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Spectral LED-Based Tuneable Light Source for the Reconstruction of CIE Standard Illuminants

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Abstract. The technological fields where solid-state lighting can be applied are constantly growing. In relation to this topic, we built a spectral LED-based tuneable light source for the reconstruction of CIE standard illuminants. This light source consists of 31 spectral channels from 400nm to 700nm, an integrating cube and a control board with 16 bit resolution. Moreover, a minimization routine was developed to calculate the weighting values per channel for reproducing standard illuminants. The differences in colorimetric and fitting parameters between standard spectra and the theoretical and experimental ones, showed that the reconstructed spectra were very similar to the standard ones, specially for the D65 and A illuminants. However, there was a certain mismatching from 500nm to 600nm due to the lack of LEDs in this region. In conclusion, the developed LED-based light source and minimization routine are able to reproduce CIE standard illuminants with high accuracy.

Keywords: Solid-state lighting, reconstruction of CIE standard illuminants, minimization routine.

1 Introduction

Choosing the proper illumination for an experiment or an industrial test is not an easy task and must obey specific international standards. Furthermore, the use of more than one light source is sometimes needed. Due to that, illumination systems that contain different light sources (xenon, tungsten, fluorescent, etc.) and filters resembling CIE standard illuminants are nowadays available, such as lighting booths or panels [1], [2].

Nevertheless, they usually employ different light sources to simulate the illuminants [3], which implies that an accurate design is needed to achieve a uniform illumination all over the sample. In addition, other systems that contain spectral integrators which are based on liquid-crystal displays (LCD) have also been

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developed with the aim of simulating specific spectra [4] [5]. However, due to the transmittance of LCDs, the performance of these instruments is considerably limited in spite of optimizing the distribution of the light [5].

With the aim of bringing a new approach to this topic, illumination systems based on LEDs have been developed in the last few years [6], [7], [8], [9]. The main advantage of this technology lays on the fact that it allows reproducing different illuminants with high flexibility and with only one light source. Moreover, LEDs are very efficient, have a long-life cycle, are in constant evolution and they are also relatively low cost components. Regarding the computational part, recent approaches apply minimization methods in order to match as maximum as possible the generated spectrum by the LEDs with that of the illuminants [7], [10]. These methods started to be used as an alternative to lengthy convergence procedures [6].

Our contribution to this field is focused on the spectral reconstruction of CIE standard illuminants by means of a novel spectrally tuneable LED-based light source with high spectral resolution that uses an integrating cube to achieve an uniform field of illumination over the sample and a more precise LED driver control than the previous one [11]. In this work, apart from computer simulations that were also included in previous works [11], [12], real spectral reconstructions (measured spectra) are presented.

2 Methods

2.1 Setup

The spectral LED-based tuneable source is composed by a LED cluster located inside an integrating cube . The LED cluster (Fig. 1) contains 31 types of LEDs with different spectral emission in the visible range (Fig. 2).

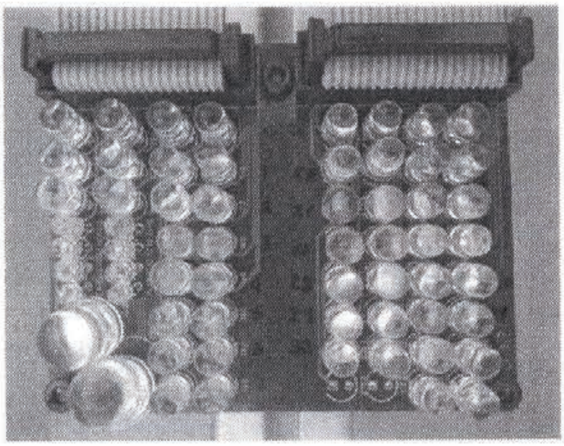

Fig. 1. LED cluster

For each type of LED, two units are included in the prototype. Peak wavelengths are spread between 400nm and 700nm, with a mean gap of 10.06nm and a mean FWHM of 22.51nm (This spectral characterization was performed by the using the PR-655 telespectroradiometer of Photo Research, Inc.).

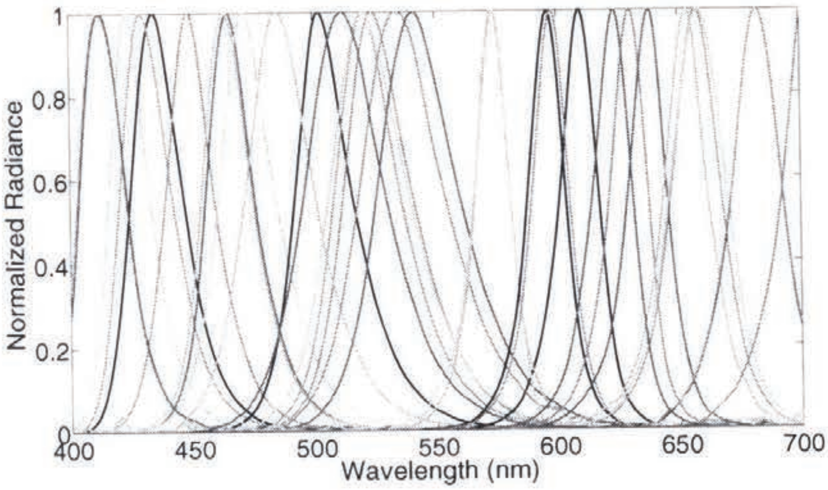

Fig. 2. Spectral power distribution with normalized spectral radiance

An integrating cube containing the LED cluster in the center was built with the purpose of combining the light of the different LEDs, for obtaining a uniform field of illumination for all wavelengths over an squared aperture of 2cmx2cm (Fig.3). The cube dimensions are 20cmx20cm (side) and a white diffuser paint coating was used to achieve high reflectivity along the whole spectral range. A baffle was also included to avoid direct light of the LED cluster reaching the aperture. Similar approaches with excellent results [11], [12] had been already proposed by the research group as a means of generating a field with uniform illumination[13].

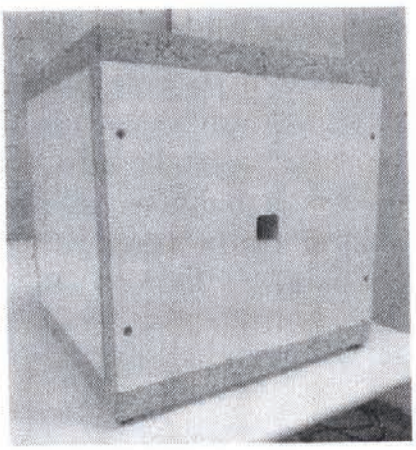

Fig. 3. Integrating cube

Emission of LEDs is controlled with a driver and a control board of 16 bit resolution, which offers a very precise control of the emission of each LED independently.

A previous prototype had a control board [11], [12] with only 7 bit resolution (100 steps), which limited both the potential of the diodes and the performance of the routine. With the new control board the emission can be controlled by using 65536 steps, thus offering resolution enough for precise spectral matching.

2.2 Algorithm

In order to reconstruct several CIE standard illuminants by means of the described setup, a minimization routine was developed. The algorithm diminishes the distance between the targeted spectrum (CIE standard illuminant) and the one achieved with the LED-based light source. This algorithm is based on the Matlab (version 7.11) function *fmincon*:

$$\psi(w) = \sum_{i=400}^{700} (I_i - wL_i)^2 \tag{1}$$

where I_i represents the spectral radiance of the CIE illuminant, L_i is the spectral radiance emitted by the LEDs and w denotes the weighting values. The function computes the weighting values for each spectral channel (individual LED) to resemble the target CIE illuminant.

Before applying this expression, some steps must be executed. First, the spectral radiance of each LED is measured independently at its maximum emission, which serves as input for the algorithm. After that, the spectral radiance of the illuminant is normalised taking into account the maximum emission of the LEDs. Next, the normalised spectral radiance of the illuminants and the maximum spectral radiance of the LEDs are introduced in the routine to compute the weighting values for each of them. These values range from 0 to 65535 as 16 bit resolution are used, as mentioned above. The routine assumes that the LEDs emit the same relative profile at different weighting values and that their emission is linear. Fig. 4 shows the spectral emission of the LED06 ($\lambda_p = 464$nm) at different weighting values as well as the linearity of its emission in terms of radiance, which confirms the validity of the former assumptions. This was also tested with other LEDs and none of them exhibited any spectral shift or, at least, it was lower than 4nm (spectral resolution of the telespectroradiometer). In consequence, it was not considered in the algorithm used. However, despite Mackiewicz et al. [7] also employed a minimization routine, they had to take into consideration the spectral shift since the peak wavelength of their light source showed a variation of almost 20nm.

The spectra of the CIE standard illuminants were later compared with the theoretical spectrum calculated by the routine, which weights the maximum emission of the LEDs. In addition, the CIE standard spectra were compared with the ones experimentally measured by switching all LEDs on at the same time with the corresponding weighting values, in order to generate each specific illuminant.

Finally, in order to analyse the differences between spectra, the following parameters were used: the correlated colour temperature (CCT), the colour rendering indexes (Ra and Rb), the chromaticity coordinates CIE-xy, CIELAB colour

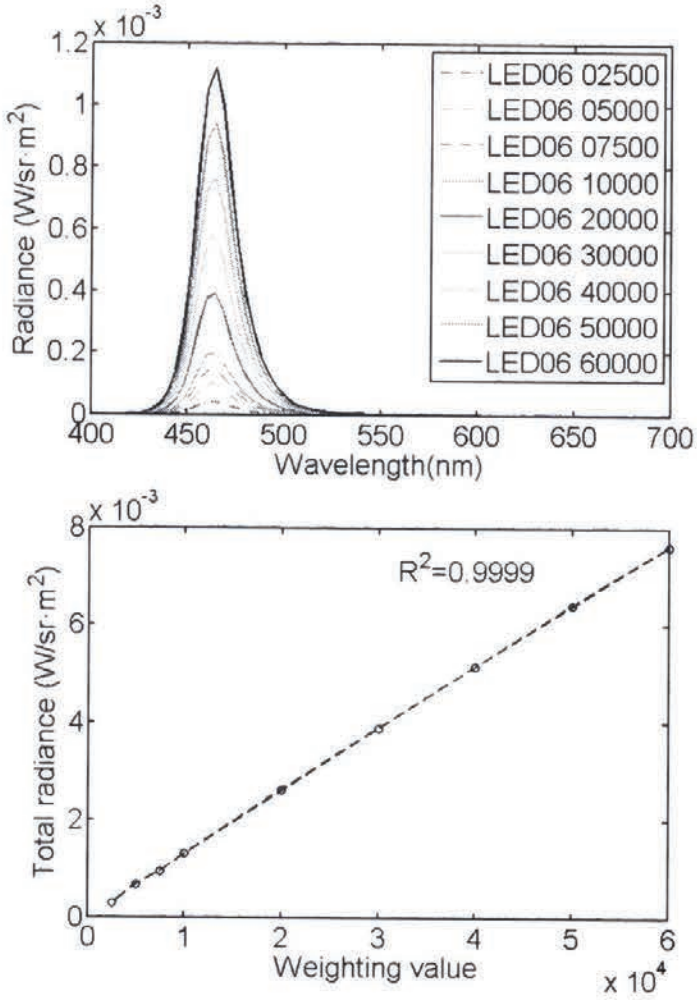

Fig. 4. Spectral emission of the LED06 (λ_p = 464nm) at different weighting values (top). Linearity of the radiance with respect to the same weighting values, from 2500 to 60000 (bottom).

difference (ΔE), the goodness-of-fit coefficient (GFC), the mean absolute error (MAE) and the root-mean-square error (RMSE).

3 Results and Discussion

Three CIE standard illuminants were simulated: D65, A and F2. Fig. 5 shows the comparison between the standard spectra and the theoretical and experimental ones generated by the routine and measured after weighting each LED, respectively. In addition, in Table 1, the CCT (K), Ra, Rb, CIE-xy, ΔE, GFC, MAE ($W/sr.m^2$) and RMSE ($W/sr.m^2$) values for the three illuminants are shown.

Regarding the results obtained, two statements can be made;

On one hand, the minimization routine achieved a quite good fitting along the whole spectral range with the exception from 500nm to 600nm, and specially for the D65 and A illuminants. In these cases, the GFC was greater than 0.99, the MAE was less than $0.04 mW/sr.m^2$ and the RMSE was under $5 mW/sr.m^2$.

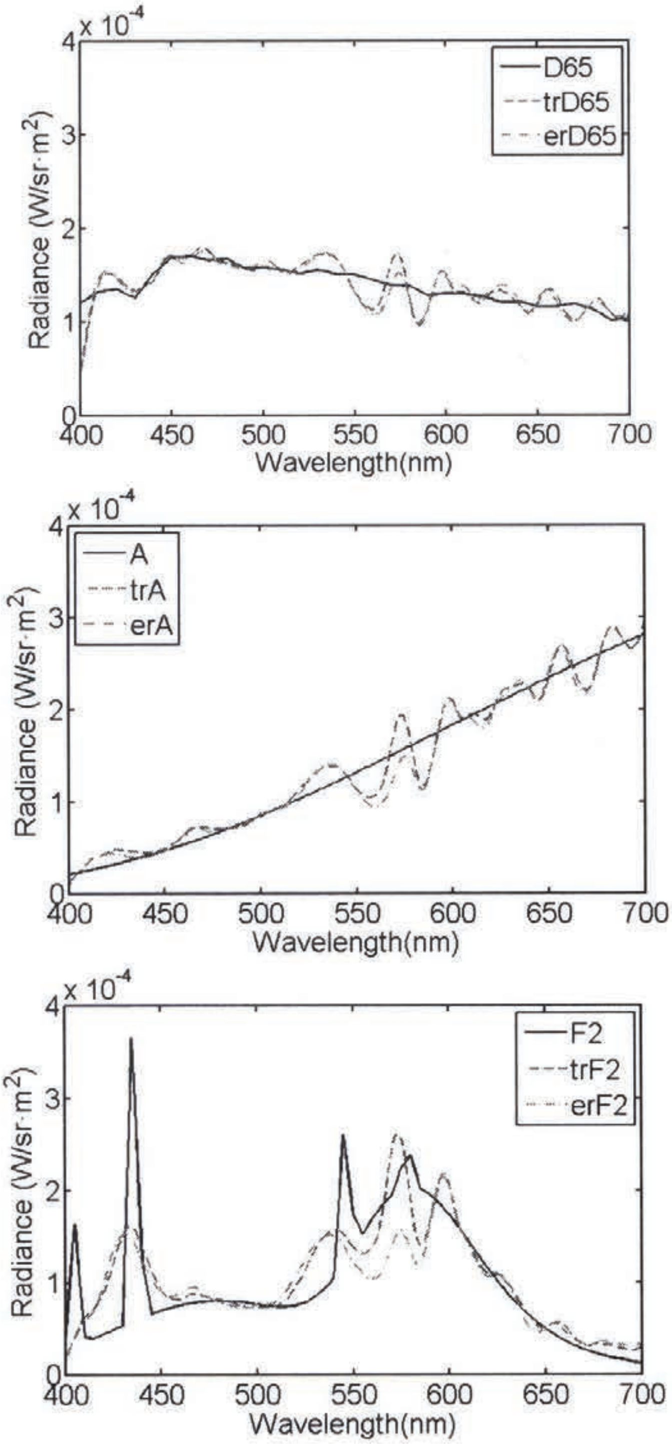

Fig. 5. Spectral reconstructions of the CIE standard illuminant D65, A and F2 (tr = theoretical reconstruction; er = experimental reconstruction)

In other words, these values of MAE mean that the differences between the theoretical spectra and the standard ones were very small in relation to the spectral radiance values. The higher values of the RMSE were a consequence of the worse fitting in the green range. The rising of this parameter with respect to the MAE can be explained by the fact that some values at specific wavelengths were larger than mean. Concerning the behaviour of the routine between 500nm and 600nm, it was not a computational problem, as it can be proved that it is a limitation of solid-state technology: in general, LEDs in this region have lower radiance than in the rest of the visible spectrum.

Table 1. CCT(K), Ra, Rb, CIE-xy, ΔE, GFC, MAE ($W/sr.m^2$) and RMSE ($W/sr.m^2$) parameters (MRT = Minimization Routine - Theoretical; MRE = Minimization Routine - Experimental)

	CIE			MRT			MRE		
	D65	A	F2	D65	A	F2	D65	A	F2
CCT	6505	2864	4224	6600	2931	4392	6578	2889	4651
Ra	99.55	99.47	62.79	97.40	95.71	69.14	93.96	90.41	81.41
Rb	99.50	99.24	50.57	96.76	94.54	58.56	92.29	87.88	73.97
x	0.3127	0.4472	0.3721	0.3112	0.4389	0.3654	0.3119	0.4402	0.3552
y	0.3293	0.4077	0.3752	0.3274	0.3997	0.3702	0.3253	0.3971	0.3562
ΔE	-	-	-	0.01	0.02	0.06	0.02	0.04	0.12
GFC	-	-	-	0.9943	0.9948	0.9503	0.9944	0.9936	0.9272
MAE	-	-	-	1.06E-05	1.25E-05	2.44E-05	1.09E-05	1.29E-05	3.07E-05
RMSE	-	-	-	1.51E-03	1.64E-03	3.73E-03	1.49E-03	1.80E-03	4.51E-03

The colorimetric parameters also reflected the good performance of the algorithm. The CCT, Ra, Rb and CIE-xy of the theoretical reconstruction were very close to the ones of the standard illuminants as ΔE confirmed. Colour differences were smaller than 1, which involves that the human eye would not be able to distinguish between the standard illuminants and the generated by the algorithm.

On the other hand, the new LED-based light source reproduced very precisely the spectra calculated by the routine. The colorimetric parameters as well as the fitting values were extremely similar to the theoretical ones. Consequently, the spectra reproduced experimentally, for the human eye, would look exactly equal to the CIE standard illuminants.

In general, the reconstructions for the D65 and A illuminants are more accurate than for the F2. This fact can be justified by the greater smoothness of D65 and A illuminants, while F2 has sharpest spectral peaks. This phenomenon was also indicated by Farup et al. [5]. In that work, they were neither able to compensate the typical spikes of fluorescent light sources.

In comparison to previous studies, Fryc et al. [6] achieved better reconstructions of standard illuminants by means of a convergence algorithm. Moreover, their light source also included around 30 spectral channels like the one describe in this work. Nevertheless, in spite the good performance of that spectrally tunable light source, the convergence procedure took a long computational time due to the large number of iterations for each measurement. On the other hand, the system developed by Mackiewicz et al. [7] was implemented as well with a minimization routine but, in that case, the generation of illuminants were not accurate enough because of the reduced number of spectral channels (9).

4 Conclusions

In this work, a LED-based spectrally tuneable light source with 31 channels in the visible range (400-700nm) was built. An integrating cube was also built to reach very high accuracy levels with that light source. Moreover, a minimization routine able to reproduce the spectrum of CIE standard illuminants was developed. The results obtained showed an excellent relationship between the theoretical predicted spectra provided by the algorithm and that later experimentally measured. Nevertheless, the fitting was worse in the green region of the spectrum, specially from 500nm to 600nm as a consequence of the current status of LED technology in this range, with less powerful diodes. In the near future, this accuracy could be improved as this limitation will be overcome. In spite of that, the algorithm can be considered a solid and applicable method to any set of quasi-monochromatic light sources (LEDs or any other future technology). Furthermore, it offers a powerful alternative to conventional bulbs used in the manufacturing of lighting booths or panels for industrial and research applications.

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