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Spectrally tunable light source based on light-emitting diodes for custom lighting solutions

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This study describes a novel spectral LED-based tunable light source used for customized lighting solutions, especially for the reconstruction of CIE (Commission Internationale de l'Éclairage) standard illuminants. The light source comprises 31 spectral bands ranging from 400 to 700 nm, an integrating cube and a control board with a 16-bit resolution. A minimization algorithm to calculate the weighting values for each channel was applied to reproduce illuminants with precision. The differences in spectral fitting and colorimetric parameters showed that the reconstructed spectra were comparable to the standard, especially for the D65, D50, A and E illuminants. Accurate results were also obtained for illuminants with narrow peaks such as fluorescents (F2 and F11) and a high-pressure sodium lamp (HP1). In conclusion, the developed spectral LED-based light source and the minimization algorithm are able to reproduce any CIE standard illuminants with a high spectral and colorimetric accuracy able to advance available custom lighting systems useful in the industry and other fields such as museum lighting.

Keywords: solid-state lighting, light-emitting diodes, CIE standard illuminants, minimization algorithm, customized lighting design, radiometry.

1. Introduction

The choice of a proper illumination with good colorimetric features is crucial in any industrial quality control process. Evaluations are usually performed under very specific conditions which require the use of CIE (Commission Internationale de l'Éclairage) standard illuminants [1]. To this end, companies such as X-Rite, BYK-Gardner and

VeriVide have developed lighting booths and panels based on traditional light sources and filters. Although these systems have good illuminance uniformity, luminous efficacy can often be low, especially when incandescent bulbs are used. Furthermore, they do not always reproduce all illuminants with enough spectral accuracy. Consequently, custom lighting systems are required for conventional visual tasks to improve accuracy, feasibility, ease of use and speed under different conditions of illumination. Other fields such as museum lighting [2–4], where the technical features of the light source must be precisely controlled, also demand custom lighting solutions.

One suggested approach consists of the combination of a unique type of light source and a liquid crystal (LC) panel so as to spectrally reshape the incoming light and simulate any kind of spectrum from its output [5, 6]. However, due to the transmittance properties of LC panels, the performance of these systems was considerably limited in spite of optimizing the distribution of the light.

Alternatively, the introduction of light emitting diodes (LEDs) [7] in the market has contributed to overcome most limitations of traditional light sources. LEDs are very efficient, present a long-life cycle, evolve constantly and are comparatively economical. Moreover, these diodes have a narrow spectral emission and, depending on the composition and the condition of the semiconducting material, they are available in several wavelength peaks over different spectral ranges: ultraviolet (UV), visible (VIS) and infrared (IR).

Another significant advantage of LEDs technology is the modulation of their emission as a function of the forward current. In the last decade, much research has been conducted on the development of tunable light sources based on LEDs [8–10]. The main goal has been to reproduce different illuminants, especially CIE standard illuminants, with high accuracy, flexibility and high luminous efficacy. FRYC *et al.* [8] proposed a spectrally tunable light source that used an algorithm for the spectral matching between the standard illuminants and those generated by the light source. This algorithm consisted of an iterative convergence procedure based on partial derivatives. However, even if the spectra generated were accurate, the computing process required too much time to calculate the weighting values for each LED. Recent studies [9, 10] have used minimization algorithms to avoid these lengthy convergence procedures. PARK *et al.* [9] developed a multispectral system that used a LED-based light source to match known spectral reflectances of a specific set of samples by choosing the proper combination of LEDs. On the other hand, MACKIEWICZ *et al.* [10] worked on a system constituted by a one-meter integrating sphere and six RS-5BTM spectrally programmable light sources manufactured by Gamma Scientific. Despite the good performance of their minimization algorithm, the number of spectral channels (different LEDs) was not enough to precisely match the real illuminants.

In this study we developed a spectral LED-based tunable light source for custom lighting solutions, especially for the reconstruction of CIE standard illuminants. It consisted of an integrating cube and a cluster with 31 types of LEDs. This system aimed

to obtain more accurate spectral reconstructions of the illuminants as well as to improve the uniformity of the field of illumination through the exploration of LEDs of different emissions and the use of a fast minimization algorithm. The advantages of this new light source are the larger number of LEDs, the practically negligible spectral shift of their peak wavelengths with applied current, and a low cost and easy-to-build integrating structure. Therefore, the main goal of this study was to assess the spectral reconstruction of CIE standard illuminants using the built light source.

2. Methods

2.1. Setup

The main component of the tunable light source developed was an integrating cube that included a LED-cluster (Figs. 1a and 1b). The LED-cluster was composed of 31 different types of LEDs with two units per each type. All of them had a peak wavelength within the VIS range (400 to 700 nm) with a mean full width at half maximum (FWHM) of 22.51 nm. The mean step between consecutive peak wavelengths along the whole spectral range was of 10.06 nm (Fig. 1c). The number of wavelengths was

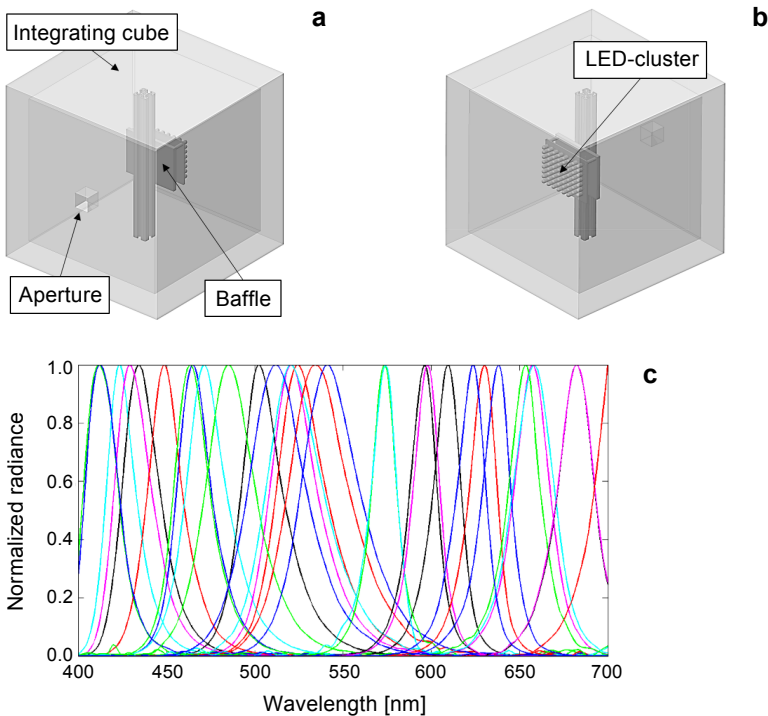


Fig. 1. Two views of the integrating cube containing the LED-cluster, front view (a), rear view (b), and the normalized radiance of the LEDs (c).

chosen in order to cover the range from 400 to 700 nm with a LED, each 10 nm approximately. This spectral characterization was performed with the Photo Research PR-655 telespectroradiometer.

The integrating cube contained the LED-cluster and guaranteed a good combination of the light emitted by different LEDs over the illuminated field. The dimensions of the cube were 20 cm×20 cm and it was coated with a white diffusing layer to achieve high reflectivity at all wavelengths. A baffle was also included to avoid direct light from the LED-cluster reaching an aperture of 2 cm×2 cm. This reduced size was chosen to guarantee a high integration of the light coming from each LED with the limited number of LEDs used. The intensity of the LEDs was regulated via a customized control board with a 16-bit depth of resolution (65536 digital steps), which achieved a very precise control of the emission of each LED independently. A previous study [11] demonstrated that a 100-digital step resolution was not enough to achieve good accuracy in terms of spectral reconstruction.

2.2. Algorithm

Similarly to previous studies [9, 10], the function chosen for the spectral reconstruction was a minimization algorithm based on an interior-point method [12, 13]. The goal of this algorithm is to diminish the distance between the targeted spectrum (CIE standard illuminant) and that achieved with the light source under the followings conditions:

$$L_i(\lambda)w_i = I(\lambda), \quad w_i \geq 0 \quad (1)$$

where $I(\lambda)$ is the spectral radiance of the CIE illuminant, w_i denotes the weighting values for i -th LED and $L_i(\lambda)$ is the spectral radiance emitted by each LED. This expression forced all values of the weighting matrix w_i to be nonnegative.

This algorithm was implemented through the Matlab function *fmincon*, which attempts to find a constrained minimum of a scalar function of one or several variables as follows:

$$\min_w [f(w)] = \sum_{i=1}^{31} [I(\lambda) - w_i L_i(\lambda)]^2 \quad (2)$$

The interior-point method searches for the 31 weighting values (w_i) to be applied to each one of the 31 spectral channels ($L_i(\lambda)$) that composed the proposed light source to resemble the standard illuminant. The algorithm stops when it finds a minimum value or reaches the established maximum number of iterations. Namely, $I(\lambda)$ is a $m \times 1$ vector representing the m sampling points over the VIS spectrum ($m = 301$, from 400 to 700 nm in steps of 1 nm) of the real illuminant; $L_i(\lambda)$ is a $m \times n$ matrix that indicates the n spectra of the LEDs sampled (31) at m points (301); w_i is a $n \times 1$ vector containing the 31 weighting values. In other words, one vector with the 31 weighting values was generated for each reconstructed standard illuminant. As previously mentioned, each spectral channel is composed of two equal LEDs controlled under the same conditions.

Prior to the application of the former expression, the following steps must be executed: firstly, independent measurements of the spectral radiance of each pair of

LEDs at its maximum emission must be carried out as an input for the algorithm; secondly, the spectral radiance of the illuminant is normalized considering the maximum emission of the LEDs; thirdly, the normalized spectral radiance of the illuminants and the maximum spectral radiance of the LEDs are introduced to the algorithm in order to compute the weighting values for each LED; finally, the matrix of weighting values provides values from 0 to 65535 to make use of the whole dynamic range of the 16-bit controller. These are, respectively, the lower and upper limits for the minimization carried out by means of the interior-point algorithm.

The algorithm assumes that the LEDs emit the same relative profile at different weighting values, *i.e.*, it considers that no spectral shift of the wavelength peak exists because of the input forward current. In a previously published study [14], a spectral shift less than 4 nm was found for every LED and it was therefore considered negligible. Moreover, the algorithm considers that the radiance emitted at a specific weighting value is constant over time. This is further discussed in Section 3.

2.3. Measurements

Before carrying out the reconstructions of CIE standard illuminants with the aforementioned setup, the temporal stability of the LEDs was analyzed since the algorithm used assumed that no temporal variation in their emission existed. To this end, three different digital values were tested for each LED to encompass most of the dynamic range. They corresponded to the value with the minimum emission detectable by telespectroradiometer (between 1000 and 2000 depending on the LED), 5000 and 65535. Smaller weighting values required special attention as LEDs are more unstable at lower emissions. In general, six measurements of radiance ($\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2}$) were taken from 0 to 25 min every 5 min.

Once the stability of LEDs was established, the spectra of seven CIE standard illuminants (D65, D50, A, E, F2, F11 and HP1) were reconstructed using the tunable light source developed. The simulated and the experimental spectra of all illuminants were obtained. The simulated spectra correspond to those balanced by the weighting values computed by the algorithm and taking into account the spectra of the LEDs at their maximum emission (maximum digital level: 65535) and the normalized CIE standard illuminants. With regard to the experimental spectra, they refer to those directly measured from the light source once the weighting values were applied to each spectral channel and all LEDs were turned on simultaneously to generate each specific illuminant. The comparison between the simulated and experimental spectra allowed the evaluation of the accuracy of the light source when reproducing the spectra computed by the algorithm.

In this study, the following parameters were used to analyze the differences between spectra: the correlated color temperature (CCT) [15], the color rendering indexes (R_a and R_b , mean of the color rendering index from the first 8 and 14 Munsell samples, respectively) [16], the chromaticity coordinates CIE- xy [15], the goodness-of-fit coefficient (GFC) [17, 18], the mean absolute error (MAE) [19] and the root-mean-square error (RMSE) [19, 20]. The colorimetric parameters were computed by means of

the software CIE109, which is based on the Technical Report CIE 109-1994 [21]. The equations that define the fitting parameters (MAE, RMSE and GFC) are:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |I(\lambda_i) - R(\lambda_i)| \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n [I(\lambda_i) - R(\lambda_i)]^2} \quad (4)$$

$$\text{GFC} = \frac{\left| \sum_{i=1}^n I(\lambda_i) R(\lambda_i) \right|}{\left| \sum_{i=1}^n [I(\lambda_i)]^2 \right|^{1/2} \left| \sum_{i=1}^n [R(\lambda_i)]^2 \right|^{1/2}} \quad (5)$$

where n corresponds to the 301 sampled points of each spectrum, $I(\lambda_i)$ is the spectrum of the standard illuminant and $R(\lambda_i)$ is the reconstructed spectrum (previous $w_i L_i(\lambda)$).

The selection of these three fitting parameters was based on the different information they provide, resulting in a very complete fitting assessment. The MAE and the RMSE are metrics in absolute terms of the differences among two sets (spectra in this case). However, as in the RMSE each term influences in proportion to its square, larger errors have a greater influence on the total square error. Comparing it with the MAE, it is possible to know if the larger values of RMSE are due to generalized large errors or if they are due to a few errors larger than MAEs. On the other hand, the GFC is a relative measure between 0 and 1 based on the Schwartz inequality commonly used when comparing spectra and, especially, color differences [17, 18]. According to the scale commonly linked to this parameter [17], a $\text{GFC} \geq 0.995$ is considered to be “colorimetrically accurate”, a $\text{GFC} \geq 0.999$ “good spectral fitting” and a $\text{GFC} \geq 0.9999$ “excellent spectral fitting”.

Apart from these parameters, the reconstructions of daylight illuminants (D65 and D50) were assessed by the metamerism index (MI), which is divided in VIS and UV range [22]. MI is calculated as the mean of the individual color differences between metameric samples of the same pair, both under the same test source (the same reconstructed illuminant in the case of this study). The VIS range evaluation is performed for five metameric pairs while the UV range employs only three pairs. The pairs used in the MI_{UV} are different from the five used in the MI_{VIS} and each one contains one fluorescent sample. The color difference formula applied was the CIE 1976 $L^*a^*b^*$ color difference [15].

3. Results

3.1. Temporal stability of LEDs

A preliminary test was conducted to evaluate the temporal behavior of the LEDs at different digital values: 1000–2000, 5000 and 65535. As previously stated, six measurements of radiance ($\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2}$) were taken from 0 to 25 min every 5 min.

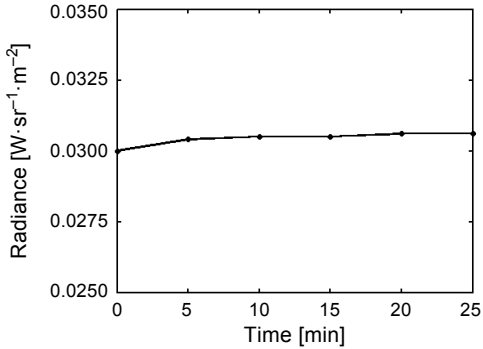


Fig. 2. Temporal stabilization of LED22 at the digital value of 65535.

For the lowest weighting values larger variations were obtained, reaching a maximum 7.14% fluctuation, whereas for 5000 and 65535 they were 4.13% and 1.73%, respectively. Most of these variations were registered during the first 5 min, and a longer time did not guarantee a significant decrease of the fluctuations. Figure 2 represents the total radiance over time of a LED with a peak wavelength of 632 nm (LED22) at a digital value of 65535 as representative example of the temporal behavior of

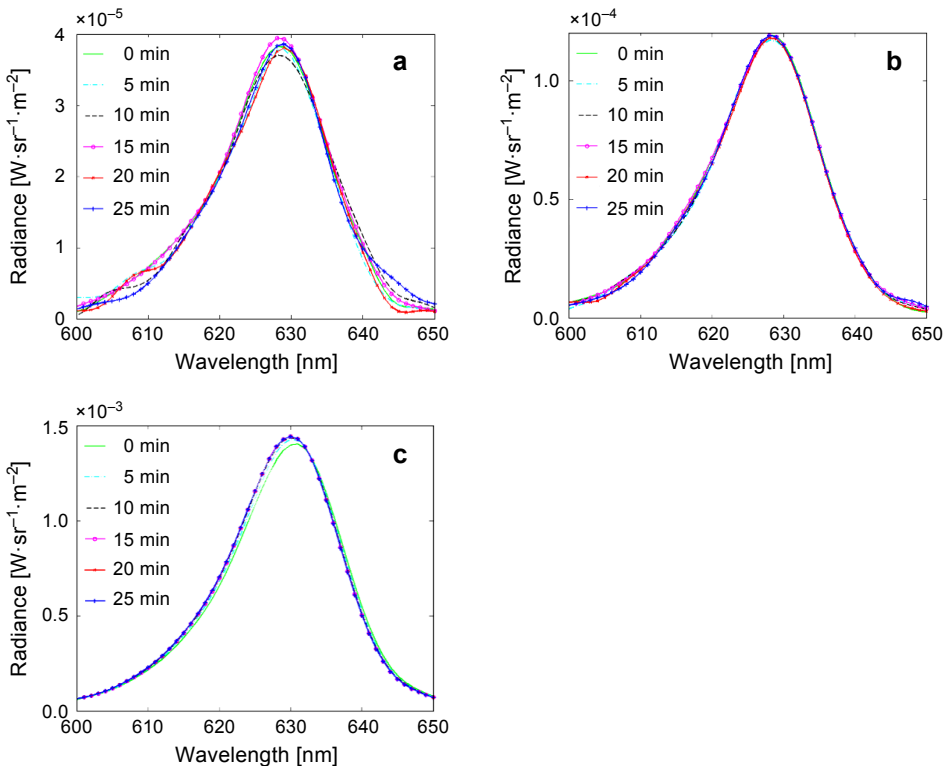


Fig. 3. Temporal behavior of LED22 at different digital values: 1600 (a), 5000 (b), and 65535 (c).

the whole cluster of LEDs. It can be seen in this figure that after 5 min the curve is almost flat while in other cases, the radiance was completely stable after switching on the light source. Accordingly, 5 min were chosen as the time needed to stabilize all the LEDs and no measurements were taken before.

Besides radiance emission, wavelength changes over time were also analyzed during the first 25 min every 5 min. A shift smaller than 4 nm was registered for all LEDs and it was thus considered negligible. As an example, Fig. 3 shows the spectral radiance over time of the same LED used in the previous evaluation.

3.2. Spectral reconstructions of CIE standard illuminants

Figure 4 shows the theoretical and the corresponding simulated and experimental spectra for all seven CIE standard illuminants. In addition, Table 1 shows the corre-

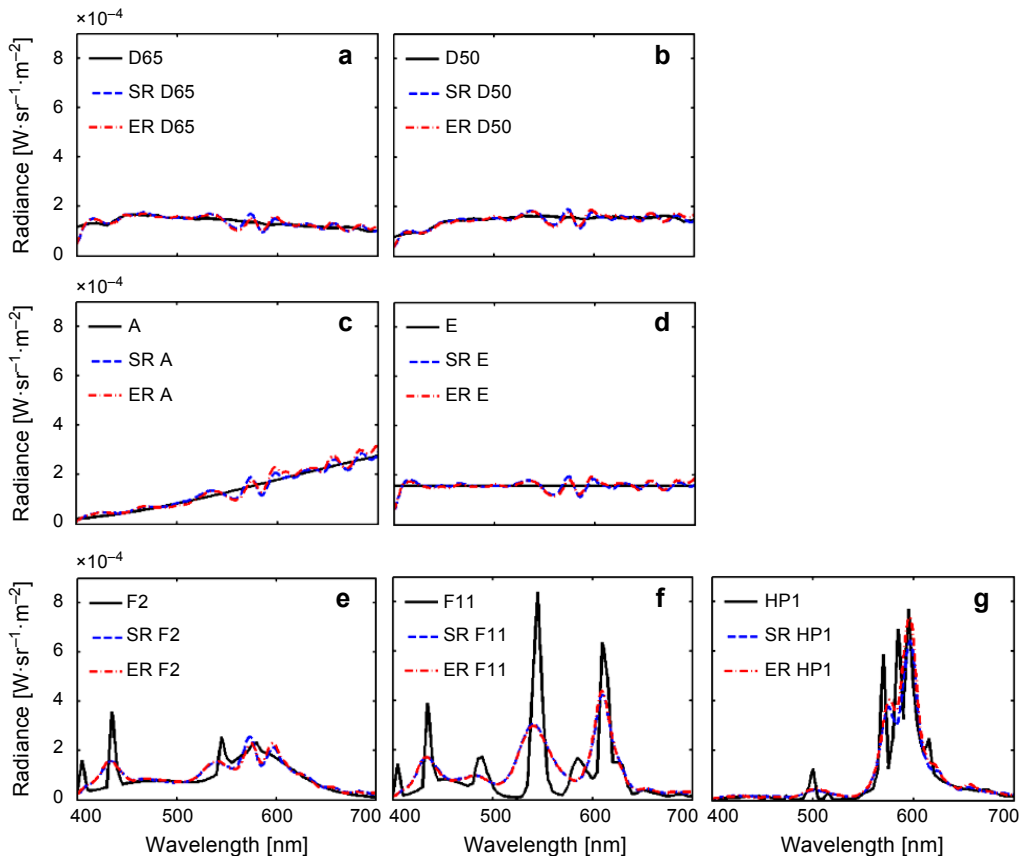


Fig. 4. Spectral reconstruction of the CIE standard illuminants D65 (a), D50 (b), A (c), E (d), F2 (e), F11 (f), and HP1 (g). SR – the simulated reconstruction obtained taking into account the weighting values given by the algorithm and the spectral emission of each LED measured individually at the maximum digital level (65535); ER – the experimental reconstruction measured when all LEDs are emitting at the same time with the corresponding weighting values.

Table 1. CCT, R_a , R_b , CIE- xy , GFC, MAE and RMSE parameters (SR – simulated reconstruction, ER – experimental reconstruction).

| | CCT [K] | R_a | R_b | x | y | GFC | MAE [W·sr ⁻¹ ·m ⁻²] | RMSE [W·sr ⁻¹ ·m ⁻²] |
|-----|------------|-------|-------|-------|--------|--------|---|--|
| CIE | D65 | 6505 | 99.55 | 99.57 | 0.3127 | 0.3293 | – | – |
| | D50 | 5008 | 99.56 | 99.58 | 0.3457 | 0.3585 | – | – |
| | A | 2864 | 99.47 | 99.56 | 0.4472 | 0.4077 | – | – |
| | E | 5457 | 95.31 | 93.58 | 0.3333 | 0.3338 | – | – |
| | F2 | 4230 | 64 | 50.61 | 0.3721 | 0.3751 | – | – |
| | F11 | 4000 | 83 | 73.26 | 0.3805 | 0.3769 | – | – |
| | HP1 | 1959 | 8 | -7.72 | 0.5330 | 0.4150 | – | – |
| SR | D65 | 6589 | 97.46 | 96.82 | 0.3114 | 0.3275 | 0.9945 | 1.02×10^{-5} |
| | D50 | 5062 | 97.71 | 97.28 | 0.3439 | 0.3571 | 0.9956 | 9.66×10^{-6} |
| | A | 2931 | 95.89 | 94.73 | 0.4388 | 0.3995 | 0.9951 | 1.20×10^{-5} |
| | E | 5550 | 92.83 | 90.73 | 0.3313 | 0.3320 | 0.9934 | 1.19×10^{-5} |
| | F2 | 4386 | 69.03 | 58.44 | 0.3657 | 0.3703 | 0.9509 | 2.37×10^{-5} |
| | F11 | 4264 | 84.76 | 76.93 | 0.3734 | 0.3874 | 0.8273 | 6.55×10^{-5} |
| | HP1 | 2014 | 15.34 | -0.23 | 0.5308 | 0.4212 | 0.9432 | 2.83×10^{-5} |
| ER | D65 | 6472 | 94.69 | 93.20 | 0.3138 | 0.3259 | 0.9939 | 1.11×10^{-5} |
| | D50 | 4891 | 96.59 | 95.77 | 0.3486 | 0.3577 | 0.9952 | 1.06×10^{-5} |
| | A | 2715 | 94.91 | 93.76 | 0.4494 | 0.3997 | 0.9939 | 1.53×10^{-5} |
| | E | 5321 | 91.53 | 88.86 | 0.3362 | 0.3330 | 0.9934 | 1.27×10^{-5} |
| | F2 | 4337 | 70.91 | 60.73 | 0.3667 | 0.3680 | 0.9507 | 2.38×10^{-5} |
| | F11 | 4122 | 85.02 | 77.02 | 0.3786 | 0.3870 | 0.8241 | 6.57×10^{-5} |
| | HP1 | 1979 | 13.61 | -2.12 | 0.5371 | 0.4236 | 0.9450 | 3.08×10^{-5} |

sponding CCT (K), R_a , R_b , CIE- xy , GFC, MAE (W·sr⁻¹·m⁻²) and RMSE (W·sr⁻¹·m⁻²) values. The parameters of comparison (GFC, MAE and RMSE) refer to the values of CIE standard illuminants.

In general, the results suggest that for most standard illuminants the LED-based tunable light source together with the minimization algorithm provides good reconstructions. In all cases, simulated and experimental spectra were very similar, which reinforce the suitability of the algorithm's performance. The GFC of D65, D50, A, and E were greater than 0.99. Consequently to the description in Section 2.3 of the GFC scale, the accuracy of the fitting for D65, D50, A, and E illuminants could be considered colorimetrically acceptable. In the case of illuminants F2 and HP1, the GFC was above 0.9, whereas it was above 0.82 for illuminant F11. These results can be explained by the narrow peaks included in these illuminants, which are more difficult to reproduce. In the case of the experimental reconstructions, the illuminance levels for all the reconstructed standard illuminants were between 30 and 40 lux.

On the other hand, MAEs and RMSEs also proved the good fitting of the spectra. The values of MAE were, at least, one order of magnitude below the spectral radiance of the illuminants because it took values of up to 0.8 mW·sr⁻¹·m⁻², approximately, and

MAEs that were within a range of 9.66×10^{-3} and $6.57 \times 10^{-2} \text{ mW} \cdot \text{sr}^{-1} \cdot \text{m}^{-2}$. The higher values of the RMSE were a consequence of the less successful fitting in the green range of the spectrum as this parameter grows significantly due to values larger than the mean. Regarding the color metrics, the CCT, R_a , R_b and CIE- xy of the reconstructed spectra were very close to those of the standard illuminants. Specifically, as most of the R_a are very close to 100, there would not be noticeable color differences between the reconstructions and the standard illuminants [16].

The values for the MI concerning the particular evaluation of daylight reconstructions (D65 and D50) are shown in Table 2. These indexes revealed that the developed tunable light source simulated D65 and D50 standard illuminants with a very high accuracy in this range of the electromagnetic spectrum. In all cases, the results were in the two highest categories (A and B). In contrast, MI in the UV range was classified as category E.

T a b l e 2. Metamerism index (MI) for the simulated (SR) and experimental (ER) reconstructions of the CIE standard illuminants D65 and D50.

| | | MI_{VIS} | MI_{UV} | Category |
|----|-----|-------------------|------------------|----------|
| SR | D65 | 0.15 | 4.69 | AE |
| | D50 | 0.10 | 3.19 | AE |
| ER | D65 | 0.31 | 4.66 | BE |
| | D50 | 0.18 | 3.15 | AE |

With regard to the technical limitations of the light source, the two main reasons why the reconstructions did not perfectly match the standard spectra were the large variability of radiances among LEDs and the worse performance of green LEDs. Indeed, the radiance of the LEDs used varied significantly along the spectral range due to technological limitations, *i.e.*, two LEDs that should emit the same amount of energy to match the target illuminant had to be weighted very differently. In this case, some of the LEDs worked at very low intensities, where their performance is worse and difficult to predict. As a consequence of this, the total radiance of the reconstructed illuminants was low even though the spectral matching was accurate. Figure 5 shows the variability of the weighting values generated by the algorithm in order to simulate illuminant D65. The graphic shows that the difference in terms of weighting values is large, even for an illuminant whose spectrum does not exhibit such amount of variation. In other words, although low power LEDs worked at their maximum emission (large weighting values in Fig. 5), their contributions in radiance were poor. Accordingly, the emission of LEDs with the greatest power had to be decreased to reach a level closer to lower power LEDs in order to reconstruct illuminants with an almost flat spectrum (as the D65). In relation to the worse results along the green region of the electromagnetic spectrum, *i.e.*, from 500 to 600 nm, it was caused by limitations of the solid-state technology, which still has not developed LEDs with high power at a reasonable price.

All the former results show the suitability of the LED-based tunable light source to precisely reconstruct the spectrum of the CIE standard illuminants, especially day-

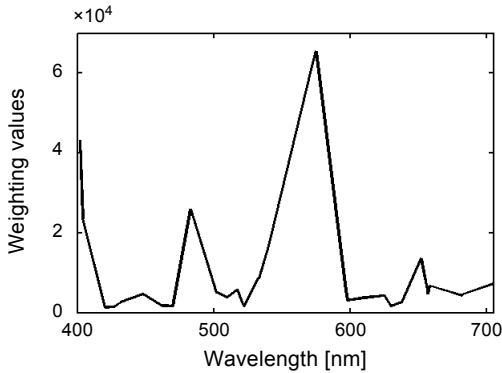


Fig. 5. Weighting values of each LED for the reconstruction of the CIE standard illuminant D65. On the x-axis, the peak wavelength of each LED is represented.

light illuminants, such as the D65 and D50, A and E with a greater spectral smoothness of their spectrum. It is also worth noting the possibility of resembling other illuminants such as fluorescents (F2 and F11) and a high-pressure sodium lamp (HP1), which have sharpest spectral peaks.

4. Conclusions

A LED-based spectrally tunable light source with 31 channels in the VIS range (400 to 700 nm) was purpose-built for this study. This light source was built within an integrating cube in order to reach very high accuracy levels. Additionally, a minimization algorithm able to reproduce the spectrum of CIE standard illuminants was developed. The results obtained showed an excellent correlation between the simulated predicted spectra provided by the algorithm and the spectra experimentally measured. However, the algorithm did not generate a better fitting due to the difference in radiometric power among LEDs. The fitting was worse in the green region of the spectrum, especially from 500 to 600 nm, as a consequence of the current status of LED technology in this range, with less powerful diodes. This accuracy will improve by increasing the number of LEDs, especially at these wavelengths. Nonetheless, the algorithm can be considered a solid and applicable method to any set of quasi-monochromatic light sources such as LEDs, OLEDs (organic LEDs), AMOLEDs (active matrix OLEDs) or any other future solid-state lighting technology.

Although the fitting technique has been employed by other authors [9, 10], the high spectral density (31 LEDs from 400 to 700 nm) and the small spectral shift of LEDs' peak wavelengths (≤ 4 nm) have a significant impact on the use of this algorithm. The study also showed the potential of the new tunable light source in reproducing certain illuminants such as the sodium lamp, which cannot generally be matched by using other existing conventional lighting booths. Concerning the evaluation of daylight reconstructions, MI_{VIS} reached category A, the uppermost classification. This was a result of the optimization of the proposed light source for the reconstruction of standard

illuminants in the VIS region, where they are mostly used. MI_{UV} showed category E, which means that fluorescent samples evaluated under the developed light source would present more differences in comparison with the use of D50 and D65 CIE standard illuminants than in the VIS range.

The generation of customized lighting, beyond the reconstruction of standard illuminants, is also part of the huge potential of this device because of the enormous amount of fields where it can be implemented such as museum lighting, quality control of many industries (automotive, graphic arts, *etc.*), and in general lighting for homes and public buildings.

Future studies will focus on improving the proposed spectrally tunable light source in order to enlarge the illumination field since it is currently limited by the size of the aperture, to increase the total radiance of the reconstructed illuminants and also on the minimization of the current light source for lighting applications, both for diffuse and directional uses.

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