Analysis and Realization of a Low-Cost Hybrid LED-Halogen Solar Simulator

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Abstract—**A low-cost hybrid solar simulator which combines solid-state light sources (LEDs) with low voltage halogen lamp to produce an output beam that can closely match a desired solar spectrum is proposed and analyzed in this paper. In particular, a summary of the design and optimization procedure for spectral match is given, on the basis of the photometric values taken from data sheets and converted to the corresponding radiometric values. As an example of application, the output spectrum is preliminary compared with standard global terrestrial solar spectra air mass AM 1.5. The results of simulating spectra calculations and some experimental measurements on a solar simulator prototype are given. Experimental tests have shown the possibility of reaching the Class B of spectral matching with better than 6% spatial non-uniformity over an area of 125x125 mm^2.**

Keywords—***Photovoltaic, solar simulator, LED, halogen lamp, radiant flux, irradiance.***

I. INTRODUCTION

The main objective of a solar simulator is to provide a controllable indoor test facility under laboratory conditions, used for testing and developing of solar cells. Currently, there are various types of commercial solar simulating systems; most of them are realized with a xenon lamp as the light source. In spite of good spectral distribution, close to the sunlight, the xenon lamp has a very high cost, extensive maintenance and very short operating life. A further drawback of xenon-based solar simulators is the small working area, up to 30x30 cm nowadays, being difficult to combine more xenon lamps due to the related lens/mirrors optical system. Furthermore, in case of xenon lamps, optical filters are needed to change the shape of spectral distribution, or radiation intensity, to simulate the different period of the day or year, effects of clouds, fog, pollution, etc.

There are other types of solar simulators which were designed in the last 30 years. For instance, tungsten- or quartz-halogen, sodium or mercury discharge lamps were used to reproduce a sun radiation [1]-[3].

Nowadays, it becomes quite clear that the constantly falling price of power LEDs and their growing luminous efficiency make them very interesting to simulate the sunlight by a multi-LED source with a proper combination of colors (i.e., wavelengths). The main advantages of LEDs are high efficiency, moderate price, small dimensions, radiation intensity adjustability, long operating lifetime etc.

LEDs have been recently used in research laboratories, one of the first attempts appears in [4], where part of the solar spectrum has been simulated by three LED colors, obtaining good uniformity. The latest projects of solid state solar simulators were conducted at the NIST [5], where with few monochromatic and white (5500K), near infrared, and ultraviolet LEDs was achieved an approximation of the air mass (AM) 1.5 sun spectrum in the wavelength interval from 400 to 970 nm. As the output optics was used the 5 m long light tapered guide which allowed a relatively low nonuniformity: less than 10% for illuminated area of 25x50 cm^2. Another good example of solid-state simulator was designed by the group of scientists from USA [6]: high-brightness LEDs with current-mode controllers were used for a low-cost sun simulator with wavelength interval 400-1100 nm. This simulator provides Class C uniformity over an area of 10x5 cm^2.

In above-listed simulators were used near-infrared and near-ultraviolet LEDs. Because of narrow bandwidth and their quite relevant cost, in this paper it is proposed to avoid using them. In particular, halogen lamps are introduced to cover the near-infrared range of the solar spectrum. Note that halogen lamps generate wavelengths in the range of visible-infrared, are cheap, and the radiation intensity can be easily modulated.

II. SOLAR-SIMULATOR STANDARDS

There are several organizations that provide performance requirements and parameters used for classifying both pulsed and steady-state solar simulators intended for indoor testing of photovoltaic devices. Most important of them are the standard of the American Society for Testing and Materials ASTM E-927-10 and the IEC 60904-9 of International Electrotechnical Commission [7], [8].

The solar simulator's irradiation performance is evaluated with three parameters: spectral concurrence (matching), irradiation non-uniformity, and temporal instability. Three classes of solar simulators are defined (A, B, C), and the criteria for these classifications are shown in Table I.

TABLE I
CLASSIFICATIONS OF SIMULATOR PERFORMANCE

Performance Parameter	Standards Organization	
	ASTM	***IEC***
Spectral match		
Class A	0.75-1.25	0.75-1.25
Class B	0.6-1.4	0.6-1.4
Class C	0.4-2.0	0.4-2.0
Irradiation non-uniformity		
Class A	≤3%	≤2%
Class B	≤5%	≤5%
Class C	≤10%	≤10%
Temporal instability		
Class A	≤2%	≤2%
Class B	≤5%	≤5%
Class C	≤10%	≤10%

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TABLE II
DISTRIBUTION OF IRRADIANCE PERFORMANCE REQUIREMENTS

Wavelength	Percentage of Total Irradiance		
[nm]	AM 1.5D	AM 1.5G	AM 0
300–400	no spec	no spec	8.0%
400–500	16.9%	18.4%	16.4%
500–600	19.7%	19.9%	16.3%
600–700	18.5%	18.4%	13.9%
700–800	15.2%	14.9%	11.2%
800–900	12.9%	12.5%	9.0%
900–1100	16.8%	15.9%	13.1%
1100–1400	no spec	no spec	12.2%

The spectrum is also characterized by the irradiance integral across eight wavelength intervals. The percentage of total irradiance is shown in Table II for the standard terrestrial spectra of AM 1.5G (Global) and AM 1.5D (Direct), and the extraterrestrial spectrum AM 0.

The goal of the project presented in this paper is to realize a steady-state solar simulator with high spectral matching class. In the following, the standard terrestrial spectra of AM 1.5G will be considered, which is appropriate for solar panel testing. To verify the spectral matching, the solar spectrum from 400 nm to 1100 nm has been divided into six intervals, with reference to the IEC 60904-9 Reference Solar Spectrum Irradiance Distribution, shown in Fig. 1.

III. LEDS AND HALOGEN LAMP SELECTION

High power LEDs were chosen to reduce the number of LED and the required supply voltages. The module is a single unit of simulator with multiple lamps reproducing the sun radiation. Combination of many modules allows increasing the operating area. The AM 1.5G solar spectrum is used here to demonstrate the selection procedure of the light source.

A. From Photometric to Radiometric Quantities

One of the first complications encountered when working with light sources in the visible spectrum is the photometric values specified in their datasheets. Because all standards operate with radiometric values, it becomes necessary to convert all values in the radiometric system.

Radiant flux can be determined from (1) that relates the luminous flux to the radiant flux through photopic luminosity function and the maximum spectral luminous efficiency [9]:

$$\Phi_v = 683 \int_{380}^{780} V(\lambda)\Phi_e d\lambda \,, \tag{1}$$

where Φ_v and Φ_e are the luminous flux [lm] and radian flux [W], respectively; 683 is the value of maximum spectral luminous efficiency of human eye; $V(\lambda)$ is the photopic luminosity function.

Thereby to calculate the spectral power distribution of every LED should be known the spectral distribution of luminous flux. But in this step there is another obstacle. The LED manufactures provide a relative radiant power distribution curve, total luminous flux in lm, but no total radiant power. Thus, the

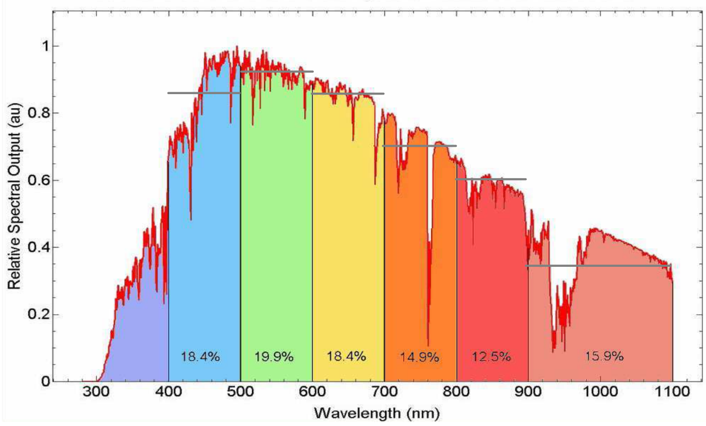

Fig. 1. IEC 60904-9 Reference solar spectrum irradiance distribution.

curve of each light source must be discretized, and then by using (1), with simple mathematical manipulations, can be found the absolute values of radiant flux per wavelength.

B. Designing for Spectral Match

The goal of the solid-state light simulator presented in this paper is to simulate the AM 1.5G spectrum with the characteristics given in Tables I and II. The solar irradiance in the wavelength interval 400-1100 nm is found by integrating the standard solar spectrum (Fig. 1), leading to the approximate value of 755 W/m^2.

By the knowledge of the dimension of simulator's emitting surface, A, and the required radiant flux incident on the working area, E_e, the total radiant flux of light sources can be determined as [9]

$$\Phi_e = E_e \cdot A \,. \tag{2}$$

For a test plane area (A) of 12.5×12.5 cm, the total required flux is 11,8 W. The radiant flux in equation (2) is a flux of the light sources that reaches the test area. To calculate the radiant power of light sources, the attenuation of radiation must be considered. If the solar simulator is surrounded by a perfectly reflecting surface, i.e., an ideal waveguide, the irradiance of a test plane E_e is equal to radiant emittance M_e of simulator

$$E_e = M_e \,. \tag{3}$$

In this paper, straight aluminum lightguides are adopted having three different lengths: 20, 13.5, and 6.5 cm. In this case, (3) exactly applies only in the ideal case of unity spectral reflectance, $\rho_{Al} = 1$.

Two white LEDs (3700K and 8300K), four monochromatic LEDs, and a low voltage halogen pin based lamp were chosen. Because of high price of power ultraviolet and infrared LEDs, it was decided to use the cold white LED to compensate the spectrum close to 400 nm, and the halogen lamp for the (near) infrared region. In order to estimate the expected combined spectrum of the light sources, each spectral power distribution curve was obtained from the calculation and processed in MS Excel. To calculate the spectral irradiance of each light source, (3) was used under hypothesis of perfectly reflecting light-

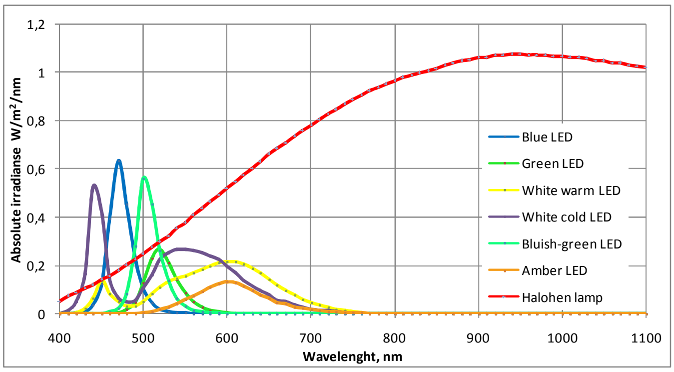

Fig.2. Calculated spectral irradiance of each radiation source (rated current).

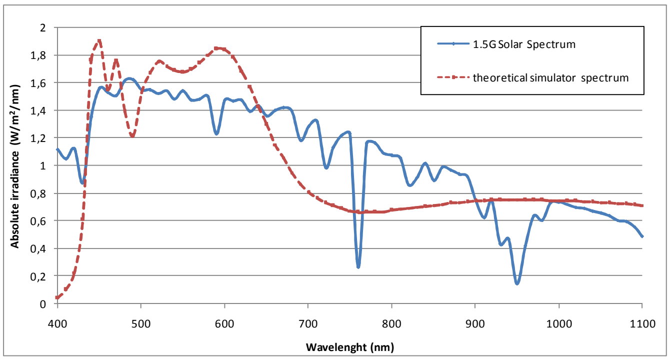

Fig. 3. AM 1.5G solar spectrum and hybrid solar simulator spectrum.

guide ($\rho_{Al} = 1$). The calculated spectral irradiance of each LED is shown in Fig. 2, and the preliminary theoretical spectrum of simulator is shown in Fig. 3, together with the reference solar spectrum AM 1.5G. The simulator spectrum in Fig. 3 was obtained on the basis of the spectra shown in Fig.2 multiplying each curve of absolute irradiance by an appropriate weight coefficient *k*. Rounding up the coefficient *k*, was found necessary (minimum) number of light sources per simulator module (125x125 cm^2 area). Then, by the current-flux relationship depicted in Fig. 4, established for each source, was found the supply current in terms of fraction of rated lamp current, % I_r. The results are shown in Table III.

C. *Description of the Optimization Procedure*

To improve the matching of the two spectra, the optimization procedure described in the following has been adopted.

The simulator's spectrum is discretized in the six wavelength intervals $[\lambda_{h-1}, \lambda_h]$ defined by Table I and Fig. 1. For each interval $\Delta\lambda_h$, the contribution of the n radiation sources (both LEDs and halogen lamp) is calculated. The difference between the solar irradiance $E_{sun}(\lambda)$ and the sum of irradiance of all sources in each wavelength interval, $\varepsilon(\Delta\lambda_h)$, should be minimized. This concept is expressed by the following set of equations

$$\left\{ \overline{E}_{sun}(\Delta\lambda_h) - \sum_{i=1}^{n} k_i\, \overline{E}^{\,i}_{sim}(\Delta\lambda_h) = \varepsilon_{\text{error}}(\Delta\lambda_h)\right. , \tag{4}$$

being $h = 1, 2, \ldots, 6$, and

$$\overline{E}(\Delta\lambda_h) = \int_{\lambda_{h-1}}^{\lambda_h} E(\lambda)d\lambda\,. \tag{5}$$

The quantity $\overline{E}(\Delta\lambda_h)$ represents the integral of either absolute solar or simulator irradiance in the wavelength interval (defined by International Electrotechnical Commission [8]). The parameters k_i are the unknown coefficients, whose meaning was explained in previous paragraph. The coefficient $\varepsilon_{error}(\Delta\lambda_h)$ represents an error, the difference between solar (ideal) irradiation and actual irradiation of solar simulator. In ideal case, the error will be equal to zero. To meet class A of spectral matching, the value of relative error $\varepsilon_{error,rel}(\Delta\lambda_h)$ should be lower than ±0,25 (see Table I).

$$\varepsilon_{error,rel}(\Delta\lambda_h) = \frac{E_{sun}(\Delta\lambda_h) - E_{sim}(\Delta\lambda_h)}{E_{sun}(\Delta\lambda_h)}\,. \tag{6}$$

Equation (6) describes the relative error, where $E_{sim,tot}(\Delta\lambda_h)$ is total irradiance produced by all light sources per each wavelength interval. Simulator spectrum designed in this project should have the relative error less than ±0,25 in all the 6 intervals. Overall relative error is found as weighted average of the absolute relative error of each interval.

The combinatorial optimization approach was used to resolve this problem. To resolve the particular set of equations (4) was used the "proof by exhaustion" or so called "brute-force" method. For realisation of computer program that will solve the set of equations by exhaustion method was selected the C++ programming language. The algorithm permits to generate all possible combination of k_i-variables and using them to resolve the set of equations. Then, the program will select only sets of k_i-variables with the result that the equation set will satisfy the range of tolerance ($\varepsilon_{min} \div \varepsilon_{max}$). Next problem is to find the best solution that minimizes the total error. The sum of errors in all 6 intervals from 400 to 1100 nm will be calculated for each sets of k_i-variables and the algorithm will choose only minimum sums.

TABLE III
WEIGHT COEFFICIENT *K* AND FRACTION OF RATED LAMPS CURRENT %I_R.
(PRELIMINARY SPECTRUM)

Light source	*k*	N. of lamps	% I_r
Blue LED	2	2	100
Green LED	1	1	100
White warm LED	2.7	3	84
White cold LED	2.5	3	80
Bluish-green LED	1	1	100
Amber LED	4	4	100
Halogen lamp	0.7	1	90

TABLE IV
RESULT OF OPTIMIZATION PROCEDURE

Interval, nm	400-500	500-600	600-700	700-800	800-900	900-1100
Relative error	0.011	–0.196	–0.062	0.203	0.003	–0.552
Overall relative error	–0.098					

The program has shown the best result with a minimum overall relative error equal to –0,098 (Table IV). All regions barring the region 900-1100 nm satisfy class A of spectral matching.

IV. Design and Realization of a Simulator Module

The simulator module is populated with an optimum number of LED chips of different wavelengths. Each module consists of 20 high-power LEDs of different wavelengths and pin-halogen based lamp; all light sources are mounted on a cooler substrate. Four white warm LEDs (3700 K), four white cold LEDs (8300 K), two bluish-green (500 nm), two green (530 nm), three amber (600 nm) and five blue (470 nm) LEDs were chosen for a single simulator module. These LEDs were mounted on a square heat sink about 12.5×12.5 cm^2. Each LED is mounted on printed circuit board (PCB), colored LEDs are located on square (1x1 cm) PCB and white LEDs are located on a bigger hex-shape PCB.

To understand if the cooler will be able to conduct enough heat from the LED system, the calculation of maximum thermal resistance of cooler is needed. To calculate the thermal conditions of various electronic components, including LEDs, the most commonly used is the equivalent resistance method. To simplify the calculations all thermal resistances at the joints of connecting parts and transfer of heat to ambient directly from the LED can be neglected. It is assumed that the entire heat is conducted only on the LED system – cooler – ambient. Thus, the thermal resistance of heat-sink cooler was calculated using the next equation [10]:

$$R_{hc} = \frac{T_j - T_a - P\,(R_{js} + R_{base})}{P_{tot}} \,, \tag{7}$$

being T_j the junction temperature of LED (100 °C), T_a the ambient temperature (30 ºC), P the power of a single LED, R_{js} the thermal resistance junction-to-solder point (2,5 – 15 K/W), R_{base} the thermal resistance of PCB, and P_{tot} the dissipated power by all the light sources.

Heat is transferred by thermal conduction from PCB to cooler. In this case thermal resistance depends on the physical properties of the PCB material and on its geometrical dimensions

$$R_{base} = \frac{\rho}{\lambda S} \,, \tag{8}$$

where ρ is length of the material (measured on a path parallel to the heat flow) (m), λ is the thermal conductivity of the material (W/K·m) and S is cross-sectional area (perpendicular to the path of heat flow) (m^2).

The heat-sink cooler has been selected on the basis of the calculations above. The thermal resistance of cooler should be equal or less than the thermal resistance calculated by (7).

Each LED module is positioned at end of an aluminium lightguide. Three different lightguides long 20, 13.5 and 6.5 cm were realized to avoid the attenuation and scattering of light waves and to study the output radiation of simulator at a three different distances. The finished simulator module comprising 20 LEDs and halogen lamp mounted on heat-sink and surrounded by one of the lightguides is shown in Fig. 4.

To have the possibility of simulating the different shapes of spectral distribution, the flux-current-mode control of light source was implemented. All LEDs of the same color are series-connected with an equalizing resistor to realize one branch. The single branch is driven by 2 bipolar transistors in the Darlington configuration, regulated by a linear potentiometer. In this way it is possible to implement a separately current-mode control for every brunch. All branches are connected in parallel. The electrical circuit is powered by a regulated dc voltage supply. The picture of circuit board is shown in Fig. 5.

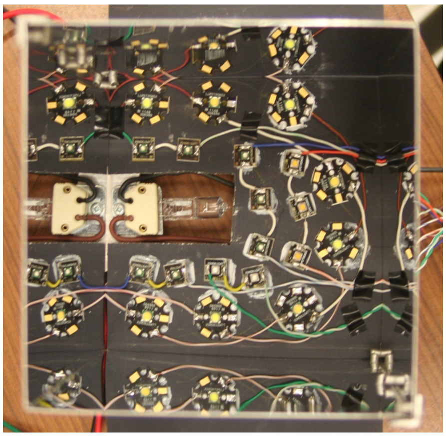

Fig. 4. Top view of the finished solar simulator prototype.

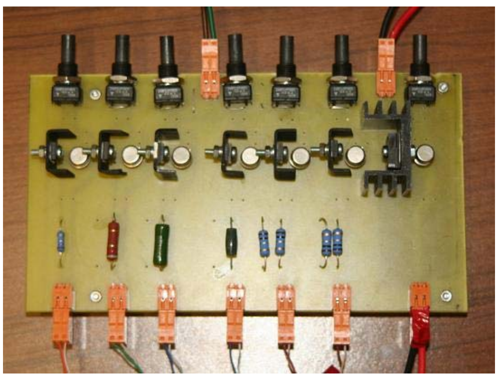

Fig. 5. Power supply unit of the simulator module.

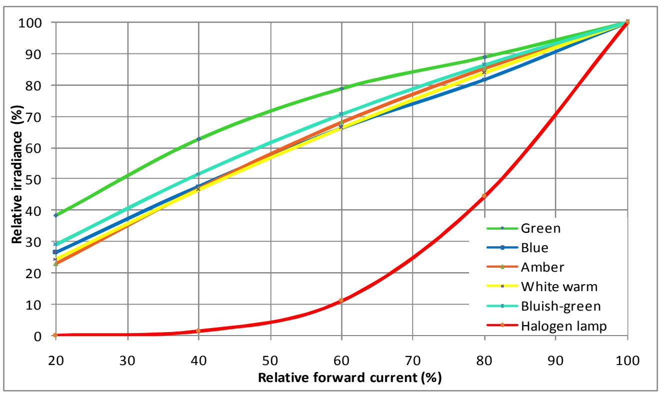

Fig. 6. LED irradiance vs. current.

V. Experimental Tests

A. Relationship Between Current and Radiant Flux

Once the number of light sources per unit of simulator has been fixed, a current-flux relationship should be established to apply current-mode control to sources and control the intensity. The resulting current-irradiance plots of some LEDs and halogen lamp used in this paper are shown in Fig. 6.

B. Correspondence Between Calculated and Measured Radiometric Quantities

Theoretical calculation of the irradiance under hypothesis of perfectly reflecting lightguide is given in section III. Obviously, the spectral reflectance of aluminum is less than unity. When measuring the total irradiance with non-perfectly reflecting lightguide, it should be noted that one part of irradiation reaches the test area without reflection and second part of radiation undergoes reflection. Thereby the total irradiance reaching the test area is composed by direct and reflected components.

The measurement of direct component made without lightguide and measurement of total irradiance with lightguide were made at a distance of 20 cm for each light source. The irradiance curve of white warm LED is shown in Fig. 7. Calculated total irradiance of white LED (green curve) is also shown in Fig.7. As expected, calculated value is overestimated due to unreal hypothesis of ideal lightguide. In addition, the manufacturer's rated wavelengths are oftentimes different from the measured emission of the LEDs. In this case the measured curves and the curves calculated from datasheet are shifted relatively to each other by about 5 nm.

C. Spectral Matching of Simulator Prototype

According to the measurements, the prototype of solar simulator meets class C of spectral matching at a distance of 20 cm from testing surface. Better spectral correspondence can be achieved at shorter distances. Using lightguides long 13.5 and 6.5 cm the solar simulator meets class B.

The maximum total irradiance measured with spectroradiometer at 20 cm distance is equal to 590 W/m^2, while the measured irradiance by solarimeter SLM018c-E is equal to 873 W/m^2. Reducing the distance up to 13.5 cm the irradiance reaches almost 750 W/m^2, this value completely satisfies the requirements of the standards. The total irradiance measured with use of solarimeter at 13.5 cm from simulator is equal to 1150 W/m^2. A significant increase of irradiance was registered at a distance of 6.5 cm, measured values by the spectroradiometer and the solarimeter are 1000 and 1500 W/m^2 respectively. Optimized theoretical spectrum and measured spectra at the three different distances are shown in Fig 8.

This significant difference of measured values can be explained by the weak accuracy of both measuring instruments. As noticed in Fig. 8, the spectroradiometer provides a great noise from 900 nm, moreover the spectroradiometer is calibrated for wavelength interval from 300 to 1045 nm. The spectroradiometer is not able to measure the radiant power with wavelength over 1045 nm. In regard to solarimeter, this instrument is calibrated with solar spectrum which is different from the simulator one. Solarimeter used for the measurements has a mounted monocrystalline silicium solar cell. The band gap of silicium is equal to 1.2eV, it means that this material is able to convert the radiant power with maximum wavelength of 1100nm. Thereby, these two measuring instruments take measurements at different wavelength intervals.

D. Non-Uniformity Study

The irradiation produced by simulator should have as low as possible non-uniformity. This parameter is definitely the most difficult to satisfy because the solar radiation is very uniform. Uniformity is a measure of how the irradiance varies over a selected (or defined) area. Usually it is expressed as non-uniformity *U*, by the maximum and minimum % differences from the average irradiance, as:

$$U = \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \cdot 100 \quad . \tag{9}$$

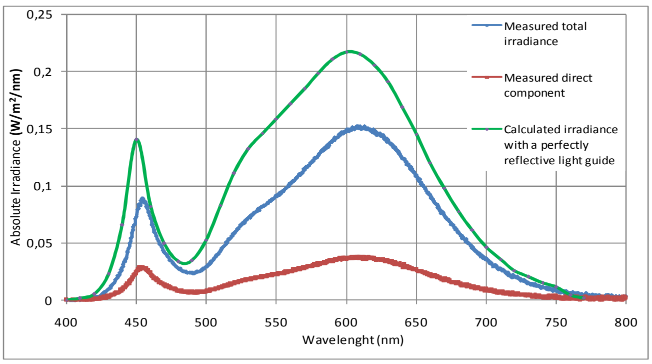

Fig. 7. Measured vs. calculated irradiance of warm white LED.

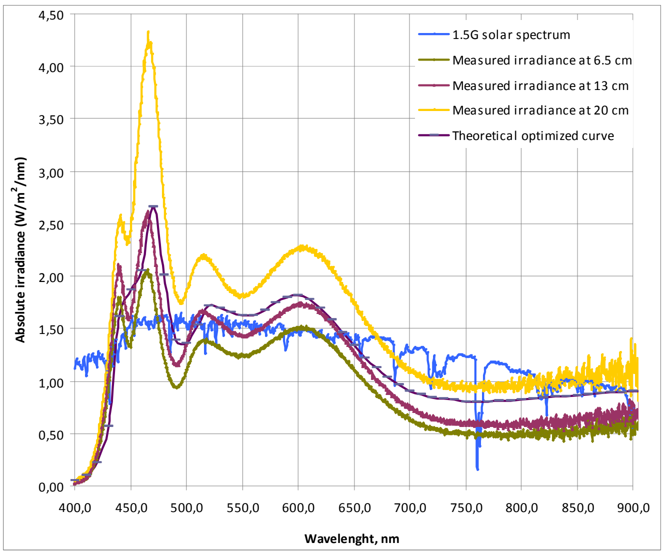

Fig. 8. Optimized theoretical spectrum and measured spectra at three different distances.

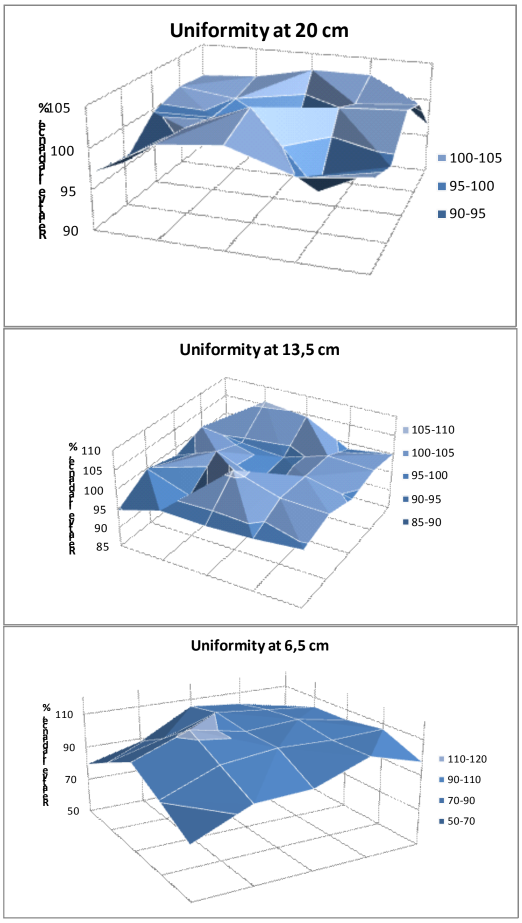

Fig.9. The irradiance uniformity at the output of three lightguide.

The simulator's uniformity within the illumination test plane of designed solar simulator was studied at three distances. The experimental results of the irradiance uniformity at the output of the lightguides long 20, 13.5 and 6.5 cm are shown in Fig. 9. The measurement shows a non-uniformity less than 5% over a distance of about 20 cm and less than 6% at a distance of 13.5 cm. At a distance of 6.5 cm, it is obtained an almost unacceptable value of uniformity equal to 17%.

V. Conclusion

In this paper, the analysis and the design of a low-cost hybrid solar simulator consisting of few types of power LEDs and one halogen lamp has been carried out. A procedure of design for spectral match class B for a working area of 12.5×12.5 cm^2 (single module) and respective measurement were presented. The optimization process to minimize the spectral mismatch between solar and simulator spectra was described. Despite of this optimization algorithm has been specifically applied to the proposed simulator, it could be also usefully adopted to design new solar simulators with different light sources. Experimental results have shown that the simulator achieves Class C uniformity over an area of 12.5x12.5 cm^2.

One of the advantages of presented hybrid simulator is the use of the halogen lamp. This source of light is very cheap and it has a high power in near infrared region, making possible to avoid the use of expensive infrared power LEDs. On the other hand, the main drawback consists in its cooling problems, being located close to other sources of light (LEDs).

By the use of low-cost and high-power light sources the proposed solar simulator is very cheap, being the estimated overall cost of the single module around 250 €.

Possible upgrades to the simulator include implementation of accurate and automatic current mode regulation, adding infrared and ultraviolet LEDs for improving spectral distribution, and achieving better uniformity classification, but despite of the greater cost.

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