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INVESTIGATION OF SOLAR SIMULATOR BASED ON HIGH-POWER LIGHT-EMITTING DIODES

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High-power light-emitting diodes for application in a solar simulator were evaluated. The solar simulator was designed using only 6 types of high-power LEDs. The irradiance non-uniformity of this simulator was investigated and it was demonstrated that a small array (only 25 units) of selected light-emitting diodes can provide sufficient irradiance to achieve AM1.5G requirements for the test area of at least several cm in diameter without any secondary optics.

Keywords: solar simulator, light-emitting diode, AM1.5G

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1. Introduction

Solar simulators are a source of light providing illumination close to the natural sunlight. They are used for controlled indoor testing of different materials and devices, but more often for solar cell investigation, characterization, quality control, and performance verification of completed modules. Several kinds of lamps have been used as light sources in solar simulators, such as various gas discharge lamps, incandescent halogen lamps or their combination. However, the most common source of light is xenon arc lamps due to a reasonably good match of the spectrum. Therefore, solar simulators with traditional lamps have the disadvantage of low luminous efficiency, high power consumption, performance changes with aging, complex control, and thermal management issues. Also, lamps have a relatively short (~1000 h) lifetime.

Most usually, AM1.5G standardized conditions [1] for the solar spectrum are simulated. The IEC 60904-9 standard defines the performance criteria for solar simulators in three categories: spectral distribution match, non-uniformity of irradiance, and temporal instability [2]. Solar simulators are classified as A, B, or C for each of these three categories.

In comparison with conventional lamps, light-emitting diodes (LEDs) have numerous specific advantages, such as high efficiency, lower thermal emission, longevity, fast switching, low operating voltage, etc. However, LEDs have a narrow spectral emission bandwidth. Nevertheless, multiple LEDs of different wavelengths can be assembled in arrays, and their outputs can be individually controlled, allowing easy adjustment of the spectrum. During the past decade several groups have reported on the design and characterisation of LED-based solar simulators and have shown their use for measurement of solar cell responses [3]. Early works have shown low intensity limitations of LED-based simulators [3, 4]. Then, a hybrid LED and halogen lamp solar imitator with B-class spectral match was demonstrated [5]. Light-emitting diodes were applied to simulate solar radiation with 90% of the intensity required by the standard [6]. AM1.5G spectral distribution reaching intensities up to 3 suns was approximated by independent tuning of 18 types of LEDs with different wavelengths in a still relatively complex array of 182 LED chips [7]. Recently, a large area solar simulator with 5-meter-long mirror waveguides and 34 types of different LEDs was presented [8]. A LED-based solar simulator prototype covering only a visible part of the spectrum with C-class uniformity on a 5 × 10 cm area was also demonstrated [9].

In this paper, we report on the design and characterization of a solar simulator prototype based on high-power light-emitting diodes as light sources. The aim of our work was to demonstrate that a compact array of only six types of LEDs (cool white, royal blue, deep red, far red, and two types of IR) can be sufficient for simulation of high (at least 100 mW/cm^2, i. e. 1 sun) light flux density with A-class [2] spectral distribution match and A-class irradiance non-uniformity for the test area of at least several cm^2. Reduction of the total number of LED chips from hundreds (used in [7]) to tens and absence of complex optics (used in [8]) were also set as additional criteria for the compactness of the system and the simplicity of its circuit design.

2. Materials

The selection of LEDs for a solar simulator was based on the fallowing considerations. First, LEDs must generate sufficient power in the wavelength interval of 400–1100 nm, and at least one type of LEDs must emit in each of the six wavelength ranges defined for AM1.5G solar simulators in [2]. Second, phosphor-converted white LEDs are preferred over RGB LEDs due to low efficiency of the green component. Third, high-power LEDs are required for achievement of a high (at least 100 mW/cm^2) irradiance level. In particular, six types of light-emitting diodes were selected for a solar simulator.

The majority of radiated power was provided by cool white *Bridgelux* BXRA-56C100-A-00 LEDs. These light-emitting diodes with approximately 10 W of electric power can provide all the required [2] radiation in the 500–600 nm spectral range and contribute most of the required optical power for the 400–500 nm range. The remainder is provided by 3 W *Luxeon* LXHL-LR3C royal blue light-emitting diodes. Deep red 10 W *LED Engin* LZ4-40R200 LEDs served as light sources in the 600–700 nm spectral range, and far red 10 W *LED Engin* LZ4-40R300 emitted in the 700–800 nm range. *Osram Ostar* SFH 4750 and *Osram Ostar* SFH 4751 infrared 10 W LEDs were used in 800–900 nm and 900–1100 nm spectral ranges, respectively.

The emission spectra of LEDs were measured to see how well the spectral distribution matches a required power distribution between 400 and 1100 nm, when partitioned into six intervals. Figure 1 presents the emission spectra of the LEDs measured using a photonic multichannel analyser *Hamamatsu* PMA-12 and spectrometer *Avantes* AvaSpec 2048.

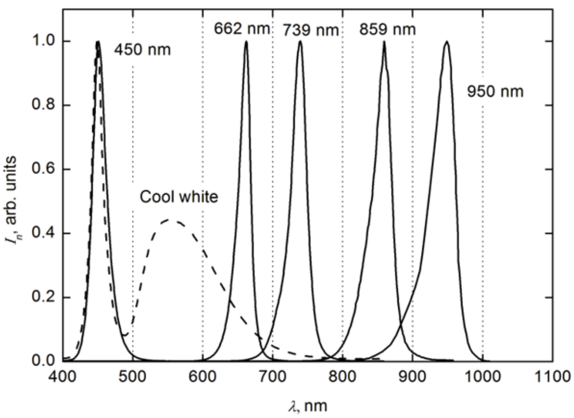

Fig. 1. Normalized spectral distributions of used light-emitting diodes. Emission peak wavelengths are indicated.

Six spectral ranges and required irradiance in these ranges are listed in first two columns of Table 2. Estimated contributions of each group of LEDs to six listed spectral ranges are presented in six columns on the right. Based on these values, a required irradiance from each group (fourth row from the bottom) was computed by solving 6 linear equations with 6 unknowns. Then the number of each type of selected light-emitting diodes was defined (last row) using information from LED data sheets. After multiplying

Table 1. LED properties, calculated values of required irradiance from each LED group, and required photocurrent density of the test photodiode.

Range, nm	Required irradiance in the range, mW/cm^2	Estimated LED power contribution to spectral ranges (%)					
		450 nm	White	662 nm	739 nm	859 nm	950 nm
400–500	18.4	99	32	–	–	–	–
500–600	19.9	1	45	–	–	–	–
600–700	18.4	–	21	100	4	–	–
700–800	14.9	–	2	–	96	2	–
800–900	12.5	–	–	–	–	97	8
900–1100	15.9	–	–	–	–	1	92
Required irradiance, mW/cm^2		4.3	44.1	8.6	14.4	11.4	17.2
Estimated* PD sensitivity, A/W		0.3	0.4	0.5	0.6	0.64	0.55
Req. photocurrent density, mA/cm^2		1.3	17.6	4.3	8.6	7.3	9.5
Number of LEDs		2	7	4	6	3	3

* Approximate values based on information presented in the data sheet.

the required irradiance values by the estimated sensitivity (third row from the bottom) of the Si photodiode *Osram* BPW34B, the required photocurrent densities of each LED group are obtained (second row from the bottom). This photodiode was later used for the characterization of the solar simulator.

All light-emitting diodes supplied have already been mounted on individual hexagonal star type aluminium-core PCBs. LEDs were arranged in a "honeycomb-like" pattern to ensure optimal flux homogeneity and assembled on an aluminium rectangular plate. The size of the cluster containing 25 units of LEDs was 105 × 125 mm, and the distance between each LED's centre to all nearby LEDs' centres was 21 mm. A plate with LEDs was mounted on a tube type aluminium heat sink with inner fins. Forced air cooling with a fan was used for heat removal. The radiant flux of each array was controlled by an independent driving current provided by *TTi* QL564-TP and *Mastech* HY-5003 laboratory power supplies.

3. Results and discussion

The distribution of the radiant flux was investigated using a motorized XY stage *Standa* 8MT195 and *Standa* 8MT295 with a test photodiode *Osram* BPW34B (crystalline silicon, 7.45 mm^2 area) connected to *Thorlabs* power meter PM100D. Arrays of different colours were switched on one by one for the estimation if photocurrent is sufficient for the given irradiance. LEDs were operated at maximum rated currents during this stage of the experiment. Table 2 presents results of measured maximum and averaged photocurrents on the test plane (6 × 6 cm) below the central part of the solar simulator. At a 12 cm distance from the LED plane, an array of white light-emitting diodes produces more than 17.6 mA/cm^2, which is estimated as a required minimum for AM1.5G irradiance in corresponding spectral ranges (see Table 1). Excess power is available from all LEDs above 600 nm. The contribution of royal blue LEDs is not sufficient for ideal match to AM1.5G; however, they are not even required for the spectral match in the 0.75–1.25 intensity range allowed by the standard [2] for A-class spectral irradiance match. With all LEDs operating at the maximum rated current, photocurrent from a Si photodiode exceeds 70 mA/cm^2, suggesting that photon flux is substantially higher than required by AM1.5G conditions.

The distance dependence of peak irradiance below the central part of the solar simulator was measured for all six light-emitting diode types. Results of these measurements are summarized in Fig. 2. For the most powerful diode group (white), the required peak irradiance is exceeded by approximately 4 and 2 times at a distance of 5 and 7.5 cm, respectively. Even a larger power excess is available from diode groups with wavelengths of above 600 nm. Royal blue (450 nm) LEDs exhibit lower peak irradiance rations; however, the main contribution to the 400–500 nm range is provided by white LEDs, so this deviation is insignificant.

After this measurement, the distance of 8.2 cm from the LEDs was selected for further optimization as the most suitable in this design compromise between irradiance level and its' uniformity. Currents of LEDs were adjusted to the required ones for the best AM1.5G approximation, and photocurrent distributions at a higher spatial resolution were measured separately for all light-emitting diode types. Then spectral irradiance distribution was computed for each type of LEDs. Results are presented in Fig. 3. Illuminated areas of royal blue (450 nm), deep red (662 nm), and both types of IR (859 and 950 nm) LEDs are asymmetric due to non-central arrangement of these LEDs on the plate. As mentioned above, spectral irradiance distribution

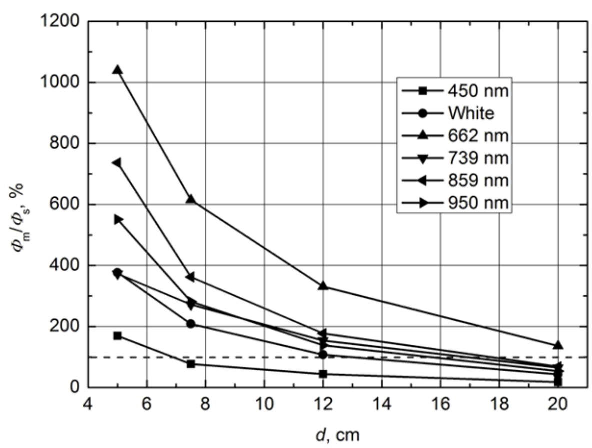

Fig. 2. Peak irradiance (normalized to irradiance required by the standard) as a function of the distance to the solar simulator.

Table 2. Maximum and averaged photocurrent on the test plane (6 × 6 cm) below the central part of the solar simulator.

LEDs	450 nm	White	662 nm	739 nm	859 nm	950 nm
Max. photocurrent, mA/cm^2	0.41	19.0	14.2	12.8	13.5	12.5
Aver. photocurrent, mA/cm^2	0.37	18.0	13.1	12.3	12.5	11.0

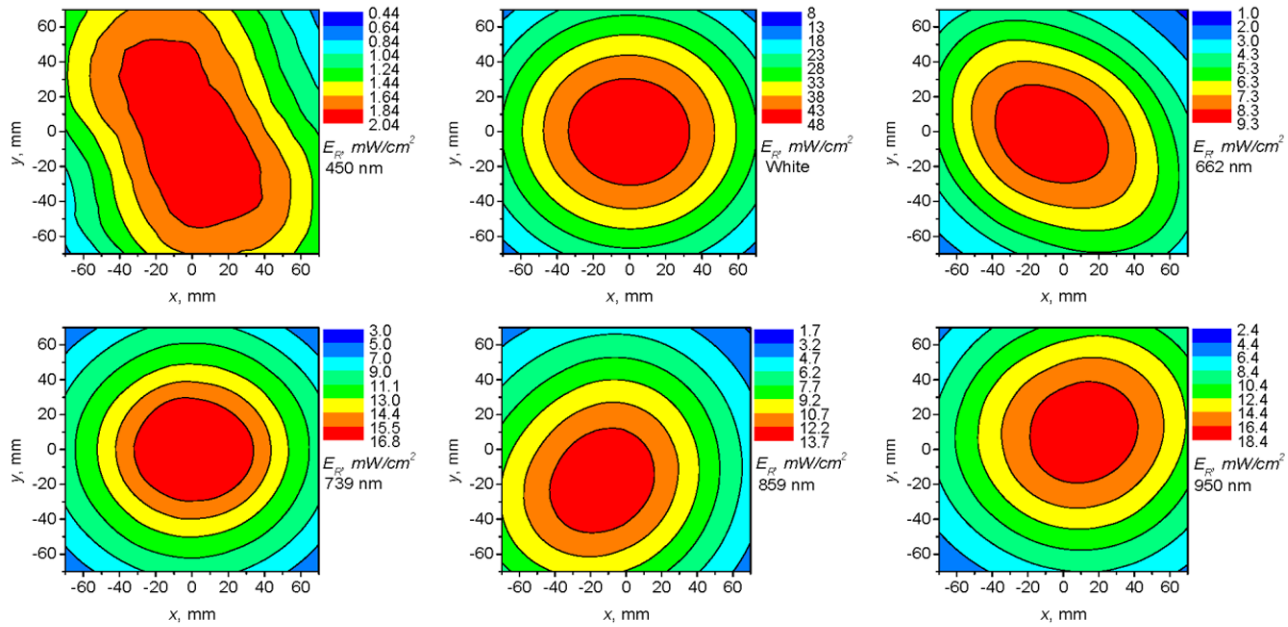

Fig. 3. Spectral irradiance distributions at a 8.2 cm distance.

of royal blue LEDs does not match AM1.5G; however, they are used as a supplemental source of light in the 400–500 nm range wherein the main contribution is provided by white LEDs. Thus, required irradiance levels for the spectral match in the 0.75–1.25 interval (A-class) allowed by the standard were achieved for an illuminated area of at least 5 × 5 cm in all six wavelength ranges.

Then the measurement of irradiance non-uniformity in the test plane was performed. All LEDs were switched on, and all driving currents were the same as in the measurement of spectral irradiance distributions. Based on the standard [2] recommendation, Si photodiode short-circuit photocurrent distribution was used as a measure of non-uniformity of irradiance. In this case, the PM100D unit served as a computer-controlled ammeter. All values were normalized to the peak photocurrent value corresponding to AM1.5G. The result is presented in Fig. 4(a). Cross sections of normalized photocurrent 2D plot at $x = 0$ and $y = 0$ are shown in Fig. 4(b).

Three horizontal solid lines indicate the lower irradiance level for 2%, 5%, and 10% deviation, corresponding to A, B, and C classes of non-uniformity, respectively. Three horizontal dashed lines depict the average values from which deviation was computed.

Less than 2% of photocurrent deviation is obtained for a round area of 4 cm in diameter or a 2.8 × 2.8 cm square, corresponding to A-class non-uniformity (see Fig. 4(b)). This diameter expands to a 6 cm or

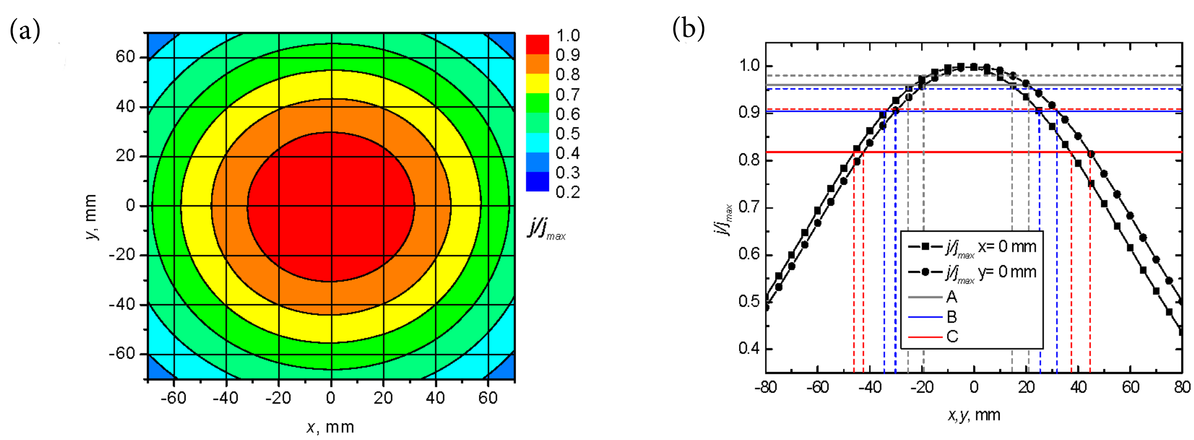

Fig. 4. Non-uniformity of induced photocurrent at a 8.2 cm distance. Photocurrent distributions at a 8.2 cm distance: (a) photocurrent is normalized to the peak value, (b) cross sections of 2D plot at given *x*, *y*.

4.2 × 4.2 cm square if 5% non-uniformity (B-class) is acceptable. For C-class this area grows to 8.2 cm in diameter or a 5.7 × 5.7 cm square.

Afterwards, measurements of spectral irradiance distributions were performed using a calibrated *Avantes* AvaSpec 2048 spectrometer with a SMA fibre patch cord and *Thorlabs* CCSA2 cosine corrector. Five points on the test plane were selected: one in the centre of the test plane and four at corners of a 60 × 60 mm square area, which is slightly larger than that defined as acceptable for C-class non-uniformity of irradiance (see Fig. 4(b)). The distance to the test plane was the same as in previous investigations with the photodiode. Measurement results are presented in Fig. 5(a). By integrating spectral irradiances, the total irradiance values at each test point were also calculated for all six spectral ranges and then non-uniformity of irradiance evaluated. From this data 12% of irradiance non-uniformity is obtained, which matches the data of Fig. 5 within the value difference

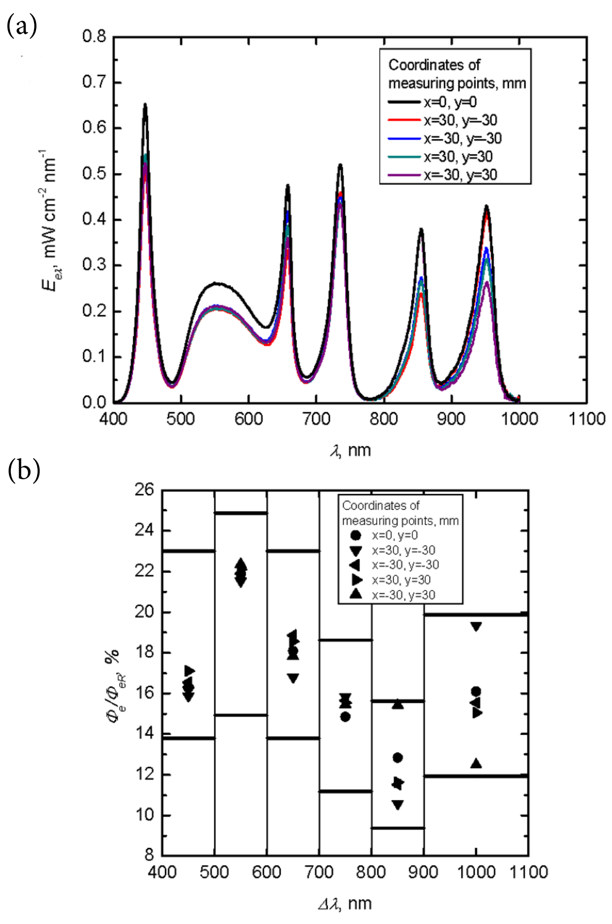

Fig. 5. (a) Spectral irradiance distributions at 5 points of the test plane. (b) Integrated spectral irradiance ratios to the total irradiance for six wavelength intervals at 5 points of the test plane. Horizontal lines indicate upper and lower limits for A-class spectral match.

between the neighbouring points. The spectral irradiance match for six wavelength intervals, which is the ratio of calculated percentage for the measured simulator irradiance and the required irradiance for each interval, was calculated at five test points. Results are presented in Fig. 5(b). Solid horizontal lines indicate upper and lower irradiance levels (in %) from the required ones for the A-class solar simulator. As one can see, the required irradiance levels for A-class spectral match in all six wavelength intervals were achieved at all five test points.

4. Conclusions

In summary, advances in light-emitting diode technologies allow construction of LED-based solar simulators. Such simulator of A-class spectrum and irradiance non-uniformity was demonstrated using just 6 types of high-power LEDs. Only 25 LEDs are needed for a usable illuminated area of 4–8 cm in diameter depending on the acceptable irradiance non-uniformity and spectral distribution match. However, further research is required for simulator's temporal stability evaluation and design improvement.

Acknowledgements

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DIDELĖS GALIOS ŠVIESTUKUS NAUDOJANČIO SAULĖS IMITATORIAUS TYRIMAS

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Santrauka

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