Solar World Congress 2025

DESIGN OF A NOVEL TUNABLE A+ LED SOLAR SIMULATOR

Summary

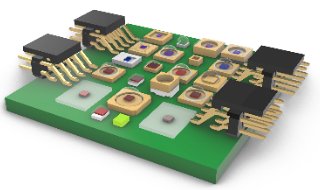
This work comprises of the preliminary spectral matching algorithm development and optical simulations for the design of an LED solar simulator with better fidelity to the AM1.5G solar spectrum than the A+ classification of the IEC60904-9 standard. The simulator is also able to replicate the AM0 solar spectrum for reliable testing of multijunction PV cells for aerospace applications as well as replicating the daily spectral variations on Earth caused by the Sun's relative movement and weather conditions. These characteristics ensure better reliability of indoor test results than the current commonly accepted standard.

Keywords: led solar simulator, spectral mismatch, tunable spectrum, modular design

1. Introduction

Indoor testing with solar simulators has cemented itself as the gold standard of the evaluation of the Power Conversion Efficiency (η) of photovoltaic (PV) devices. The clear advantage of indoor tests is the fact that they can be performed in controlled environments and thus offer easily reproduceable results. However, the IEC60904-9 (International Electrotechnical Commission, 2020), which represents the main guideline in the design and construction of simulators, encompasses only the 300-1200 nm range of the AM1.5G spectrum, leaving out the UV and NIR components that can be crucial for the evaluation of devices and technologies like multijunction PV cells and modules with downshifting layers (Tavakoli et al., 2021, Kolberg et al., 2011). In addition, while the AM1.5G is an adequate reference spectrum, the real solar spectrum varies depending on the geographic location and weather conditions. These deviations from the AM1.5G can give rise to significant discrepancies between the measured η and the real η in working conditions. To reduce this mismatch, we propose an innovative LED solar simulator able to reproduce user-defined spectra, allowing to mimic the AM0 spectrum for aerospace applications, to better match the AM1.5G and to simulate daily spectral variations on Earth. At this stage, the solar simulator is designed to be composed of 25 insulated metal substrate (IMS) printed circuit boards (PCBs) arranged in a 5x5 square. Each PCB is 30x30 mm^2 and contains 21 monochromatic LEDs. This design ensures that a 30x30 mm^2 area placed 7 cm away from the PCBs is irradiated with the desired power. The simulator is modular and can be expanded to the desired module size. This feature is extremely important as the module size is constantly increasing in time, leading to early obsolescence of standard solar simulators.

2. LED choice and characteristics



LED	Peak wavelength [nm]	FWHM [nm]	LED	Peak wavelength [nm]	FWHM [nm]
1	285	10	12	660	22
2	300	10	13	730	31
3	340	12	14	750	20
4	370	10	15	810	30
5	415	10	16	850	25
6	450	22	17	890	25
7	475	20	18	940	50
8	527	35	19	1050	60
9	566	100	20	1200	60
10	590	20	21	1550	110
11	625	17			

Fig. 1: PCB render, peak emission wavelength and FWHM of the 21 LEDs of the solar simulator.

21 LEDs have been chosen as surface-mounted devices (SMDs) as they are of relatively small size compared to other kinds of LEDs and can be easily soldered on the PCBs. Multicolor and white LEDs have been avoided for better control over the spectral distribution of radiation and for better reproducibility of different spectra

(Sun et al, 2022, Vosylius et al., 2023). The maximum optical power of the chosen LEDs is roughly double the power of the AM0 solar spectrum in the specific range of wavelengths of each LED emission. The total spectrum of the LEDs covers the 270-1600 nm wavelength range. Fig. 1 shows the PCB render and the peak emission wavelength and FWHM of the LEDs.

3. Spectral matching algorithm

The matching algorithm of the simulator spectrum S_{sim} (which is the sum of each LED spectra S_i) and the real spectrum S_r has been divided in two parts. At the end of the matching, the algorithm returns a set of 21 coefficients c_i which indicate the optical power output required from each LED. The spectral matching is performed by minimizing the error function σ shown in eq. 1, where $Err_{pow,k}$ is the error on the total power inside the k-th bin as shown in eq. 2, $Err_{shape,k}$ is the error given by the different shape of the two spectra inside the k-th bin (eq. 3), and the weight of the shape difference in each bin is given by the coefficients α_k, which are the average values of the first derivative of the EQE of the tested device (eq. 3). $Err_{pow,target}$ is the target error on the bin power and is defined via user input. The first step is the calculation of an initial set of c_i via the least square method, giving the starting weights for the individual LEDs. After that, the LEDs whose peak emission is in the k-th bin are considered and the algorithm rescales their emission spectra by searching the phase space of functions whose power matches the power of the real spectrum in the bin while minimizing $Err_{shape,k}$ at the same time. This yields the final set of c_i which are used in eq. 4 to calculate the final simulator spectrum S_{sim}. For the matching, the 270-1600 nm range has been divided into 9 bins with the following extremes: 270, 385, 470, 561, 657, 772, 919, 1000, 1200 and 1600 nm. The bins extremes coincide with the ones of the IEC60904-9 between 300 and 919 nm and reasonable additions have been made outside that interval.

$$\sigma_k = Err_{shape,k}\left(1+\frac{1}{1+e^{-\left(Err_{pow,k}-Err_{pow,target}\right)}}\right) \qquad \text{(eq. 1)}$$

$$Err_{pow,k} = \left(\frac{I_k^{sim}}{I_k^{t}}-1\right)^2 \text{ with } I_k^{sim} = \int_{\lambda_{min,k}}^{\lambda_{max,k}} S_{sim}(\lambda)d\lambda,\; I_k^{t} = \int_{\lambda_{min,k}}^{\lambda_{max,k}} S_t(\lambda)d\lambda \qquad \text{(eq. 2)}$$

$$Err_{shape,k} = \alpha_k \int_{\lambda_{min,k}}^{\lambda_{max,k}}\left(S_{sim}(\lambda)-S_t(\lambda)\right)^2 d\lambda \text{ with } \alpha_k = \frac{1}{\lambda_{min,k}-\lambda_{max,k}}\int_{\lambda_{min,k}}^{\lambda_{max,k}}\left|\frac{dEQE(\lambda)}{d\lambda}\right| d\lambda \qquad \text{(eq. 3)}$$

$$S_{sim} = \sum_{i=1}^{21} c_i S_i(\lambda) \qquad \text{(eq. 4)}$$

The matching algorithm has been tested on the AM0 and AM1.5G spectra and on a database of 1837 terrestrial spectra in the 300-1100 nm range provided by the NREL (National Renewable Energy Laboratory, 1990). Fig. 2 shows the AM0 and AM1.5G spectra (real and simulated) and the average σ and its standard deviation in each bin of the NREL spectra (the bins have been adjusted according to the smaller range of the spectra).

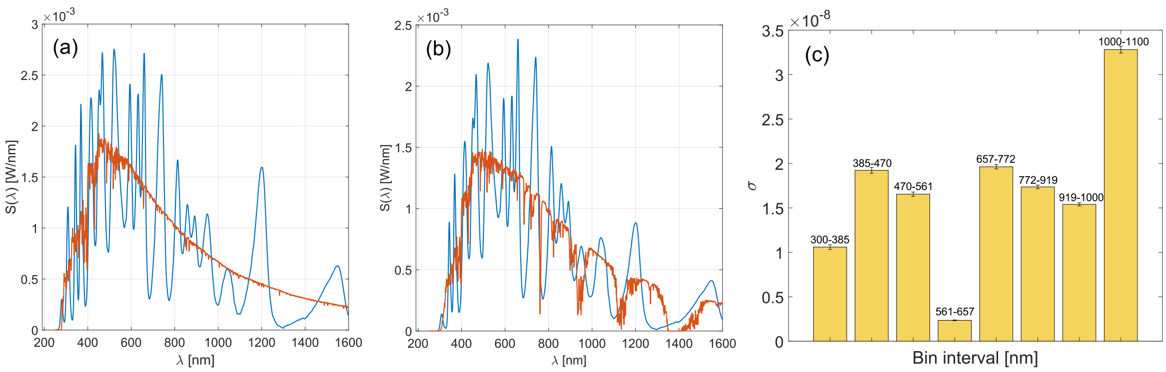


Fig. 2: (a) AM0 solar spectrum (orange) and simulated spectrum (blue). (b) AM1.5G solar spectrum (orange) and simulated spectrum (blue). (c) Average σ in each bin across the 1837 NREL spectra analyzed.

4. Optical simulations and spatial uniformity

A series of non-sequential raytracing simulations have been performed on Ansys Zemax OpticStudio, permutating the LED positions to find the configuration with the lowest spatial non-uniformity of irradiance and highest average spectral matching over the active area with respect to the AM0 spectrum. The choice of the AM0 over the AM1.5G is due to the fact that the AM0 is not attenuated by the absorption of the atmosphere and thus has a higher spectral irradiance in some wavebands of the spectrum. Given the size of the LEDs, the 1200 and 1550 nm LEDs have been constrained to occupy the same relative position to each other and have only been allowed to move up and down along the imaginary grid drawn on the PCB. Each simulation has been conducted with ~5 10^6 rays per LED and a macro has been used to change the positions of the LEDs on the PCBs. The active area has been divided into a grid of 36 5x5 mm^2 pixels. The spatial non-uniformity has been calculated as shown in eq. 5, in accordance with the IEC60904-9 standard. The best value obtained across the entire 3x3 cm^2 active area is 2.99%, corresponding to a category B solar simulator of the IEC60904-9. On the central 2x2 cm^2 area the spatial non-uniformity is 0.97%, corresponding to an A+ simulator. Fig. 3 shows the pixels spectra and the power map for the lowest non-uniformity.

$$\mathrm{Non-uniformity}\ [\%] = 100 \cdot \frac{\max(P) - \min(P)}{\max(P) + \min(P)} \quad \text{(eq. 5)}$$

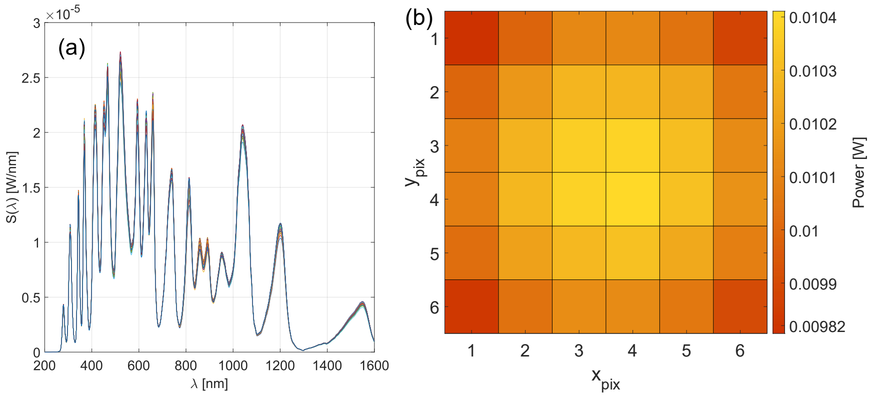


Fig. 3: (a) Spectra of all the 36 pixels. (b) Map of the power received by each pixel of the active area.

5. Conclusions and further developments

Further developments of the solar simulator will involve the design of free-form optics lens to reduce the overlap of the light pattern projected by each module and reduce the spatial non-uniformity, providing better spectral matching across the active area. The solar simulator will then be modeled in COMSOL Multiphysics to estimate the heat generated during operation and to identify the most optimal configuration to dissipate said heat and have the simulator work around an optimal equilibrium temperature. Finally, the first prototype will be presented, characterized and compared to the expected results given by the optical and thermal simulations.

6. References

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