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 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.

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
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 25–50;
Improve CRI and Scotopic-to-Photopic Ratio Simultaneously by Jong-Oh Kim et al.

(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 measured.

![Fabricated LED lighting units and measurement system](image)

**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.

![Comparison of measured results for RGB and RGBY LED lighting units](image)

**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 80 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 RGB QD-LEDs. 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% compared to those for the RGB QD-LEDs, respectively.

Even though the S/P ratio values and the resulting pupil lumens were calculated per the guidelines in [18], Table 1 summarizes the detailed measured results for the optimized lighting units and the calculated results by other groups [4, 6].

<table>
<thead>
<tr>
<th>Item</th>
<th>CCT (K)</th>
<th>$R_a$</th>
<th>$R_b$</th>
<th>$R_{10}$</th>
<th>$R_{11}$</th>
<th>$R_{12}$</th>
<th>$R_{13}$</th>
<th>$R_{14}$</th>
<th>$R_8$</th>
<th>$Q_a$</th>
<th>S/P ratio</th>
<th>LER (lm/W)</th>
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<td>89</td>
<td>99</td>
<td>2.46</td>
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</table>
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 ($R_{0,14}$) 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 showed S/P ratios of 1.46–2.46, $R_a$ of 85–95, $R_{0,14}$ 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 $R_a$, $R_{0,14}$, $Q_a$, $R_g$, and $R_f$ of the previous studies were significantly compensated to adequate levels for commercial CCT-tunable LED lighting units, in spite of lowered S/P ratios.

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REFERENCES


