Towards Simulation of a Sun Spectrum Light Source Using LEDs

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In this work we describe an approach to synthesize an equivalent Sun spectrum light source for the needs of developing novel remote sensing instruments. For this purpose we use off-shelf commercially available power LED components. The feasibility of the described approach is confirmed based on numerical simulations using catalog LED spectral data.

Introduction

The motivation of our study described in this paper is the need of designing an equivalent sun spectrum simulation source for the development of novel remote sensing instruments utilizing imaging of plant fluorescence [1]. The latter is directly induced by the solar radiation and one needs to be able to reproduce such lightening conditions, and the related natural and anthropogenic impact on the vegetation fluorescence, in a controlled laboratory environment [2].

Various sun spectrum simulation sources are being developed and applied nowadays in different science, technology and applied areas (e.g. medical). Typically, such artificial sun light sources can be used in various biomedical and photobiology studies, product testing of cosmetics, paints and other surfaces directly exposed to solar radiation – e.g. power photovoltaic cells [3, 4] and other. The existing sun light sources are divided in three classes - A, B and C [5, 6, and 7] based on their most important illumination characteristics: spectral match to sunlight, non-uniformity of the light beam and stability of the light beam over time [8]. In most of the cases, high power xenon light bulbs are used. While they provide suitable lightening power and relatively appropriate spectrum, such sources face a number of issues – flux fluctuations, sharp unrelated emission peaks, aging and other [9]. All these require the use of additional optical components and special engineering solutions to provide stabilization, require regular calibration and have difficult maintenance. Another serious issue using xenon light sources is the virtual impossibility for accurate electronic modulation of their light emission. The latter is required for the purpose of developing the advanced imaging instrumentation and its calibration.

On the other hand, LEDs are becoming nowadays increasingly attractive as light sources. Plenty of cheap power devices are presently available on the market, offering a wide range of emission wavelengths in the UV, VIS and IR spectra. Using such LEDs, potentially allows to synthesize a light flux spectrum very close to the solar spectrum at ground level [10, 11].

In this work, we describe an approach allowing to construct a light source matching the sun illumination spectrum by using existing commercial power LEDs. We illustrate the method by synthesizing a virtual sun source using catalog data [12] of available discrete wavelengths LEDs.

Method

There are several important considerations when defining a solution to simulate the solar flux in artificial environment:

- Maximum agreement between the solar and the simulated spectra in order to achieve good correlation;
- Possibility to control the incident flux intensity. This is needed in order to allow reproduction of the impact of the different synoptic and astronomical conditions on the ground surface lightening;
- Possibility for continues flux emission with a determined amplitude;
- Pulse width modulation feature of the flux, needed for precise illumination control;
- Homogeneous illumination within a dedicated test chamber.

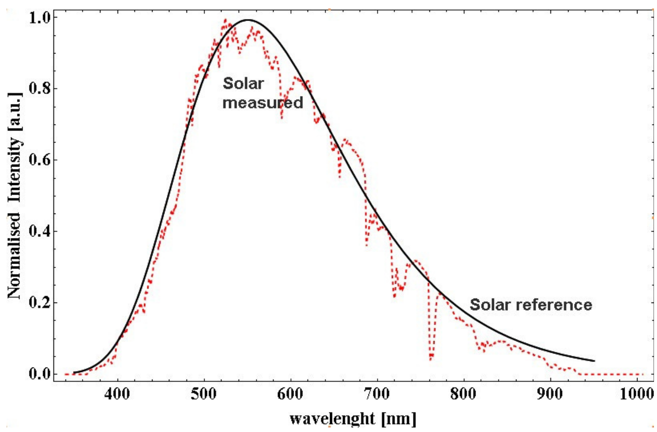

Fig.1. Measured Sun spectrum at ground level (dotted line) and the theoretically equivalent T=5500K black body emission spectrum (solid line)(both normalized to their maxima)

Fig.1 shows a typical solar spectrum measured at ground level in comparison to the equivalent theoretical black body spectrum. In this work, we will further use the described in Fig.1 black body spectra as a reference for our LED synthesized sun equivalent spectrum.

For the purpose of synthesizing the solar spectrum I_{SUN}, we assume it can be represented as a linear combination $k_j I_j(\lambda_j)$of a number of stand alone LED spectra $I_j(\lambda_j)$ as follows:

$$I_{sun} = \sum_j k_j I_j(\lambda_j) \qquad (1.1)$$

From theory, each individual LED spectra $I_j(\lambda_j)$ can be approximated using the Lorentz law:

$$I_j(\lambda_j) = \frac{2A}{\pi} \frac{w}{4(\lambda - \lambda_j)^2 + w^2} \qquad (1.2)$$

Fig. 2 shows typical LED spectra in several λ In (1.2), the coefficients A and w have correspondingly the meaning of the integral spectral power and the spectrum half-width. In general both depend on the LED junction structure and material. The coefficient A, describing the spectral power, is directly proportional to the injected electrical power and LED drive current. Thus the latter is one of the 'knobs' to control the individual LED contributions in the sum in Eq.1.1. Another practical 'knob' to control that contribution is by using the weight factor coefficients k_j. They represent the relative contribution of each individual LED luminous flux (at a fixed λ_j) in the total luminous flux of the system at the same fixed LED drive current. The coefficients k_j are also directly proportional to the number of discrete LED devices $I_j(\lambda_j)$ at each λ_j.

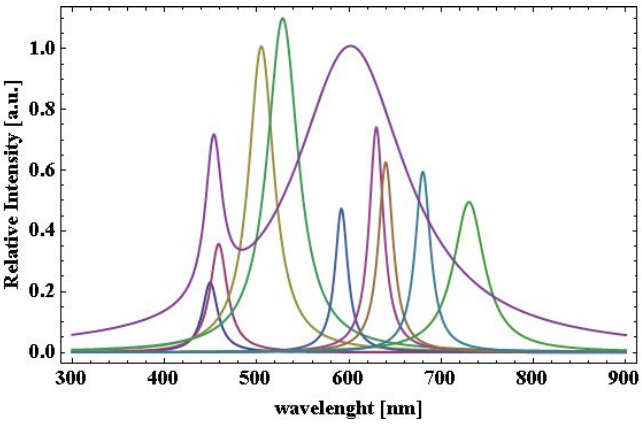

Fig.2. Relative Intensity spectra of different discrete LED sources

Considering the above, the following practical steps are needed in order to be able to synthesize the required solar spectrum:

1) Select a number of stand- alone discrete LEDs with suitable spectra $I_j(\lambda_j)$. In order to achieve the target light intensities (and power), and to reduce the number of components, high-power LEDs are needed;
2) Ensure precise DC control of the LED drive currents in order to be able to fine-tune the LED characteristics $I_j(\lambda_j)$. For our purpose it is also required to ensure possibility for a pulse-width modulation of the supply current. This is needed in order to be able to realize the dark-time period in which the imaging of the induced fluorescence emission from the objects under study will be realized;
3) Optimize the drive currents and the number of the individual LED groups with same λ_j to achieve the reference solar spectrum shown in Fig.1.

A Case Study Example

As an example to demonstrate the feasibility of our approach, we synthesized an equivalent solar spectrum using catalog data [12] from commercially available stand-alone LED's.

First we establish a database describing the electrical and spectral characteristics of the available catalog LEDs in the following wavelength groups Royal-Blue, Blue, Cyan, Green, Amber, Red-Orange, Red, Cool-White, Neutral-White, Warm-White and Near-Infrared.

Typical spectral characteristics of these LEDs are as shown in Fig.2. Based on the available catalog data, all given LED spectral intensities were first re-calculated to represent LED operation in same drive currents. Although this is not strictly needed, it helps to understand the relative contribution of the stand-alone LEDs with different λ in the total spectral intensity. By further adjusting the LED drive currents and the weight factors one can possibly achieve a total synthesized spectrum close to the sun reference one, as shown in Fig.3.

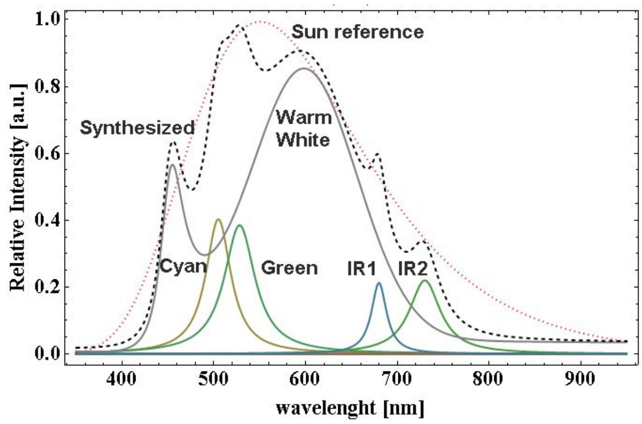

Fig.3. Relative Intensity spectra of the synthesized LED source (dashed line), the used in its construction commercial LEDs (solid lines) and the Sun reference spectrum (dotted line)

Fig. 4 shows the relative error for the achieved LED spectrum, calculated as

$$\Delta = \frac{I_{SunReference} - I_{Synthesized}}{I_{SunReference}} 100\ [\%] .$$

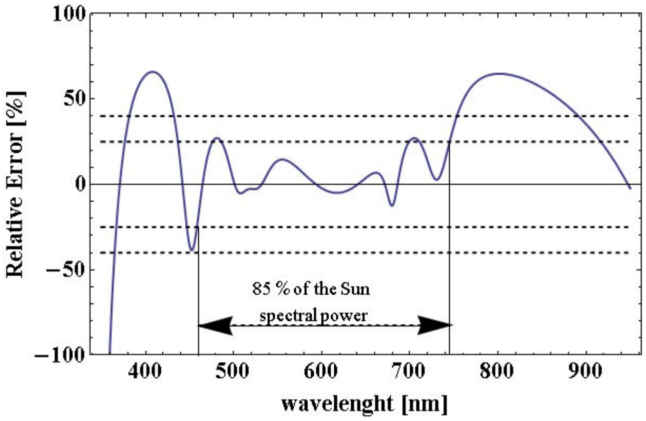

Fig.4. Relative Error of the LED synthesized light source spectrum compared to the Sun reference spectrum

It is seen that between *λ=460nm* and *λ=725nm* the relative error is within the +/- 25% limit. This corresponds to having achieved the highest correlation (Class A) artificial light source with respect to its proximity to the Sun spectrum.

It is worth to note that this wavelength region contains 85% of the sun spectral power, thus the increased error at the edges of the synthesized spectrum is not significantly affecting the achieved total irradiance. This is important when studying plant fluorescence induced by natural sunlight since the fluorescence is activated by solar radiation in all wavelengths bellow ~ λ=720nm and is negligible at higher λ [13].

Table 1. shows the measured sun irradiance distribution in the standard wavelength bands 1-5, compared to the synthesized LED source. It is clearly seen that the percentage deviation of the integral intensity of the LED source compared to the Sun's one is within ~2% in all bands, which demonstrates the high quality of the artificial light source.

Table 1
Irradiance Distribution in the Standard Wavelength Bands 1-5 [5, 6]

		Percentage of total irradiance (400nm - 900nm) [%]	
Wavelength Band	λ [nm]	Sun Measured	LED Source
1	400-500	17.7	17.1
2	500-600	38.9	41.0
3	600-700	28.7	30.6
4	700-800	11.0	9.1
5	800-900	3.4	2.2

Discussion

The results shown in Fig. 3 and Fig. 4 above clearly demonstrate the feasibility of our approach to synthesize sun-spectrum alike light source using commercially available LEDs. There are several considerations regarding the quality of the achieved correlation between the real and the artificial spectra.

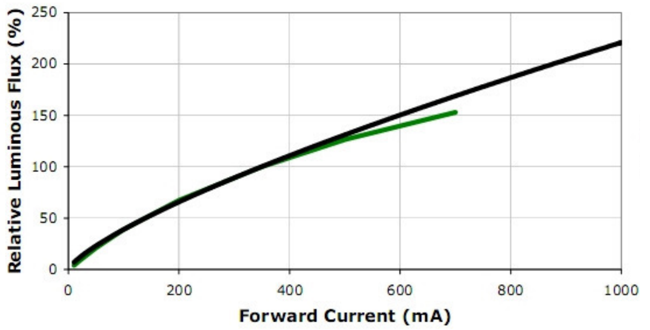

Fig.6. Typical LED flux-current characteristics [12], used to control the individual LED flux intensities in Eq.1.1

First, we disregard the details of the atmospheric absorption and we target the overall LED spectrum to match only the envelop of the sun spectrum, as shown in Fig. 1. Further studies are needed to understand the impact of this approximation on the sunlight induced plant fluorescence. Same applies to the impact of having decreased correlation between the synthesized and the reference spectra at the edges of the sun spectral band, as shown in Fig. 3 and Fig. 4. Table 1 shows that the integral power distribution for our LED source is close within 2% to the same of the actual solar radiation at ground level (at air mass=1.5). This fact allows us to believe that we can achieve good reproduction of the naturally induced fluorescence by using our synthesized 'sunlight' source.

Second, special attention is needed to implement the 'physical' mix of the discrete LED wavelengths and intensities to form the combined light flux. For the purpose of our study, this will be realized by an appropriate arrangement of the discrete LEDs in a chamber providing multiple diffusion reflections and illumination of the objects under study. Another approach is to design a collimator based optical system to generate the combined light flux. Optimizing the physical configuration and placement of the discrete LEDs to form the unite 'sunlight' pixel is another related possible issue that may need attention in the practical implementation.

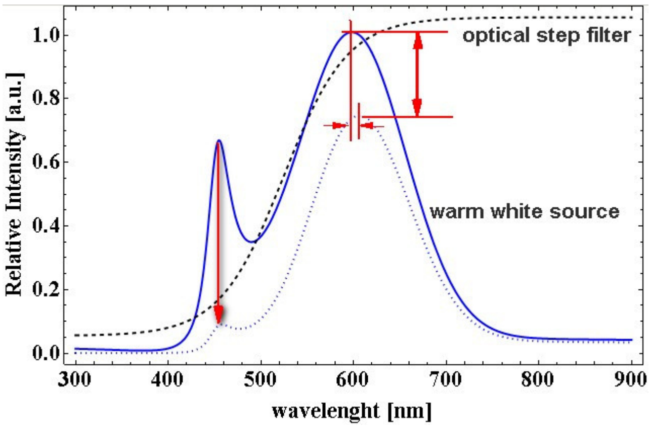

Fig.5. Effect of applying a step optical filter in front of the used discrete white LED source

Third, additional effort is required to provide the accurate electronic control of the discrete LEDs. A dedicated control circuitry and software need to be developed to allow precise control of the LED luminous fluxes and hence the total spectral function of the synthesized source.

To ensure good correlation of the synthesized LED spectrum, it is obviously desirable to have a number of different discrete LEDs with suitable λ, see Eq.1.1 and Fig. 2. It is not always possible to have discrete LEDs with the optimum spectral shape needed to optimize the total spectrum in Eq.1.1. For example, Fig. 3 shows that the main contribution in the synthesized spectrum comes from the wide bandwidth discrete white LED (warm white in our example). The main problem with such white LED sources is the presence of multiple intensity peaks. These peaks cannot be controlled independently and this implies some limitations on the possible optimization of the synthesized spectrum. To resolve this problem and to help introduce some additional degrees of freedom, one can use additional spectral filtering to remove and 'shape' the undesired peaks.

Fig. 5 illustrates how the white LED spectrum can be modified by applying a suitable optical step filter. Applying the filter has several effects, which can be used as additional 'knobs' to tune the synthesized spectrum.

In this particular case, as seen in Fig. 5, the filter significantly reduced the undesired peak at λ~450nm, reduced and shifted the main peak at λ~600nm. The advantage of this spectral modification is that now the 'parasitic' peak at λ~450nm is removed and the illumination in this spectral band can be realized (and optimized) with an unrelated, standalone discrete LED, thus introducing an additional 'degree of freedom'. The reduction of the needed main peak at λ~600nm can be compensated by modifying the LED drive current, see Fig.6, and increasing the number of discrete LEDs.

Conclusions

In this work we investigated the feasibility of synthesizing an artificial light source having spectrum close to the solar one at ground level. Using catalog data for the electro-optical characteristics of commercial high-power discrete LEDs, we show that a highly accurate class-A LED source can be achieved for the 85% of the natural sun spectral power bandwidth. Further studies are needed to understand the impact of using the approximated synthesized LED source on the light induced plant fluorescence.

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