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Development of tunable close match LED solar simulator with extended spectral range to UV and IR

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Abstract

Recent advances in high power LED technology pave the road for a fully LED based solar simulator for the PV industry. For an industrial application, the much higher lifetime of LEDs compared to conventional light sources will be an important financial benefit. For scientific research, the unique features of LEDs will allow for a new generation of solar simulators: instantaneous, tunable spectrum and the ability to modulate certain wavelengths will offer new methods in the field of PV characterization.
Here we present our achievements in developing a commercially available LED based class AAA solar simulator.

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"Keywords: Characterization, Silicon Solar Cell, Solar Simulator; LED; continuous spectrum; 350 nm to 1100 nm"

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1. Introduction

In solar cell production lines, 100% electrical performance measurements at standard test conditions STC [1] are essential for quality control and cost evaluations. Cell measurements are performed with Xenon Flash or Xenon short arc lamps as AM1.5G close match light sources in solar simulators. High throughput, low maintaining as well as high accuracy and best spectrum match to the AM1.5G standard spectrum [2] are desired. To overcome short lifetimes, long reload times for the flash generators as well as time consuming calibration procedures, we decided to develop a spectral tunable light emitting diode (LED) based Solar Simulator covering the full Si spectral range (UV to NIR).

2. LED current regulator drivers

Commercial off-the-shelf (COTS) driver electronics for high power LEDs are using switching topologies. For general lighting application, switching amplitudes of 10% at frequencies between 100 kHz to several MHz are typical. In addition, the intensity of the LED light is controlled using pulse width modulation (PWM) at frequencies of 100 Hz to 200 Hz. Both are unacceptable for a solar simulator, hence we developed a custom driver electronics for this application.

We use linear current regulators as current sinks. The current through the sink and the LED, respectively, is proportional to an input voltage. The prototype current regulator circuits shown in Fig. 1 are manufactured in-house using SMD technology. A total of 6 such drivers were available for the experiments. The final application will consist of 40 drivers to control each wavelength separately. The control voltage is supplied by a multi-channel digital-to-analogue converter (DAC) with software control. For our experiments a Kepco was used as main power supply; in the future this will be replaced by a more cost effective solution.

Special attention was given to a high temporal stability as desired for a solar simulator. The tests presented here were performed using passive air cooled power components and LEDs. Fig. 2 shows a measurement of the temporal stability of the intensity of a high power LED using this circuit. The measurement was performed using a Keithley DMM with a WPVS like cell (not calibrated) and a 100 Ohm Bürstner resistor. One data point per second was recorded after an on-time of approximately 5 min. This shows a temporal stability of the light intensity of ± 0.3%. The decrease over time is suggested to be

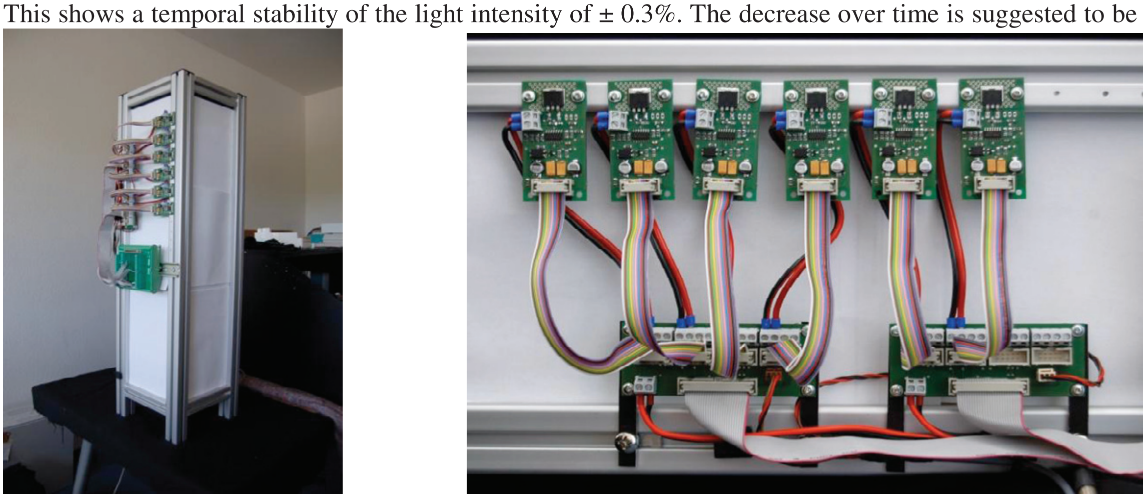

Fig. 1 (a) View of the prototype version of the LED based solar simulator; (b) Closer view to 6 of the custom-made driver circuits.

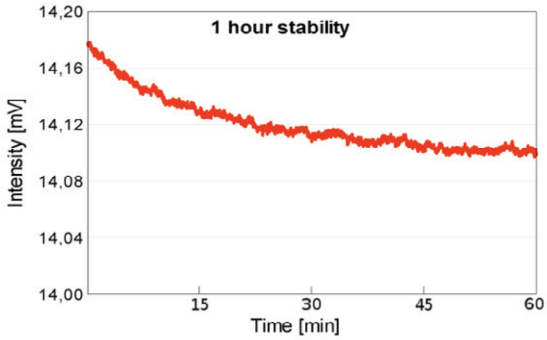

Fig. 2 Long-term stability test of one of the high power LEDs.

thermal heating. In future experiments, we will further evaluate the driver circuitry and LED, as well as we will use active temperature control by means of Peltier elements and a water cooled heat sink for both.

3. LED light source design

In Fig. 3 we show the target spectrum of our solar simulator from 350 to 1100 nm. Each of the thin lines shows the spectral distribution for one chosen wavelength, which in several cases consists of an array of more than a single chip LED. In the simulation of the full spectrum (bold black line), each LED forward current is optimized in order to fulfill the requirements of international norms for AM1.5G (amber line). However, the flexibility of the LED light source allows the user to match the spectrum to virtually any spectral distribution demanded by the user specific application.

For a proof of principle we can profit from the tremendous progress made in high-power LED

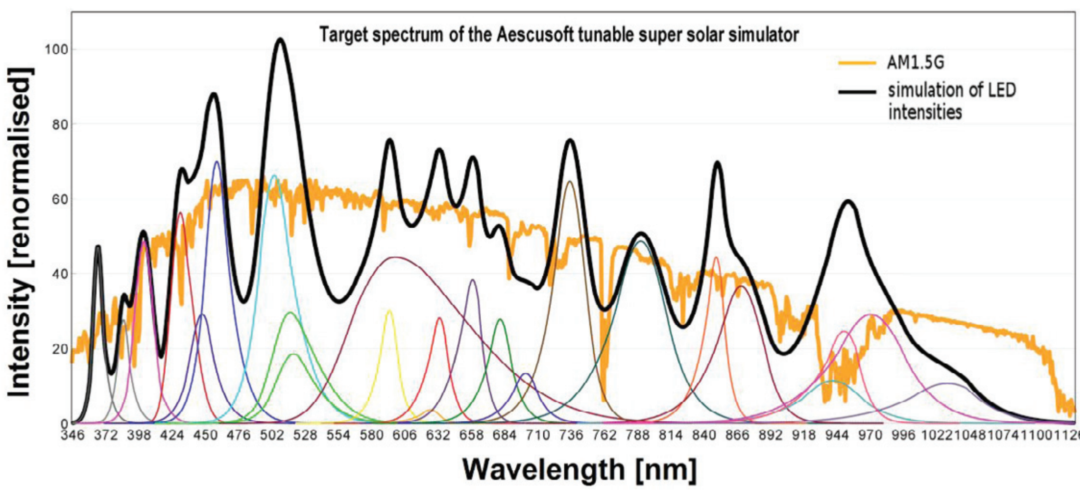

Fig. 3 The target spectrum of our solar simulator. Thin lines are the spectral distributions for each chosen wavelength; the bold black line is the simulated spectrum; amber line is AM1.5G.

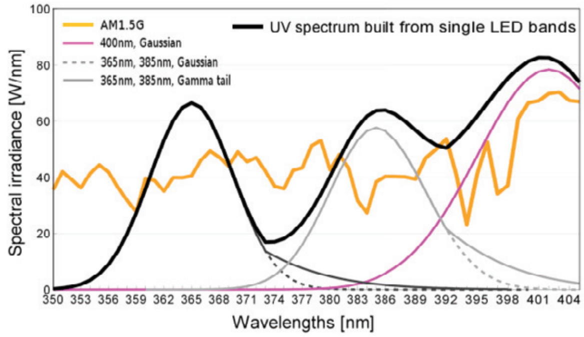

Fig. 4 Simulation detail in the UV region. The radiation band of each LED is taken to be a Gaussian distribution in first approximation. However, a better description of single LED light output is done adding a tail which follows a Gamma distribution. By doing so one fills the gaps between neighboring base wavelengths more easily.

technology during the last years. Despite this, in order to assure the high lifetime expectations for solid state devices, we are still using a total of ≈800 single dies, put into ≈70 packages.

3.1. Visible light

As one might expect, it is easiest to cover the visible wavelength range with high power light emitting diodes. One can choose from a vast number of LED packages and intensities. However, combinations of red, green, and blue, often used to produce white light, leave a rather large gap in the region around 560 nm. It is worth noting that in the spectrum in Fig. 3 even the rather large gap between green (525 nm) and yellow (590 nm) is covered without using white light LED. This preserves tunability options in this spectral region and still not using additional modules like filter wheels.

3.2. Ultraviolet

The spectral distribution of each LED has a width of a few nm for ultraviolet radiation to about 100 nm or more in the infrared. This gives the opportunity to close the gaps between the different LED base wavelengths. Fig. 4 shows the situation in more detail for the UV region. The wavelength dependence of the irradiance of LEDs of three different wavelengths is drawn as narrow lines. In a first approximation,

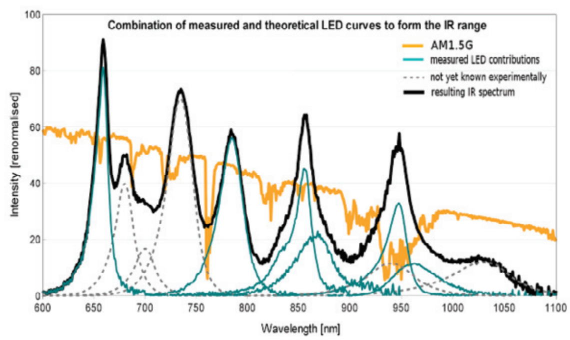

Fig. 5 Measurements in the IR region.

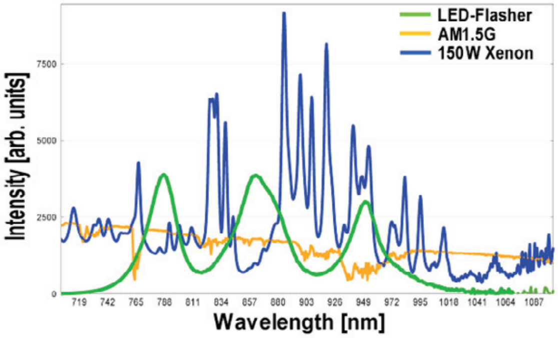

Fig. 6 Comparison to a typical 150W Xenon lamp.

the output power can be expressed as (symmetric) Gaussian functions. With a superposition of more and more of these functions (represented in W/nm), we filled up the diagram until the sum reaches the corresponding area under line for AM1.5G. Although there exist only few high power LEDs in the UV region, the forward currents needed in our solution are safely below the maximum allowed currents, hence, the lifetime increases remarkably.

3.3. Near Infrared

Fig. 5 details measurements and theoretical curves in the NIR region. An LED test head with 6 different LEDs was assembled and the resulting spectral distribution was measured using Aescusoft's FlashSpec™ spectrometer. Each individual LED was measured, as well as all LEDs together. The results are consistent with our simulations, hence we used the simulation data for the missing LEDs in the IR. Tuning the forward current separately, we can

- close the gaps between different LED base wavelengths, and
- match the solar spectrum intensity requirements according to ASTM G173 or IEC60904 in principle with any resolution demanded by the user.

Comparison with a typical Xe spectrum (Fig. 6) in the IR shows the LED spectrum to vary rather smoothly in intensity. Therefore the uncertainties in solar cell characterization due to strong and

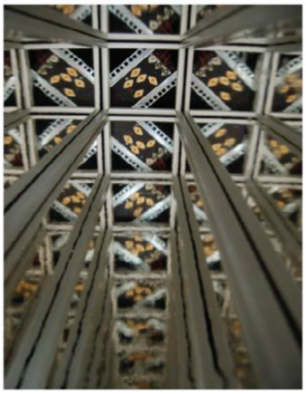

Fig. 7 Upside-down view into the mirror channel.

sometimes unstable Xe spectral peaks might be solved using LED solar simulators.

3.4. Optical design

Fig. 7 shows an upside-down view into the mirror channel, i.e., we look from the machine bottom in the direction of the IR-LED test head. The latter contains high-power light sources, which do not yet achieve the desired homogeneity demands. In the final very dense LED array this issue will be solved in combination with an improved mirror channel used as homogenizing element.

4. Conclusions and outlook

Whereas the temporal stability is already given, homogeneity still needs major development efforts on the road towards AAA specifications.

For the spectral match, our simulations have shown that we can achieve a very close match to AM1.5G and other spectra of interest. First measurements in the IR have proven that the simulated spectrum can be achieved. Using superior cooling technology, we will head for a full-intensity, full-spectrum lighting.

Further down the development road, we hope to make a new light source available to the PV research institutes and industry alike, with unique features unseen at present.

Acknowledgements

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[2] IEC 60904-9-Ed. 2: 2007, *Photovoltaic devices - Part 9: Solar simulator performance requirements*