Optimising large area solar simulation

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The solar simulator has allowed the laboratory development and testing of all PV devices. Filtered Xenon arc lamps were the gold standard source for solar simulation of small area Si PV devices, however scaling these devices to illuminate large areas is not efficient nor practical. LED based simulation allows for better electrical efficiency and uniformity of irradiance than is possible with other sources. This work details the design steps to achieve a scalable, large area LED based solar simulator featuring Class AAA performance over 640 cm^2 area with a measured non-uniformity of irradiance of 1.9%. This standard of simulation is required for testing the small finger areas of printed organo-electronic solar cells.

Introduction

Advanced testing of photo-responsive materials in a laboratory setting has seen the development of solar simulators [1] and three defined standards for solar simulation, being the International Electrotechnical Commission (IEC), IEC 60904-9:2020 [2] , the American Society for Testing and Materials ASTM E-927-19 [3] and the Japanese Industrial Standard JIS C 8912:1998/AMENDMENT 2:2011 [4]. Light sources utilized encompass; xenon and metal halide arc lamps, quartz tungsten filament lamps, and light-emitting diodes (LEDs) [5] where the selection of the emission source can depend on the desired solar simulation application. Many different types of solar simulators meeting one or more standards have been designed, developed and used since the 1960’s [6-8]. Notably, high pressure xenon gas discharge lamps provide the closest spectral match to the solar spectral output available from any artificial source, however, these lamps deliver small uniform irradiance fields due the challenge of optically imaging an electrical arc evenly over the test surface.

Rapid advances in high-power light emitting diodes (LEDs) have provided the opportunity to design and construct solar simulators from arrays of discrete LED light sources. These have been used to precisely imitate the spectral distribution of sunlight through many narrow bandwidth emitters, as well as match temporal diurnal intensity variation through advanced current control [9, 10], something not possible with conventional lamp-based solar simulator technology. In addition, with non-silicon photovoltaic cells emerging, a better match between LED emission wavelengths and device absorption has been reported in the literature [11].

These aspects attracted attention as the specific solar simulation requirement supporting roll-to roll printed organic solar cell development is to have very uniform irradiance across all spectral components over a large area. The fingers in Figure 1 form a large array requiring a uniformity of irradiance more than that required by the testing standards [2-4]. This uniformity of spectral irradiance requirement is an ongoing issue for discrete LED emitter based solar simulation [12].

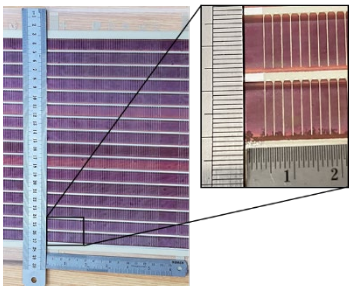


Figure 1. The large area (260 mm × 160 mm) array of 13 mm × 1.5 mm fingers of a roll-to-roll printed organic photovoltaic solar cell.

Approach

Optical design software, TracePro (Lambda Research Corp) has been employed to model the emission properties of each of ten different LED types required to cover the spectrum as shown in Figure 2 with the number of each of the 10 LEDs required to match the AM1.5G irradiance within the base design hexagon shown in Table 1. The physical arrangement of each of the 71 LEDs was determined by modelling irradiance and printed circuit board design constraints.

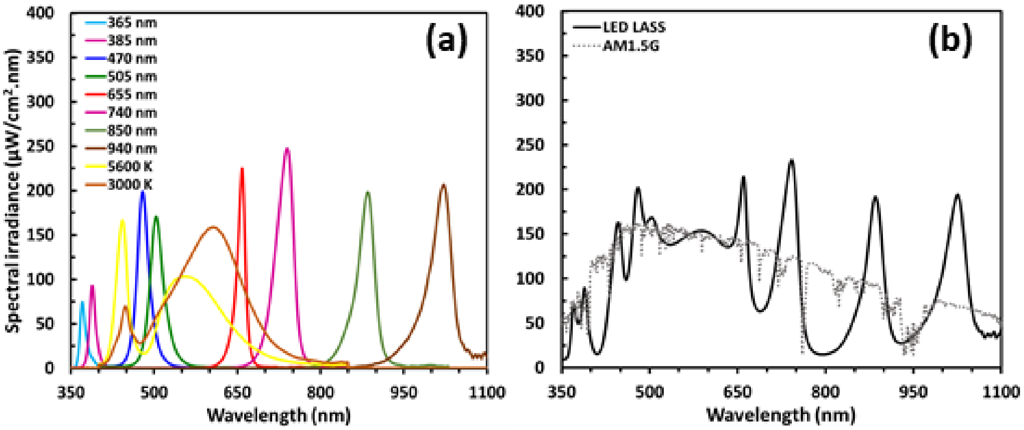


Figure 2. (a) The spectral irradiance of the ten LEDs selected for the simulator. (b) The combined emission as compared to the AM1.5G solar spectrum.

Table 1. Parameters and required numbers of the selected LEDs per hexagon.

Wavelength (nm)	LED Type	Power/ Flux	Part Number	# LED
350-380	365 nm	655 (mW)	LTPL-C034UVH365	6
370-410	385 nm	975 (mW)	LTPL-C034UVH385	8
415-780	3000 K	95 (lm)	LX 18-P130-3	6
410-780	5600 K	220 (lm)	LXML-PWC1-0120	13
460-520	470 nm	40 (lm)	LXML-PBO1-0040	10
470-550	505 nm	65 (lm)	LXMLPE010070	6
620-680	655 nm	360 (mW)	LXM3-PDOI	6
700-780	740 nm	705 (mW)	LZI-OOR302	6
820-920	850 nm	770 (mW)	SFH 4715A	4
920-1100	940 nm	425 (mW)	SFH 4725S	6

Following the irradiance balancing phase, a rectangular section that would repeat along the long edge was identified, as shown in Figure 3, and two printed circuit boards were designed and populated with 266 LEDs on each board. An optical housing with reflective sides was modelled and constructed with two diffuser stages to assist in smoothing the light emanating from the 532 individual emitters and providing uniform illumination to the sample test plane.

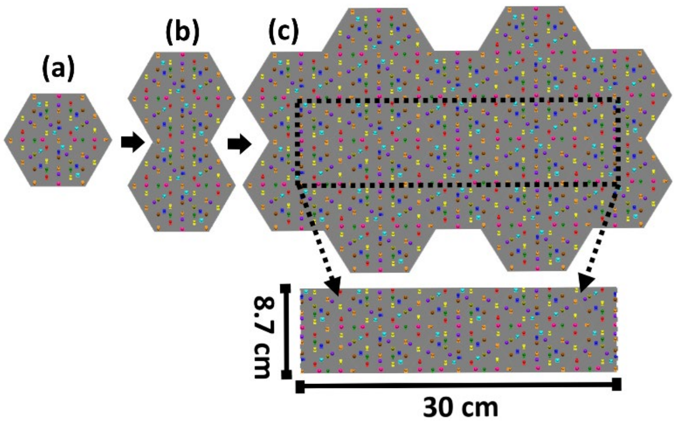
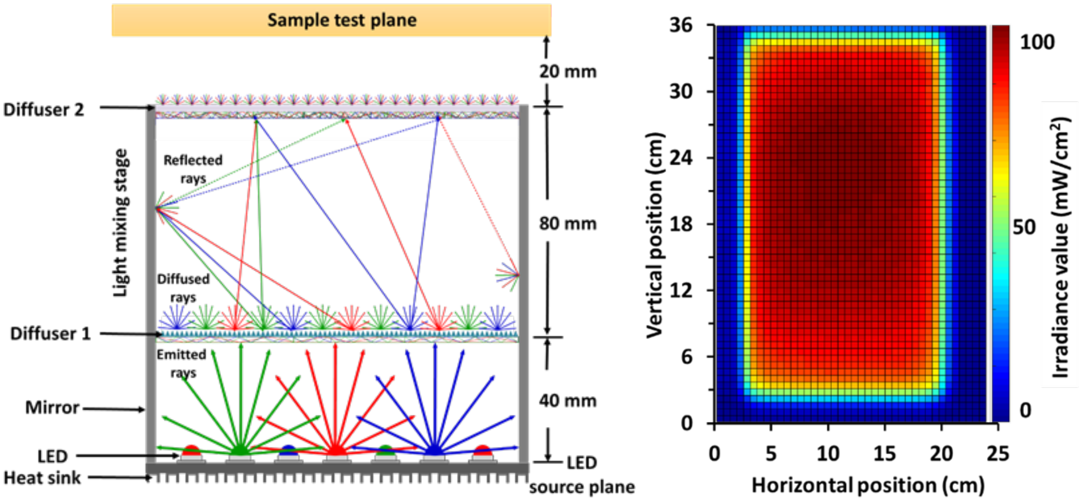


Figure 3. (a) The base hexagon unit cell. (b) Combined two cell unit. (c) Extraction of a 30 cm x 8.7 cm rectangular printed circuit board from a 12 unit cell array.

The light box design and the final test plane irradiance as measured at 3mm intervals across the test plane are shown in Figure 4.



(a) (b)

Figure 4. (a) The light enclosure designed with dual diffuser stages. (b) The measured irradiance of the completed operational system.

Table 2. Calculated and measured spatial non-uniformity of irradiance for each of the 10 selected led types.

	365 nm	385 nm	470 nm	505 nm	655 nm	740 nm	850 nm	940 nm	5600 K	3000 K	All
SNI_C (%)	2.3	2.9	1.9	1.8	2.7	2.4	2.7	2.8	2.9	2.1	2.0
SNI_M (%)	2.1	2.7	1.8	1.7	2.5	2.3	2.5	2.4	2.6	2.0	1.9

The resulting device has performed exceptionally well and maintained irradiance levels within < 0.5% over a 550 minute exposure period at 100 mW/cm^2. The spatial uniformity values for each of the ten LED types, as measured in comparison to the design values, are shown in Table 2. The spatial non-uniformity of irradiance (SNI) is defined by equation 1 where E_{max} and E_{min} are the calculated and measured maximum and minimum irradiance values for each colour and the integrated result.

$$\mathrm{SNI} = \frac{\mathrm{E_{Max}} - \mathrm{E_{Min}}}{\mathrm{E_{Max}} + \mathrm{E_{Min}}} \times 100\ \% \qquad (1)$$

Despite some edge fringing, the Class AAA irradiance area of the device is > 640 cm^2.

Future Development

This work reflected the state of LED availability at the stage of design. The LED bandgaps and brightness are changing rapidly. There is now an opportunity to fill in the 750 – 850nm region to meet solar simulation requirements for perovskite and other non-silicon PV cells as well as UV for AM-0 simulation needs.

Conclusion

A ten-colour LED solar simulator comprising 532 individual LEDS was designed and constructed to provide exceptionally uniform irradiance of 1 sun over 640 cm^2 meeting Class AAA performance over this area. The longevity and stability of the LEDs offer advantages over conventional sources.

Acknowledgment

The work was also performed in part at the Material's Node of the Australian National Fabrication Facility.

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