Spectral calibration of a LED–based solar simulator – a theoretical approach

A. GEORGESCU*, M. A. GÎRȚU, V. CIUPINĂ
Department of Physics, Ovidius University of Constanța,Constanța, 900527, Romania

The large number of solar cells efficiency reports without the proper care regarding the accuracy and reproducibility of the results are suggesting that class A solar simulators should be compulsory devices in any laboratory involved in solar cells production and testing. This paper synthesizes the study of the fabrication possibilities of a LED – based solar simulator, focusing on the task of obtaining a calculated spectral distribution that is closely matched to that of the Sun. In the first part of the paper, a numerical approach has been used to determine the LEDs central wavelengths and relative intensities, so that their cumulated spectrum can follow the Solar one to certain degrees of precision, using both the distribution as defined in the ASTM E927-05 Standard and the measured solar spectrum as a calibration reference. The second section offers the proof that the required LEDs can be fabricated, by determining the necessary semiconductor materials and calculating their concentrations according to the required wavelength.

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1. Introduction

Solar simulators are devices that allow for controlled indoor testing of different materials, such as plastic and inks or, more often, are used for solar cells characterization. As a result of the continuously rising interest in the photovoltaic market [1] and a number of papers that claim unrealistic performances of organic solar cells, Dennler and co-signatories [2] recommend that specific methods and standards are to be followed in order to maximize measurements accuracy and reproducibility [3,4].

Solar simulators have greatly evolved regarding their performances in the last years. Manufacturers are constantly searching for new and improved light sources and adequate filters for a better match with the solar spectrum [5]. Apart from traditional filament lamps, xenon discharge lamps are being used more often, because of the high intensity, low power consumption and strong emission in the blue-violet part of the spectrum. It is evident though that one cannot report standard measuring conditions efficiencies using a single lamp source [3,6]. As a result, solar simulators that make use of multiple light sources have been built [7,8], one of the key problems being the adequate filtering of those sources [9].

The two main types of solar simulators in use today, steady-state and flash simulators, have specific advantages and drawbacks [10], and care must be taken in choosing the right type for specific demands and measurements. Despite the accurate measurements of solar devices, the steady-state solar simulators have the disadvantage of high maintenance costs and thermal control issues. Flash simulators don't have these disadvantages, but the measurements can be affected by capacitive effects to a greater extent than in the previous case [11]. Both types lack in spectral matching precision because of the use of a single light source.

A LED-based solar simulator can overcome these disadvantages through the higher LED lifetime and thus reduced maintenance costs, and almost zero emission in the far infrared part of the spectrum and thus easier thermal control. Such simulators have been reported in the past [12, 13, 14], the main problems being related to the spectral match and obtaining a 1 sun intensity.

As light sources, LEDs have a much longer lifetime compared to conventional high intensity lamps (up to 100.000 hours in some cases), which reduces maintenance costs to a minimum. LEDs can be accurately controlled, the output intensity being stabilized in less than one millisecond (usually a few microseconds). The possibility of stabilizing the LED's running parameters opens new ways of determining both the short and long-term effects on the tested solar cells using the same solar simulator.

Using LEDs in the construction of a solar simulator poses a number of difficulties mainly because of the narrower output spectral width, which demands for the use of multiple LEDs with different emission wavelengths. The perfect correlation of these LED output spectrums is crucial for minimizing spectral deviations and obtaining a class A solar simulator.

The following paper will discuss the possibility of obtaining a spectral distribution closely matched to that of the sun, by using LEDs for which their spectra were calculated by means of Gaussian distributions, functions which permit an excellent correlation with the experimental determinations.

2. Calibration possibilities

In order to correctly estimate the output spectrums of LEDs with certain central wavelengths, a suitable mathematical model had to be found. Although in an entirely theoretical model the curve showing the dependence of the relative light intensity over the wavelength is not symmetrical (being directly related to the carrier concentrations in the valence and conduction bands – Figure 1), practical measurements showed spectral distributions that can be well approximated by Gaussian distributions of the following form:

$$f(x) = a \cdot \exp\left(-\frac{(x-b)^2}{2c^2}\right),$$

where:
a is the height of the curve,
x is the central wavelength,
b is the current wavelength for which the determination is made, and
c is the width at half the intensity.

Choosing the LEDs can be further simplified by considering that the half-width of the relative intensity as a function of the photon energy (Figure 1) is approximately 2.5-3$k_B T$ [15], which leads to a dependence of the half-width over the wavelength expressed as:

$$\Delta\lambda \cong \lambda^2 \cdot \frac{3k_B T}{hc}$$

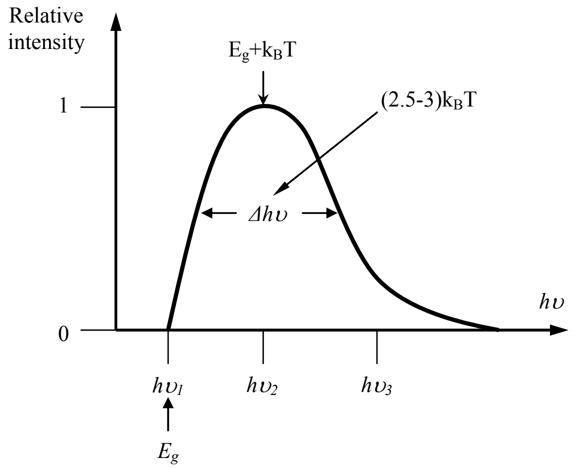

Fig. 1. Relative intensity versus the photon energy [15].

The following section will determine the minimum number of required LEDs and their relative intensities, for the best match with the solar spectrum. First, the international standard ASTM E927-05 [16] for class A solar simulators will be used as a calibration reference. As will be shown, a better calibration can be achieved by using the measured solar spectrum as a calibration reference, using three cases of maximum permitted tolerances (25%, 10% and 5%). The calculation of the Gaussian distributions has been made in the wavelength interval of 300-1100nm, using a step of a 1nm. Because of the differences between the solar spectrum as measured on Earth surface and the ideal black-body radiation, an automated algorithm for determining the LEDs parameters could not be used.

2.1 Calibration using the ASTM Standard

The values resulted from the international standards regarding the spectral match of solar simulators are listed in Table 1 and illustrated in Fig. 2. An important point is that this standard does not provide any absolute values, but only the relative intensity distribution over the specified wavelength interval. It can be easily observed that these values can be easily obtained by using LEDs with central wavelengths within the specified intervals. This leads to a number of only 6 LEDs regardless of their output spectrum half-width.

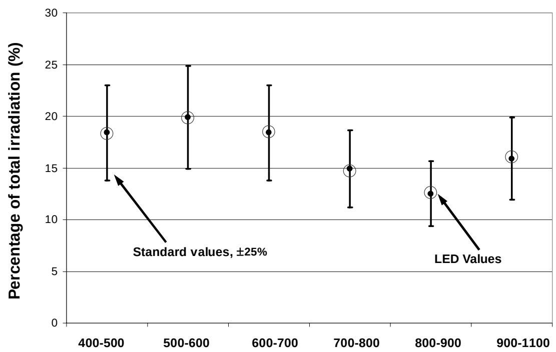

Fig. 2. ASTM E927-05 values for class A solar simulators.

Table 1

Interval (nm)	400 500	500 600	600 700	700 800	800 900	900 1100
Ideal (%)	18.4	19.9	18.4	14.9	12.5	15.9
Class A (±25% față de valorile ideale)						
Min (%)	13.8	14.9	13.8	11.2	9.3	11.9
Max (%)	23	24.8	23	18.6	15.6	19.9

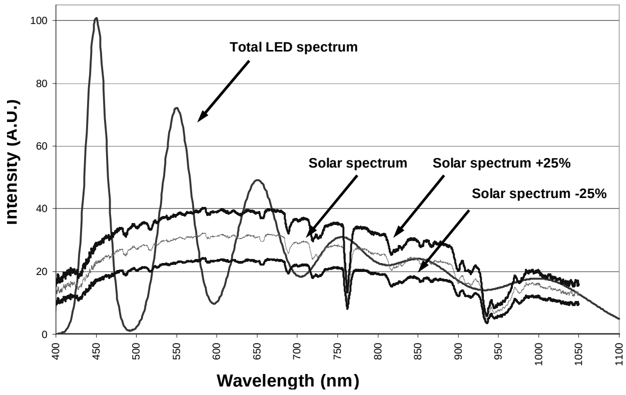

Fig. 3. Calibration 1: Total LED spectrum (required by standards) as compared to the solar spectrum in the ±25% limits.

The essential parameters for the LEDs required by this distribution are shown in Table 2. The values in red in Fig. 2 have been obtained by integrating the calculated values over a 1nm step and calculating their proportion from the complete integral.

Because these standards specify only 6 measurements intervals, it can be easily seen that such a calibration can introduce significant local deviations.

Fig. 3 shows a spectral distribution for all the 6 LEDs used by this method, and although the standard requirements are fully satisfied, the mismatch with the solar spectrum is obvious. Such a solar simulator could lead to questionable results on solar cell efficiencies and a complete lack of correlation between the measurements taken in the laboratory as compared to outside conditions, especially for solar cells with absorption wavelengths in the blue side of the spectrum, in the middle of the specified intervals or at the boundary between them.

Table 2

LED Nr.	Central wavelength (nm)	Relative intensity (A.U.)	Spectral width (nm)	Apparent color
1	450	100.8	12.65	violet
2	550	72	18.9	green
3	650	42.6	26.4	orange
4	750	28.8	35.1	red
5	850	22.5	45.1	red to infrared
6	1000	17.64	62.4	infrared

2.2 Calibration by solar spectrum ±25%

A better calibration of the spectral distribution can be achieved if the solar AM1.5 spectrum is used as a reference. First, a limit of ±25% is considered. Such condition increases the number of LEDs to a minimum of 10. The central wavelengths were chosen for an optimum correlation between the two spectra (except for the intervals presenting strong atmosphere absorptions at 720nm – ozone and 950n – water). The comparison between the two spectra is shown in Fig. 4.

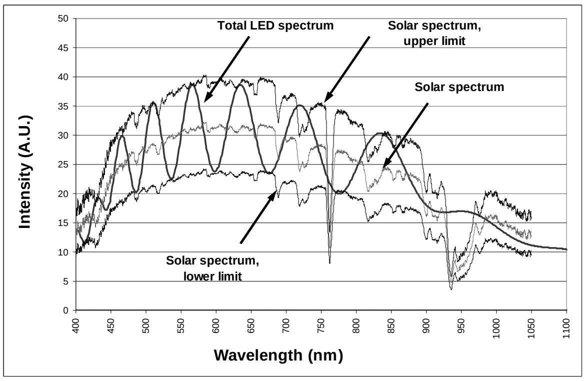

Fig. 4. Calibration 2: Total LED spectrum compared with the solar spectrum in the ±25% limits.

Table 3

LED Nr.	Central wavelength (nm)	Relative intensity (U.A)	Spectral width (nm)	Apparent color
1	400	13	10	violet
2	430	18	11.5	violet
3	465	29	13.5	blue
4	510	34.6	16.2	blue-green
5	565	37.5	19.9	green-yellow
6	633	37.4	25.4	orange
7	718	34	32.4	red
8	830	28.6	43	infrared
9	950	15	56.3	infrared
10	1100	10	75.6	infrared

The solar spectrum used as a reference has been measured using an OceanOptics HR4000CG UV-NIR Spectrometer. The essential LED parameters required for the ±25% margin error are given in Table 3.

2.3 Calibration by solar spectrum ±10%

By lowering the allowable deviations from the solar values, the resulting total LED spectrum will better approximate the solar one. The LED parameters corresponding to a deviation of ±10% have been calculated by the same method and are presented in Fig. 5 and Table 4.

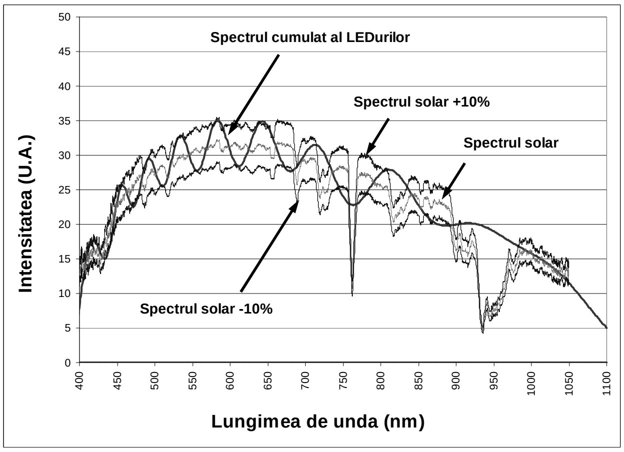

Fig. 5. Calibration 3: Comparison between the LED spectrum and the solar spectrum in the limits of ±10%.

Table 4

LED Nr.	Central wavelength (nm)	Relative intensity (U.A)	Spectral width (nm)	Apparent color
1	410	11	10.5	violet
2	425	11	11.2	violet
3	455	23.5	12.9	blue
4	490.5	27	15	blue
5	532	30	17.6	green
6	581	32	21	yellow
7	640	31.7	25.6	orange
8	711	29	31.9	red
9	805	25	40.9	infrared
10	910	17	52.8	infrared
11.	1020	13	59	infrared

2.4 Calibration by solar spectrum ±5%

The last studied case is that of the allowable deviation of ±5%. From this point forward major difficulties occur regarding the strong atmosphere absorptions in the regions around 720nm and 930-970nm. This is due to the fact that the spectral width of the LEDs spectrum at those wavelengths is too large for an exact shaping of the output spectrum.

Table 5

LED Nr.	Central wavelength (nm)	Relative intensity (U.A)	Spectral width (nm)	Apparent color
1	407	12	10.5	violet
2	425	10	11.2	violet
3	452	20	12.7	blue
4	482	24	14.7	blue
5	518	25	16.7	green
6	558	26	19.4	green
7	600	24	22.4	orange
8	647	24	26.1	orange
9	700	20	30.6	red
10	760	20	36.5	red
11	830	15	43	infrared
12	900	14	50.6	infrared
13	1000	14	62.5	infrared

3. Materials

Choosing the right semiconductors can be simplified by examining the diagram in Fig. 6 (made by the author, based on [17]), which shows possible materials that can be used to obtain specific wavelength radiation (both ternary and quaternary alloys). It has been found that it is possible to fabricate all the required LEDs even by using only ternary alloys.

To determine the required materials, the band gap energy must first be calculated:

$$h\upsilon \cong E_g + k_B T \,,$$

formula which can be re-written as:

$$E_g \cong \frac{1.24}{\lambda(\mu m)} - 0.026[eV] \cdot$$

After finding the appropriate semiconductor materials dictated by the band gap energies, a suitable substrate has to be chosen for the epitaxial growing of these materials. Each substrate has to have a closely-matched lattice constant as to avoid lattice defects which will further act as non-radiative recombination centers, will lower the efficiency of the devices and will limit the lifetime due to rapid degradation at high injection currents.

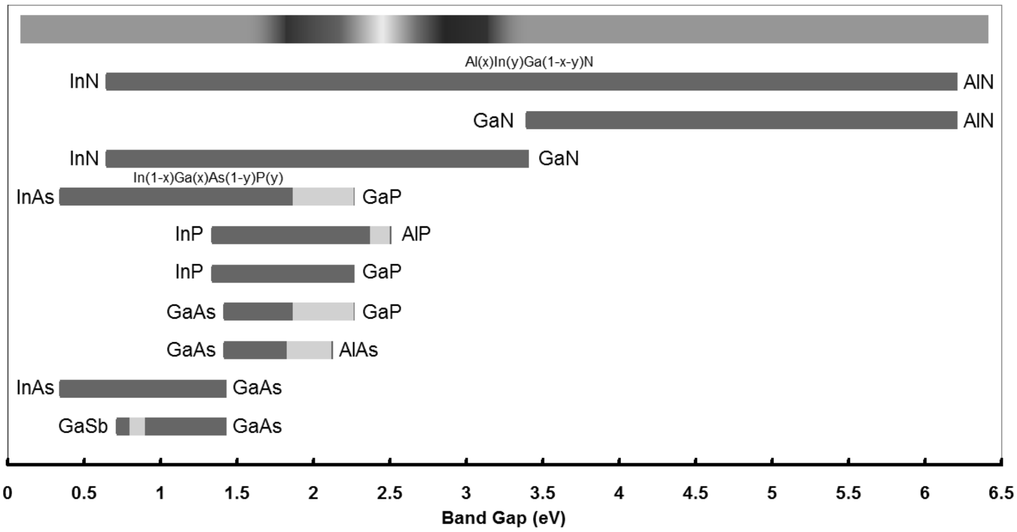

Fig. 6. Possible semiconductor alloys for different band gap values.

1st LED: λ=400nm, E_g=3.074 eV => InGaN:
E_g=3.42-2.65x-x(1-x)2.4 => x=0.408 => $In_{0.592}Ga_{0.408}N$, substrate: InGa

2nd LED: λ=430nm, E_g=2.858 eV => InGaN:
E_g=3.42-2.65x-x(1-x)2.4 => x=0.679 => $In_{0.321}Ga_{0.679}N$, substrate: GaN

3rd LED: λ=465nm, E_g=2.641 eV => InGaN:
E_g=3.42-2.65x-x(1-x)2.4 => x=0.965 => $In_{0.035}Ga_{0.965}N$, substrate: GaN

4th LED: λ=510nm, E_g=2.405 eV => InGaN:
E_g=3.42-2.65x-x(1-x)2.4 => x=0.225 => $In_{0.775}Ga_{0.225}N$, substrate: sapphire

5th LED: λ=565nm, E_g=2.169 eV => AlInP:
E_g=1.34+2.23x => x=0.371 => $Al_{0.371}In_{0.629}P$, substrate: GaAs

6th LED: λ=633nm, E_g=1.933 eV => GaInP:
$E_g=1.34+0.511x+0.6043x^2$ => x=0.266 => $Ga_{0.266}In_{0.734}P$, substrate: GaAs

7th LED: λ=718nm, E_g=1.701 eV => GaAlAs:
$E_g=1.424+1.087x+0.438x^2$ => x=0.036 => $Ga_{0.964}Al_{0.036}As$, substrate: GaAs

8th LED: λ=830nm, E_g=1.468 eV => GaAlAs:
$E_g=1.424+1.087x+0.438x^2$ => x=0.015 => $Ga_{0.985}Al_{0.015}As$, substrate: GaAs

9th LED: λ=950nm, E_g=1.279 eV => GaInAs:
$E_g=0.365+0.7x+0.4x^2$ => x=0.638 => $Ga_{0.638}Al_{0.362}As$, substrate: InP

10th LED: λ=1100nm, E_g=1.101 eV => GaInAs:
$E_g=0.365+0.7x+0.4x^2$ => x=0.746 => $Ga_{0.746}Al_{0.254}As$, substrate: InP

Table 6

LED Nr.	Central wavelength (nm)	Relative intensity (U.A)	Spectral width (nm)	Eg (eV)
1	400	13	10	3.074
2	430	18	11.5	2.858
3	465	29	13.5	2.641
4	510	34.6	16.2	2.405
5	565	37.5	19.9	2.169
6	633	37.4	25.4	1.933
7	718	34	32.4	1.701
8	830	28.6	43	1.468
9	950	15	56.3	1.279
10	1100	10	75.6	1.101

Table 6 shows the Eg values for the LEDs required in the case of the ±25% simulator margin error. Table 7 presents the final results of the calculations carried for determining the semiconductor alloys and the necessary concentrations for the specific wavelengths.

Table 7

LED	Semiconductor	Substrate
LED 1 (Eg = 3,074 eV)	$In_{0.592}Ga_{0.408}N$	InGa
LED 2 (Eg = 2,858 eV)	$In_{0.321}Ga_{0.679}N$	GaN
LED 3 (Eg = 2,641 eV)	$In_{0.035}Ga_{0.965}N$	GaN
LED 4 (Eg = 2,405 eV)	$In_{0.775}Ga_{0.225}N$	Sapphire
LED 5 (Eg = 2,169 eV)	$Al_{0.371}In_{0.629}P$	GaAs
LED 6 (Eg = 1,933 eV)	$Ga_{0.266}In_{0.734}P$	GaAs
LED 7 (Eg = 1,701 eV)	$Ga_{0.964}Al_{0.036}As$	GaAs
LED 8 (Eg = 1,468 eV)	$Ga_{0.985}Al_{0.015}As$	GaAs
LED 9 (Eg = 1,279 eV)	$Ga_{0.638}In_{0.362}As$	InP
LED10 (Eg = 1,101 eV)	$Ga_{0.746}In_{0.254}As$	InP

4. Conclusions

The possible methods for calibration of a LED-based solar simulator have been considered. The resulting configurations have been obtained, using four separate cases: the ASTM E927-05 regulations regarding solar simulators spectral match, the measured solar spectrum ±25, solar spectrum ±10% and solar spectrum ±5%. The determinations were based on Gaussian distributions for accurate approximation of the LED output characteristics. It has been found that a calibration based purely on the ASTM Standard can introduce significant local deviations in case of LED solar simulators. The LED parameters and required materials have been determined for the case of a maximum deviation of ±25% from the solar spectral distribution.

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*Corresponding author: contact.adriangeorgescu@gmail.com