color-quality scale, color gamut, color fidelity, etc., while that for outdoor lighting is the S/P ratio. CCT-controlled lighting units composed of three-hump, four-hump, QD-RGB, and QD-RGBY LEDs in the previous studies of other groups showed high S/P ratios [4, 6]. On the contrary, they presented low special CRI (R_i), color fidelity, color-quality scale, etc. In this study, S/P ratios along with CRI values were optimized at the same time for CCT-tunable LED lighting units composed of RGB or RGBY LEDs. Optimized RGB LED lighting units showed S/P ratios of 1.55~2.58, general CRI (R_a) of 78~85, special CRI ($R_{9\text{-}14}$) of 59~74, color fidelity (R_f) of 82~87, color gamut (R_g) of 105~111, and *LER* of 250~260 lm/W for CCTs ranging from 2700 K to 6500 K. Optimized RGBY lighting units presented S/P ratios of 1.46~2.46, R_a of 85~95, $R_{9\text{-}14}$ of 75~86, R_f of 82~89, R_g of 87~103, and *LER* of 250~270 lm/W. By optimization procedures, degradations in R_a, $R_{9\text{-}14}$, Q_a, R_f, and R_g of the previous studies were significantly compensated to adequate levels for commercial CCT-tunable LED lighting units, in spite of lowered S/P ratios.

ACKNOWLEDGMENT

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2017R1D1A3B03035090). The authors are also grateful to the program for supporting the Transfer of Idle and Underused Research Facilities and Equipment funded by the Korean government.

REFERENCES

1. G. He and J. Tang, "Spectral optimization of color temperature tunable white LEDs with excellent color rendering and luminous efficacy," Opt. Lett. **39**, 5570-5573 (2014).
2. P. Zhong, G. He, and M. Zhang, "Optimal spectra of white light-emitting diodes using quantum dot nanophosphors," Opt. Express **20**, 9122-9134 (2012).
3. G. He and H. Yan, "Optimal spectra of the phosphor-coated white LEDs with excellent color rendering property and high luminous efficacy of radiation," Opt. Express **19**, 2519-2529 (2011).
4. Z.-Q. Guo, T.-M. Shih, Y.-J. Lu, Y.-L. Gao, L.-H. Zhu, G.-L. Chen, J.-H. Zhang, S.-Q. Lin, and Z. Chen, "Studies of scotopic/photopic ratios for color-tunable white light-emitting diodes," IEEE Photonics J. **5**, 8200409 (2013).
5. L. Zan, D. Lin, P. Zhong, and G. He, "Optimal spectra of white LED integrated with quantum dots for mesopic vision," Opt. Express **24**, 7643-7653 (2016).
6. T. Wu, Y. Lu, Z. Guo, L. Zheng, H. Zhu, Y. Xiao, T.-M. Shih, Y. Lin, and Z. Chen, "Improvements of mesopic luminance for light-emitting-diode-based outdoor light sources via tuning scotopic/photopic ratios," Opt. Express **25**, 4887-4897 (2017).
7. S. M. Berman, M. Navvab, M. J. Martin, J. Sheedy, and W. Tithof, "A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children," Light. Res. Technol. **38**, 41-49 (2006).
8. P. Tregenza and D. Loe, *The Design of Lighting* (Taylor & Francis, UK, 1998).

9. P. R. Boyce, *Human Factors in Lighting*, 2nd ed. (Taylor & Francis, UK, 2003).
10. SP ratios and mesopic vision, LIA TS24, UK, 2013. [Online]. Available: https://www.thelia.org.uk
11. Specification of Colours According to the CIE 1931 Standard Colorimetric System and the CIE 1964 Supplementary Standard Colorimetry Standard Colorimetrc System, KS A0061, Korea Standard Association, Korea (30 June 2015).
12. Method of Measuring and Specifying Colour Rendering Properties of Light Sources, CIE Publ. 13.3 (Vienna, CIE Central Bureau, 1995).
13. Solid-state Lighting Technology Fact Sheet: Evaluating Color Rendition Using IES TM-30-15, ANSI/IES TM-30-15 (Washington, DC, DOE, 2015).
14. J. O. Kim, H. S. Jo, and U. C. Ryu, "A study on changes of the S/P ratio and CRI based on the wavelength spectra of RGB 3-chip LED lightings," J. Korean Inst. IIIum. Electr. Install. Eng., **31**, 17-25 (2017).
15. J. O. Kim, H. S. Jo, and U. C. Ryu, "A study on variation of S/P ratio and CRI by changing spectral characteristics of RGBY multi-chip LEDs," J. Korean Inst. IIIum. Electr. Install. Eng., **31**, 10-19 (2017).
16. J. O. Kim, H. S. Jo, and U. C. Ryu, "Mesopic luminance improvement and CRI optimization of CCT-tunable multi-chip LED outdoor lighting," in *Proc. KIIEE Annual Autumn Conference & General Meeting* (Incheon, Korea, Nov. 2018) p. 4
17. H. S. Jo, J. O. Kim, and U. C. Ryu, "Simulation study on variations of color rendition properties according to combination of 455 nm blue led and phosphor emission spectra," J. Korean Inst. IIIum. Electr. Install. Eng., **33**, 1-8 (2019).
18. U. C. Ryu and Y. W. Lee, "Verifying calibration effectiveness and simulation exactness in comparison between measurement and simulation on optical properties in integrating sphere," J. Korean Inst. IIIum. Electr. Install. Eng., **31**, 32-39 (2017).
19. S. Fotios and Q. Yao, "The association between correlated colour temperature and scotopic/photopic ratio," Light Res. Technol. **51**, 803-813 (2019).
20. S. M. Berman, "Energy efficiency consequences of scotopic sensitivity," J. Illum. Eng. Soc. **21**, 3-14 (2013).