 Improvements of mesopic luminance for light-emitting-diode-based outdoor light sources via tuning scotopic/photopic ratios

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Abstract: Outdoor light sources must guarantee excellent mesopic luminance ($L_{mes}$) for traffic safety at night. Here, we propose a solution to improve mesopic-related parameters, which include especially the scotopic/photopic ratio and the $L_{mes}$, of multi-chip light-emitting diode (LED) light sources. Generally, these sources are driven by pulse-width-modulation currents, and possess readily-controlled spectral power distributions (SPDs). An updated version of the optical power ratio algorithm developed in this article can select suitable overall SPDs and yield corresponding duty cycles to drive individual chips at different correlated-color temperatures and operating temperatures. Its accuracy and practicality are proven by experimental results. In addition, our study introduces a temperature-feedback technique that can instantly adjust duty cycles for each chip according to real-time operating temperatures in order to avoid undesirable color drifts at different operating temperatures. It can also be regarded as a model for practitioners who desire to improve the quality of outdoor light sources.

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References and Links


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1. Introduction

Recent developments in the field of light source technologies have opened new perspectives for sustainable and highly efficient light sources in the form of light-emitting diodes (LEDs) for the outdoor lighting [1–3]. Generally, mesopic luminance (\( L_{mes} \)) of such lighting ranges from photopic to scotopic visions (0.005 to 5 cd/m\(^2\)) [4]. Mesopic parameters of light sources are closely correlated to object-detection abilities, which are greatly required for traffic safety at nights [5,6]. However, current photometric practice is primarily based on the photopic sensitivity function \( V(\lambda) \), and fails to gauge mesopic parameters of light sources, due to the fact that spectral sensitivity of mesopic vision shifts towards shorter wavelengths. Thus for outdoor lighting applications, such as the road lighting, it is necessary to optimize mesopic parameters of LEDs via combining both the photopic sensitivity function \( V(\lambda) \) and the scotopic sensitivity function \( V'(\lambda) \) as spectral weighting functions (Fig. 1) [7].

\[
\begin{align*}
\text{Fig. 1. Normalized spectra of the scotopic sensitivity curve } V'(\lambda), \text{ the photopic sensitivity curve } V(\lambda), \text{ and mesopic sensitivity curves } V_{mes}(\lambda) \text{ when } L_{mes} = 0.1, 0.3 \text{ and } 2 \text{ cd/m}^2. \\
\end{align*}
\]

Red-green-blue-white (RGBW) LEDs become one of the best candidates for the solution of intelligent lightings that work for both indoor and outdoor cases, because adding spectra of
white chips can extend hue, saturation and brightness values available in color systems [8]. Usually, pulse-width-modulation (PWM) operation is selected to drive these RGBW LEDs since the linearity between light intensity and duty cycle greatly facilitates tuning SPDs, compared with DC-driving condition [9,10]. Therefore, we can readily obtain desirable spectral power distributions (SPDs) of RGBW LEDs by changing optical powers of each chip [11], via PWM currents. However, commonly known as the phenomenon of metamerism, lights with two different SPDs display the same color to human eyes as they share identical chromaticity coordinates (thus identical correlated color temperatures (CCTs)), but different color qualities [12]. Therefore, the set of PWMs of RGBW LEDs should be designed carefully, not only to ensure desirable chromaticity coordinates but also to meet fundamental requirements of mesopic visions and color qualities for the outdoor lighting [13].

In previous studies on optimizing SPDs of white LEDs for mesopic parameters [14,15], theoretical functions, e.g., double Gaussian, are adopted for fitting the SPD of each single color. By altering peak height, peak wavelength and bandwidth of each SPD, overall SPDs with decent mesopic parameters can be achieved. However, this method appears inadequate in a couple of aspects. First, SPDs of real LEDs and simulated counterparts cannot match precisely, leading to the difficulty of achieving theoretical highest mesopic parameters. Second, the method lacks a detail solution for driving actual LEDs by PWM current signals and a thorough analysis on how to maintain mesopic parameters and color qualities under different operating temperatures.

In this article, we introduce a solution to drive actual multi-color-LED-based outdoor light sources to reach high mesopic parameters for road lighting. As the core of the solution, an optical power ratio algorithm II (OPRA-II) functions as a liaison between desired mesopic parameters and PWM driving currents at different operating temperatures. Considering possible thermally-induced drifts in performances that result from self-heating effects as well as diurnal and seasonal temperature variations (which are more intense for outdoor light sources than indoor counterparts), we introduce a temperature-feedback technique for minimizing this drifting. Via this solution, we can obtain proper light emissions with finely tailored SPDs that comfort both vehicle drivers and pedestrians.

2. Relationship between key parameters

The Commission internationale de l’éclairage (CIE) has recommended a mesopic photometry system in the document (CIE 191:2010). According to this document, scotopic/photopic (S/P) ratio and $L_{mes}$ have been introduced as key mesopic parameters [16,17].

If the SPD of a light source $S(\lambda)$ is given, the S/P ratio is defined as the ratio of two luminous outputs evaluated by $V'(\lambda)$ and $V(\lambda)$ respectively. The explicit expression is written as

$$\frac{S}{P} = \frac{1699 \int_{380}^{780} S(\lambda) \cdot V'(\lambda) d\lambda}{683 \int_{380}^{780} S(\lambda) \cdot V(\lambda) d\lambda}.$$  \hspace{1cm} (1)

The S/P ratio is usually used for optimizing the mesopic vision because of its positive correlation with $L_{mes}$ under the same photopic luminance ($L_p$). Generally, higher values of S/P ratio indicate better perceived brightness as well as being more energy efficient [18].

The mesopic sensitivity curve $V_{mes}(\lambda)$, a linear combination of $V(\lambda)$ and $V'(\lambda)$, and $L_{mes}$ are defined as

$$V_{mes}(\lambda) = \frac{mV(\lambda) + (1-m)V'(\lambda)}{M(m)}, \quad \text{for} \ 0 \leq m \leq 1,$$

$$L_{mes} = \frac{683}{V_{mes}(\lambda)} \int_{380}^{780} V_{mes}(\lambda) S(\lambda) d\lambda,$$  \hspace{1cm} (2) (3)
where $m$ stands for a coefficient associated with observers’ adaptation state, $M(m)$ denotes a normalizing constant that ensures the maximum value of $V_{\text{mes}}(\lambda)$ to attain 1, and $V_{\text{mes}}(\lambda_0)$ represents the value of $V_{\text{mes}}(\lambda)$ at 555 nm [16].

Values of the adaptation coefficient $m$ and the mesopic luminance $L_{\text{mes}}$ can be obtained iteratively with equations below

$$m_0 = 0.5,$$

$$L_{\text{mes},n} = \frac{m_{(n-1)} + (S/P)(1-m_{(n-1)})(683/1699)}{m_{(n-1)} + (1-m_{(n-1)})(683/1699)} L_p,$$

$$m_n = 0.7670 + 0.3334\log_{10}(L_{\text{mes},n}) ,$$

and this calculation converges to final values in five or six iterations in most cases. According to Eqs. (4)-(6) [16], $L_{\text{mes}}$ depends not only on the $L_p$ of the stimulus (in practice, the mesopic background on which the detection target appears) but also on its S/P ratio. The SPDs would reach higher values of $L_{\text{mes}}$ if they possess higher S/P ratios with same $L_p$. With this tendency in mind, we intend to tailor overall SPDs for higher S/P ratios and, eventually, for higher values of $L_{\text{mes}}$.

3. Methodology and algorithm

A methodology named optical power ratio algorithm (OPRA) for obtaining overall SPDs of indoor light sources has been proposed in our previous work [12]. In this work, although it works well for optimizing SPDs to realize both decent mesopic parameters (high S/P ratio) and good color rendering index (CRI) at the same time, this methodology cannot solve the problem that color drifts are commonly observed due to environmental temperature variations. To eliminate the undesirable thermally-induced drift, we update the OPRA to a new version, namely OPRA-II, which takes temperature variations into account. According to OPRA-II, the relative SPD of overall output white light can be indicated as

$$R_i = \frac{P_i}{P_r + P_g + P_b + P_w}, \quad (i = r, g, b, w),$$

$$E_\lambda = R_r E_r(\lambda) + R_g E_g(\lambda) + R_b E_b(\lambda) + R_w E_w(\lambda),$$

where $R$, $P$ and $E(\lambda)$ denote the optical power ratio, optical power, and relative SPD which is normalized to the area under curves; subscripts “r”, “g”, “b” and “w” denote overall, red, green, blue, and white, respectively. With the aid of Eqs. (7) and (8), an overall SPD can be resolved into four SPDs from these individual chips by one unique power-ratio set, which corresponds to one unique duty-cycle set of PWM signals, and vice versa. Therefore, a bijective relationship is established between duty cycles and overall SPDs. In addition, at the same temperature, shapes of SPDs of four individual chips are independent of PWM duty cycles. Being benefited from these two facts, by simply changing optical power ratios, we can simulate all relative overall-SPDs of RGBW LEDs, and select those that possess proper CRIs as well as highest S/P at different CCTs (Fig. 2).
The process of optimization can be divided into five steps below.

Step I: Set optimization goals of mesopic parameters.

Step II: Measure SPDs of each LED chip respectively at a certain initial temperature ($T_i$). Each color is independently driven by several different duty-cycle PWM currents with a constant amplitude. Additionally, we identify the correlation between optical powers and duty cycles of each LED chip.

Step III: Enumerate all available relative overall SPDs by changing the optical power ratio of each RGBW chip.

Step IV: Calculate chromaticity coordinates for each overall SPD. If the chromaticity coordinate is accepted, then we calculate all other parameters concerning color qualities and mesopic vision, such as CRI and S/P ratio. Afterwards, we select the relative overall SPD that has highest mesopic parameters as well as proper color qualities for each CCT. Note that, optical powers of absolute overall SPDs with the same relative overall SPD will reach the maximum value when the largest duty cycle of individual chips equals 100%. In this situation, with the set of optical power of RGBW chips, the corresponding set of four duty cycles can be calculated via functions (obtained in step II) between optical powers and duty cycles. Next, we store all sets of duty cycles within the required CCT range.

Step V: Drive RGBW LEDs with PWM duty cycle at the operating temperature ($T_o$) that equals $T_i$, and adjust the mesopic luminous intensity by tuning the set of four duty cycles as a whole.

4. Simulation and experimental results

4.1 Optimization goals and hardware

The optimization in road lighting applications is aimed to primarily avoid collisions by improving the mesopic luminance, and to secondarily discern colors of objects that appear as road obstacles [14]. Therefore, goals are set to maximize S/P ratio for better detection performance and to assure $\text{CRI} \geq 70$ [5,6]. In addition, the CCT ranges from 2700 to 7500 K with $|\Delta u_r| \leq 0.005$.

The LEDs are solid-state devices and can be easily integrated into digital control systems, facilitating complex lighting programs such as varying intensity or spectral composition. In this article, we employ a system to evaluate the accuracy of the OPRA-II for optimizing mesopic parameters. It consists of the controller, the PWM current driver, and the RGBW LED (Fig. 3).
The controller can be any modules that can create PWM signal, and in this article we choose Texas Instruments CC2540 Bluetooth module as the controller. CC2540 can receive commands sent by a cell phone via an excellent RF transceiver and generate four PWM signals to control current drivers via an 8051 microcontroller unit. The MBI6661, an integrated circuit of the step-down DC/DC converter, can be regarded as a current source for LED chip, and is controlled by the PWM signal generated by CC2540.

The OPRA-II can be applied universally to any multiple-chip LED light sources, and Cree XLamp XM-L Color LED is adopted as an example of the RGBW LED in this section. Figure 4 presents instruments for the experiment. Each chip is driven by the 330 mA continues-wave current (duty cycle = 100%), and the temperature of the heat sink on which the RGBW LED is fixed is maintained at 75 °C ($T_i = 75 ^\circ C$), namely a typical operating temperature according to our experiences. Spectra and parameters of four LED chips, shown in Fig. 5(a) and Table 1, are measured by an integrating sphere (ISP-500) and an optical spectrometer (Spectro 320, Instrument Systems, Germany). Multiple measurements ensure a high stability of overall SPDs.

Then, we use a cell phone to change duty cycles of PWM currents to drive each chip and set up the relationship between optical powers and duty cycles of individual chip respectively [Fig. 5(b)]. Duty cycles of individual chips are denoted by $D_r$, $D_g$, $D_b$ and $D_w$. All R-squares reach 0.999, indicating a strong linearity that greatly simplifies the control of optical powers.
4.2 Results and discussion

According to the OPRA-II, we change values of $R_r$, $R_g$, $R_b$ and $R_w$ to simulate all possible relative overall SPDs, and choose those that possess maximum S/P ratios with CRI $\geq 70$ and CCTs ranging from 2700 to 7500 K. Then, we use corresponding PWM currents of each combination to drive individual LEDs when operating temperature $T_o$ equals 75 °C as $T_i$, and measure parameters. Data in Table 2 exhibit satisfactory agreements between measured and set values, with less than 2.06% relative errors, indicating high accuracies and practicalities of the OPRA-II.
The considerable similarity between set and measured values of CRI and S/P ratio is also shown in Fig. 6(a). Additionally, a positive correlation between S/P ratio and CCT is proved, and it indicates that bluish lights behave more efficiently than the reddish ones do in terms of the detection performance to avoid nighttime traffic accidents. In Fig. 6(b), $D_w$ is kept in the saturated level, while $D_g$ and $D_b$ apparently increase with CCT rising from 2700 to 4500 K. Moreover, because of the low luminous efficacy problem of the green LED (known as the "green gap") [19], $D_g$ is mostly maintained at high levels while $D_w$ and $D_r$ both decrease and $D_b$ increases steadily with CCT from 5000 to 7500 K.

### 4.3 Applications in the road lighting

In order to fulfill the road lighting standards in the USA [20,21] for the freeway (0.40 - 0.60 cd/m²), collector (0.40 - 0.80 cd/m²), and local road lighting (0.30 - 0.60 cd/m²) conditions, we choose the $L_p$ of 0.5 cd/m². Under such a circumstance, the optimized mesopic luminance $L_{mes}$ (shown in Fig. 7) can be calculated in different CCTs with measured S/P values in Table 2. It is obvious that the cool-white light (7500 K) possesses about 15.3% more $L_{mes}$ than the warm-white light (2700 K) for the purpose of achieving the same $L_p$. Therefore, except for some extreme situations such as in the fog (warm-white light has greater penetration in the fog), the cool-white light exhibits better performances for outdoor lighting. If S/P ratio is not optimized to the maximum value, the curve of $L_{mes}$ will drop entirely, and this dropping may cause the insufficient $L_{mes}$ for object detections of nighttime traffic.
4.4 Effects of the temperature

Color, electrical, and thermal properties of LED devices are highly dependent on one another [22], thus the operating temperature can cause the change of SPD, such as the drift of the peak wavelength. If we use PWM currents with duty cycles generated by OPRA-II at $T_i = 75$ °C [Fig. 6(b)] to drive the same RGWB LED at different heat-sink temperatures, $T_o = 50$ °C and $T_o = 25$ °C, experimental results cannot be consistent with set values any more (Table 3 and Table 4).
According to data from Table 2 to Table 4, we plot set values and measured values of CCT, CRI and S/P at 75 °C, 50 °C and 25 °C in Fig. 8, respectively. These results suggest that measured values of CCT, CRI and S/P cannot closely match set values if $T_o$ cannot be consistent with $T_i$. Therefore, $T_o$ and $T_i$ must remain the same in order to ensure the consistency between measured values and set values.

In practice, we can first generate and save all PWM duty cycles under several initial temperatures. For example, if the operating temperature $T_o$ is estimated to range from 80 °C to 120 °C, duty cycles for driving RGBW LEDs should be generated at every temperature step, such as 5°C, according to different requirements of accuracy. Therefore, nine groups of duty cycles are stored in controller (at $T_i = 80 °C, 85 °C, 90 °C, \ldots, \text{and } 120 °C$). Then, utilize the temperature detector integrated in the light source to obtain the exact operating temperature $T_o$ every certain time interval (such as ten minutes) and employ one of nine groups of duty cycles of which the $T_i$ is closest to the actual $T_o$. By such a feedback system, the overall output SPD of the outdoor light source can be practically ensured to meet optimization goals of mesopic vision and color qualities.

5. Conclusions

In this article, we propose the OPRA-II that further takes into consideration the temperature variation for driving actual light sources to meet requirements of the outdoor lighting. A RGBW-LED-based light source, of which SPDs can be readily tailored, has been accomplished. In addition, accuracy and practicality of the OPRA-II are proven by experimental results. Finally, we introduce a temperature-feedback adjustment technique to maintain mesopic parameters and color qualities under different operating temperatures. We believe that these outdoor light sources concerning mesopic vision will prosper in the near future.

Appendix

For the purpose of condensing the article, experimental results at $T_o = 50 °C$ and $T_o = 25 °C$ are listed in Table 3 and Table 4, respectively.

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<td>−5.97</td>
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Table 4. Experimental results (operating temperature $T_o = 25 \, ^\circ\text{C}$, initial temperature $T_i = 75 \, ^\circ\text{C}$)

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<td>2.000</td>
<td>2.140</td>
<td>2.262</td>
<td>2.364</td>
<td>2.452</td>
<td>2.541</td>
<td>2.599</td>
<td>2.656</td>
</tr>
<tr>
<td>Measured Error (%)</td>
<td>-8.33</td>
<td>-7.90</td>
<td>-6.61</td>
<td>-6.38</td>
<td>-5.57</td>
<td>-5.49</td>
<td>-5.48</td>
<td>-5.21</td>
<td>-5.76</td>
<td>-5.48</td>
<td>-5.41</td>
</tr>
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</table>

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