Received: 13 April 2018 | Revised: 19 July 2018 | Accepted: 6 August 2018
DOI: 10.1002/pip.3072

APPLICATIONS

WILEY PROGRESS IN PHOTOVOLTAICS

Modular LED arrays for large area solar simulation

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Funding information
Priority Research Centre for Organic Electronics, University of Newcastle

Abstract

A modular array of light emitting diodes of six different wavelengths is modelled and experimentally tested to provide Class AAA solar simulator illumination over an area of 20 cm^2. The module demonstrates uniform distribution of light flux density across the sample test plane region, achieving Class A AM 1.5 G irradiance (100 mW/cm^2) across the 400 to 1100-nm wavelength range. The new system has a spectral match of 99.5%, a spatial non-uniformity of 2.0%, and a temporal instability of <0.2%. The performance of the design (which will allow for large area simulators to be cheaply assembled from multiple modules) is then critically assessed in terms of the existing solar simulator standards and benchmarked against a conventional simulator.

KEYWORDS

LED, solar simulator, solar simulator standards

1 | INTRODUCTION

The advent of organic photovoltaics has enabled the development of truly low-cost large area solar cell technology emerging from the ability to manufacture devices using reel-to-reel printing.[1,2] This large-scale manufacture of printed solar presents new challenges associated with scaling materials and testing.[3] Recently, advances in scaling of materials have been reported,[4] but laboratory characterisation of large area (> 1 m^2) solar modules using simulated solar illumination remains an ongoing issue.[5]

The solar simulator is an essential solar energy research tool, replicating the spectral emission and spatial irradiance of the sun within the laboratory and providing reproducible, controllable, test conditions for solar cell development.[6] As such, solar simulators are necessary for the direct comparison of device performance between research groups and across material platforms, and play an integral role in the advancement of the photovoltaic field.

Solar simulation can be broadly classified into the irradiance above the atmosphere, ie, with zero air mass (AM), AM 0, and air mass 1.5, corresponding to an optical path through the atmosphere of 1.5 times the vertical path of AM 1. AM 1.5 is further separated into AM 1.5 D for direct illumination of solar concentrators and AM 1.5 G, an integrated irradiance of 100 mW/cm^2 for global illumination inclusive of sky emission and scatter. In order to generate these emission spectra, a wide range of light sources have been employed, including Xenon arc discharge, sulphur emission, and tungsten incandescent lamps.[7] The broadband emission of these lamps is well suited to approximating the solar spectrum; however, large area solar simulation based upon these sources has proven both difficult and prohibitively costly.[8] Consequently, there is an increasing need for low-cost, large area solar simulation solutions driven by the ongoing transitioning of printed solar technologies from the laboratory to the commercial scale.[9]

Over the past decade, on the back of lowering cost and improving spectral range and stability, solar simulators based upon light emitting diodes (LEDs) have become an increasingly viable option. The emission spectrum of each individual LED is typically narrow (~20 to 60 nm[10]), and a simulated solar spectrum can readily be constructed from arrays of LEDs of varying wavelengths. Indeed, the ability to individually control LED intensities allows for a highly tuneable and calibrated light source. Moreover, as we will demonstrate, the tessellation of these LED arrays offers the prospect of a scalable, large area solar simulator at low cost.

The first reports of LED based solar simulators occurred in the early 2000s, with initial systems limited by the low power output of the available LED technology.[11] In 2009, the first LED simulator with 1-Sun intensity was achieved.[12] Subsequently, researchers turned their attention to developing LED-based solar simulators which could meet the AAA rating[13-16] as specified by the standards of (1) the American Society for Testing and Materials (ASTM) E-927-10[6]; (2) the International Electro-technical Commission (IEC) IEC60904-9[17]; and (3) the Japanese Industrial Standard (JIS) JIS C 8912.[18] Stuckelberger et al reported the first limited wavelength range (400-700 nm) AAA LED solar simulator in 2014, providing illumination over 18 × 18 cm.[19] However, the first entirely LED-based AAA simulator was only reported in 2015, providing Class A 1-Sun irradiance over a maximum area of less than 20 cm^2.[20] Subsequent studies by Schubert et al confirmed that LED solar simulators can be comparable to the industry standard filtered Xenon solar simulator.[21] LED simulators have recently been developed for use in student laboratories and shown to give superior performance to classical halogen simulators,[22] and a small range of commercial devices are now available on the market.[23] Indeed, Wavelabs have very recently demonstrated a custom 18 LED solar simulator scaled to a test surface of 1 m × 2 m.[24] However, to date, the development of an inexpensive LED-based Class AAA solar simulator for large area solar cells has not been reported.

Here, we present a rational approach to the development of a low-cost LED-based solar simulator that is explicitly designed for testing large area printed organic solar cells. In particular, optical modelling has been used to develop a Class AAA LED solar simulator module that can be tessellated to illuminate large areas with uniform irradiance. We ensure a low-cost design by minimising the number of LEDs with different emission wavelengths. Finally, we demonstrate a prototype version of the basic module in the new LED large area solar simulator and show that it meets the AAA standard.

2 | LED SOLAR SIMULATOR OPTICAL MODELLING

2.1 | Selecting LED sources to match the solar spectrum

There are two general approaches to achieving a solar simulator based on discrete wavelength components. In the first case, the designer can attempt to maximise the number of LEDs to follow the reference solar spectrum as closely as possible. This approach is limited by the fact that the LED sources are not perfect narrow band emitters and that there are not LEDs that emit at all wavelengths across the solar spectrum. Alternatively, the designer can attempt to minimise the number of LED emitters to achieve an effective AM1.5 spectral profile. This approach is limited by the maximum width of the LED sources. The current standards for solar simulators were developed for use with broadband emission light sources. As such, judicious selection of both the wavelength maximum and width of each LED emitter is required to prevent significant spectral mismatch within the wavelength intervals defined by the standards.

The first criterion in our rational design approach was to minimise the number of LED sources through combining both narrow and broad band LED emitters. This criterion was driven by the goal to develop as low a cost class AAA solar simulator as possible. As a first step, the absolute spectral irradiance of a range of LEDs was measured using a spectro-radiometrically calibrated fibre optic coupled spectrometer (Ocean Optics) with a cosine corrector fitted to the fibre input end. Using these spectral profiles, an optimal combination of LEDs was selected that minimised the number of sources whilst still covering the AM1.5 spectrum according to the guidelines of the ASTM E-927-10 standard.[6] Previous work by Bliss et al showed that it is possible to meet the Class AAA standard with a combination of just eight LED colours and halogen lamps to cover the IR part of the spectrum.[12] More recently, Novičkovas et al were able to develop a Class AAA LED-based solar simulator using a combination of just six different LED colours.[20] Based on these previous studies, it was determined that the initial solar simulator design would be based on a minimal six different LED sources. Table 1 lists the set of six LED sources (both broad and narrow band) that were selected from the range of LEDs surveyed, and Figure 1 shows the normalised spectral profiles of these LEDs superimposed on the normalised solar AM1.5 G irradiance.

2.2 | Determining the LED spatial emission profiles

The next stage of the optical model development was to characterise the spatial emission profiles of the individual LEDs as a function of lateral displacement so that their lateral arrangement could be optimised. The lateral spatial emission profile for each LED (as distinct from the polar emission data given in the LED datasheets) was needed as an input file to the optical modelling software (TracePro) since the combined LED emission was to be projected onto a two-dimensional plane. All of the individual LEDs were driven at 3-V forward voltage and a forward current of 700 mA. Twelve centimetres was chosen as the design source to test plane distance for the final illuminator, and all measurements were made at that distance. The lateral spatial distribution of each individual LED emission was measured and is displayed in Figure 2.

TABLE 1 Characteristics of the LEDs selected for the solar simulator design. Measured wavelength range (to nearest 5 nm) at 10% of maximum irradiance values

LED Type	Primary/Secondary Peak Wavelength, nm	Wavelength Range, nm	LED Part Number
Warm white	636/450	425–775	LXML-PB01-0040 blue
Cool white	449/555	415-690	LXML-PWC2 cool white
Blue	478	450-510	LX18-P135-3 ANSI warm white
Deep red	735	685-760	LED Engin LZ1-00R300
Infra-red	887	820-925	Osram Opto SFH 4715A (850 nm nominal)
Deep infra-red	1008	910-1060	SFH 4725S OSLON black (940 nm nominal)

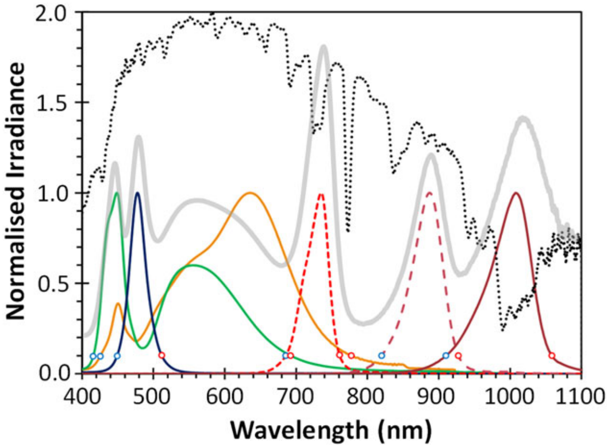

FIGURE 1 The normalised irradiance of the six types of LEDs: A, warm white (solid orange line); B, cool white (solid green line); C, blue (solid blue line); D, deep red (short crimson dashes); E, infra-red (long red dashes); and F, deep infra-red (solid burgundy line). The open blue and red circles indicate the 10% irradiance threshold levels. Also shown is the normalised solar AM1.5G irradiance (black dotted line, multiplied by two for clarity), and the spectral irradiance distribution of the LED based solar simulator (grey line) [Colour figure can be viewed at wileyonlinelibrary.com]

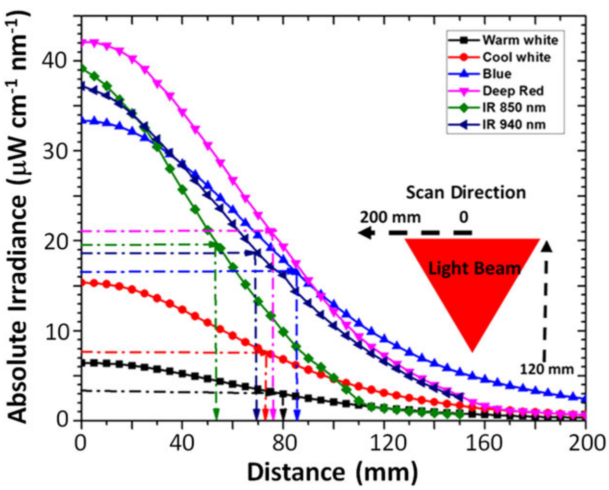

FIGURE 2 The measured LED intensity distribution as a function of lateral distance for each of the six sources used in the simulator. The arrows show the lateral positions of the full width half maximum position for each LED [Colour figure can be viewed at wileyonlinelibrary.com]

2.3 | Optimising LED module layout

The second criterion in our rational design approach was to develop an LED layout that could be tessellated to increase the area of illumination arbitrarily without the presence of edge effects in the irradiance map. A hexagonal unit cell geometry was chosen since it provides a convenient footprint for expanding the solar simulator from a single unit up to as many units as required for the desired testing area. The size of the hexagonal module was set at 80-mm edge length to ensure compliance with the Class A uniformity requirements. The location and number of LEDs within the hexagonal module were optimised by using optical ray tracing to determine the irradiance map for a given arrangement of LEDs within the hexagonal array. The spectral and spatial emission profiles for each LED were used as the input for the ray tracing model (TracePro, Lambda Research Corp.). Each LED in the array was modelled as a source of 100 000 rays with all the component structures associated with each LED (eg, lens, packaging and substrate) and the module (including the reflective concentrator required to meet Class A irradiance values and improve uniformity) included in the simulation (Figure 3).

Optical modelling was also used to determine the number and layout of LEDs within each hexagonal unit cell that would provide a tessellating structure with uniform irradiance across the entire optical layout. The optimised arrangements for the six different types of LED within the hexagonal unit cell are shown in Figure 4 together with an example layout of three hexagon unit cells combined to create a larger area. The layout has been arranged so that the LEDs along the shared edges of the hexagonal units are part of both hexagons, thus, maintaining the uniformity of the testing area regardless of its size.

The TracePro optical modelling package was used to determine the irradiance at the sample test plane from the hexagonal unit cell of the combined 43 LED sources (Figure 4G) as a function of the distance between the source and sample test planes. The model included a prismatic diffuser placed at 40 and 120 mm from the source plane. As shown in Figure 5, the prismatic diffuser acts to create a source of secondary wavelets from every ray that strikes the diffuser, thereby creating a more uniform light distribution within the simulator. This process is enhanced by the mirrored sides which ensure that non-normal rays make multiple passes across the light mixing stage.

Figure 6A,D shows the irradiance maps for source-sample test plane separations of 2, 40, 60, and 100 mm, respectively. A sample test plane located at 2 mm from the LED source plane is illuminated non-uniformly with the discrete LED positions clearly evident. Moving the sample test plane further away from the LED source plane allows increased overlap of irradiance within the light mixing stage of the solar simulator. At the design distance of 120 mm, the presence of a second prismatic diffuser combined with the increased light mixing ensures that the irradiance from the hexagonal unit cell LED array module is highly uniform across the centre region of the sample test plane. Irradiance maps of each single colour LED cluster are shown in Supporting Information (Figure S1).

The modelled sample test plane area was divided into a 12 × 12 grid, and the irradiance was calculated using TracePro for each grid location. The irradiance data for the source-sample distance of 120 mm are shown in Supporting Information (Figure S2).

Matlab software was written to identify the maximum (E_{Max}) and the minimum (E_{Min}) irradiance values of the grid locations that lay entirely within the illuminated part of the sample test plane area in order to calculate the irradiance non-uniformity (NU) across the 144 equal gridded sections using Equation 1:

$$NU = \frac{E_{Max} - E_{Min}}{E_{Max} + E_{Min}} \times 100\%. \quad (1)$$

Figure 7 shows the variation in the NU parameter as a function of source-sample test plane distance. The variation in irradiance across the grid elements provides the error bars for the NU data.

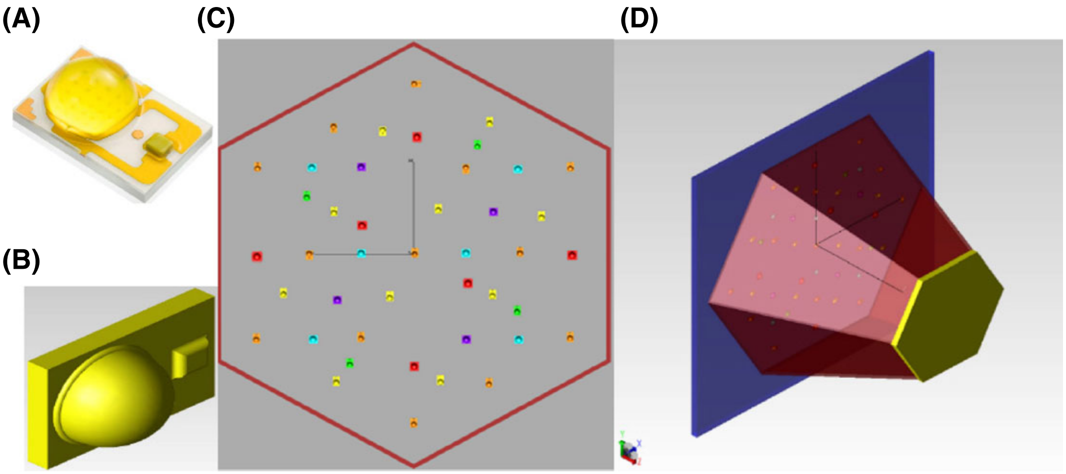

FIGURE 3 Examples of the component structures used in the TracePro optical model of the solar simulator set up. A, The package layout for the Luxeon LX18 LED. B, The CAD model of the Luxeon LX18 LED package layout. C, The TracePro modelled hexagonal array of LEDs (80-mm edge length). D, The model reflective concentrator (red shaded trapezoidal hexagon sides). The final diffuser plane is shown in yellow [Colour figure can be viewed at wileyonlinelibrary.com]

The simulation shows that at a distance of 40 mm, NU = 10%; corresponding to Class C uniformity. At source-sample distances greater than 60 mm, NU <5% (Class B uniformity), while for source-sample distances of more than 100 mm, Class A uniformity performance is achieved with the variation in NU being less than 2%.

The optical layout was designed to ensure that when tessellated the overlapping light fields eliminate boundary effects between the modules ensuring uniform irradiance across the composite test plane area. In order to demonstrate this effect, a series of multi-module arrays were optically modelled using TracePro. As an illustrative example, Figure 8 shows a comparison of the modelled irradiances (across the central 14 × 14 cm area at the sample test plane) for an isolated two-module array and a two-module array including LED contributions from neighbouring hexagonal units. The corresponding LED layouts are shown in Supporting Information (Figures S3 and S4).

It is clear that there is no boundary artefact at the interface between the two hexagonal modules; confirming that hexagonal unit cells can be tessellated whilst maintaining a uniform irradiance. Furthermore, by including the additional LED sources from neighbouring hexagonal modules, the NU of the two-module array is improved from 3.37% to less than 2%, ie, within Class A classification. As such, the modelling demonstrates that this design enables solar simulators of arbitrary size with Class A uniformity to be constructed by simply tessellating base units.

3 | LED SOLAR SIMULATOR PROTOTYPE MODULE FABRICATION

With the layout of the 43 LEDs within the hexagonal unit cell finalised using the TracePro optical model, a prototype system was fabricated. The individual LEDs were mounted on a 150-mm-square aluminium plate in the locations defined by the optical model as shown in Figure 9.

As shown in Figure 9A, the aluminium plate was attached to a 125 mm × 75 mm dual aluminium heatsink of 1.4°C/W thermal resistance combined with a 255 mm × 84 mm × 84 mm tunnel heatsink of 0.3°C/W with forced air cooling at a flow rate of 0.97 m^3/min. The LED junction temperature and FLIR thermal image of the LED source plane are shown in Supporting Information (Figures S5 and S6, respectively). To allow for flexibility in tuning the simulated spectrum, the drive current of each LED colour cluster is controlled individually. While this drive setup allows for accurate matching of the AM1.5G spectrum, it also provides the opportunity to simulate other irradiance spectra and conditions such as AM1, AM0, and sunrise/sunset, as shown in Supporting Information (Figure S7). Figure 9D shows the final operational LED solar simulator with the reflective concentrator panels in place, where these reduce the hexagonal edge to 50 mm and the total area illuminated to 65 cm^2.

4 | LED SOLAR SIMULATOR PROTOTYPE MODULE CHARACTERISATION

The next stage of the prototype development was to classify the performance of the new simulator against the relevant standard. There are three official bodies with defined standards for solar simulation: (1) the ASTM E-927-10; (2) the IEC IEC60904-9; and (3) the Japanese Industrial Standard (JIS) JIS C 8912.[6,17,18] The standards for terrestrial photovoltaic testing classify a solar simulator as an A, B, or C class simulator against three key parameters, namely (1) the spectral match to AM1.5; (2) the irradiance spatial uniformity at the sample test plane surface; and (3) the temporal instability of the source. The classification criteria for the three parameters as defined by the three standards are given in Supporting Information (Table S1). Here, we focus on the more commonly used ASTM[6] classification and characterise the performance of the new LED solar simulator with respect to spectral match, irradiance uniformity, and temporal instability.

4.1 | LED solar simulator prototype module spectral match

The spectral match percentage for a solar simulator was measured over the six set wavelength intervals defined by the ASTM standard and

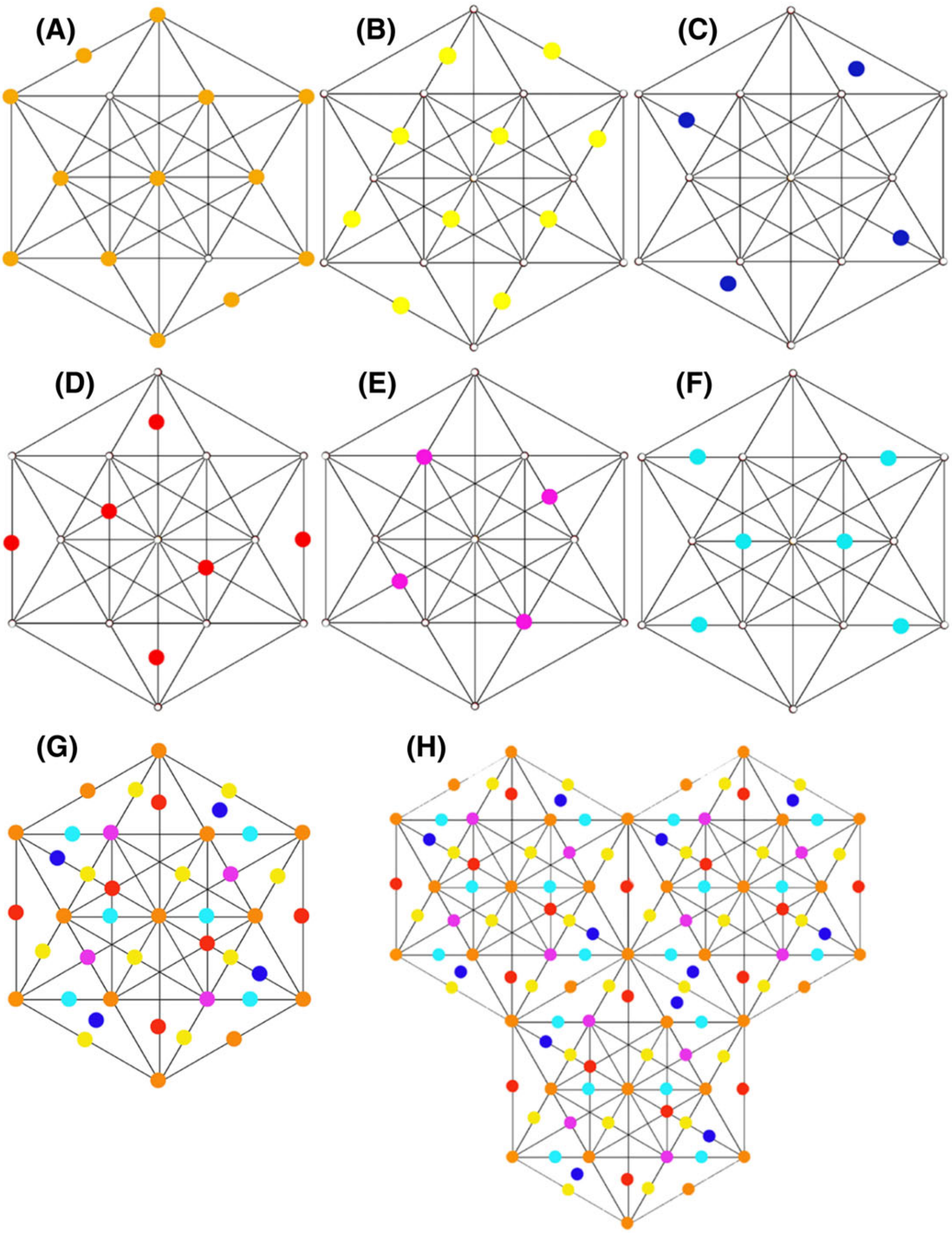

FIGURE 4 The number of LEDs and the corresponding arrangement for each individual coloured source inside the hexagonal unit cell: A, 13 warm white; B, 10 cool white; C, 4 blue; D, 6 deep red; E, 4 IR 850 nm; and F, 6 IR 940-nm LED sources. Also shown are as follows: G, the overall arrangement of all of the LED sources within the optimised hexagonal unit cell, and H, an example layout of three hexagonal unit cells illustrating that the LEDs along each hexagonal interface are shared between neighbouring hexagons [Colour figure can be viewed at wileyonlinelibrary.com]

listed in Table 2.[6] For each of the wavelength intervals, the percentage spectral match lies within the 75% to 125% range required for Class A classification (Table S1), with an overall 99.5% match across all of the six wavelength intervals. The total irradiance in the 400 to 1100-nm wavelength range of the LED solar simulator is 767.3 mW/cm^2 compared with the AM 1.5G standard which is 758.6 mW/cm^2.

Figure 10 illustrates the spectral match characteristics of the LED solar simulator module to AM1.5G and Class A upper and lower limits as a function of wavelength. The plot shows that for each wavelength interval, the irradiance fraction achieved by the LED solar simulator lies well within the two limits. Overlaid on the spectral match characteristics is a normalised plot of the actual irradiance of the hexagonal LED solar simulator at the sample test plane. It is clear that, whilst the overall interval values are in good agreement with the Class A classification requirements, there remain significant irradiance deviations within each wavelength interval. Indeed, work is already underway in this laboratory to examine the use of additional or broader emission LED sources to improve subinterval mismatch.

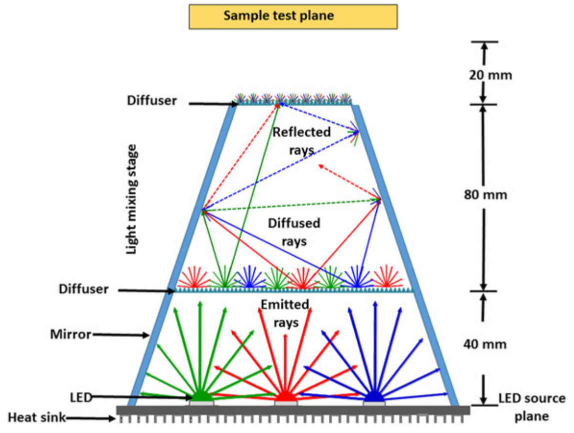

FIGURE 5 Physical arrangement of the hexagonal solar simulator module [Colour figure can be viewed at wileyonlinelibrary.com]

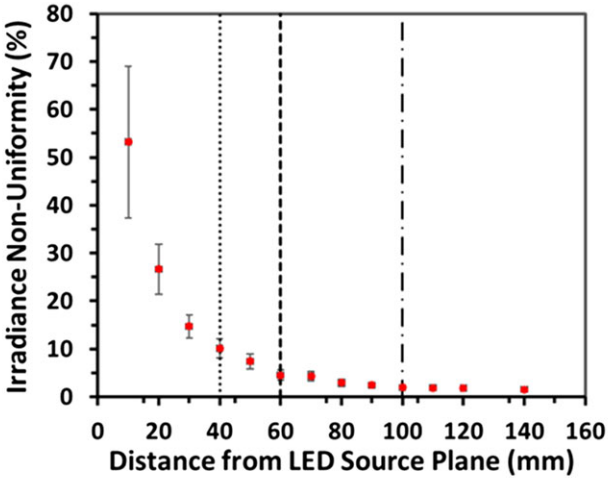

FIGURE 7 The irradiance non-uniformity across a 144-element grid at the test plane for different distances from the LED source plane [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | LED solar simulator prototype module irradiance non-uniformity

The irradiance NU (Figure 11) was measured with a calibrated Ocean Optics USB2000 spectrometer connected to a cosine corrector with a 7 mm aperture. The spectrometer was calibrated to measure absolute irradiance and subsequently connected to a homebuilt 2D linear X-Y stage. The cosine corrected input was then rastered across the sample test plane area. At each test location, an irradiance spectrum from 400 to 1100 nm was collected and integrated to derive the irradiance value (in mW/cm^2). The value was background corrected and then plotted at the corresponding test location. The spectrometer was then moved to the next test location and the process repeated. The step size in the x and y directions was chosen to be 5 mm, ensuring that there was at least 2 mm of overlap between each irradiance test location.

Figure 11 shows the illuminated sample test plane together with the corresponding 2D irradiance distribution map for a single solar simulator module with a diffuser at 40 and 120 mm from the LED source plane. The hexagonal modules have been designed to ensure uniform irradiance across the boundaries of neighbouring modules. As such, the size of the uniformly illuminated area for a single

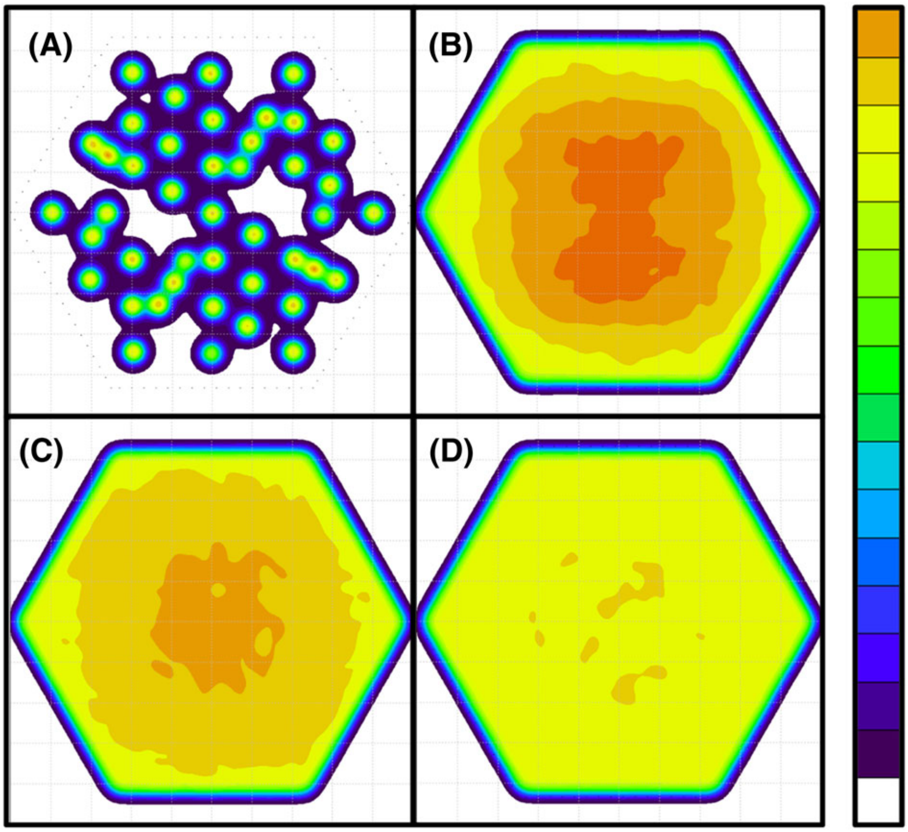

FIGURE 6 The modelled irradiance maps (at left) and the profile (at right) of an 80-mm side hexagonal module with the illuminated test plane at A, 2 mm; B, 40 mm; C, 60 mm; and D, 100 mm, respectively from the LEDs. The colour bar shows the linear irradiance between 0% and 100% of the maximum irradiance in each map [Colour figure can be viewed at wileyonlinelibrary.com]

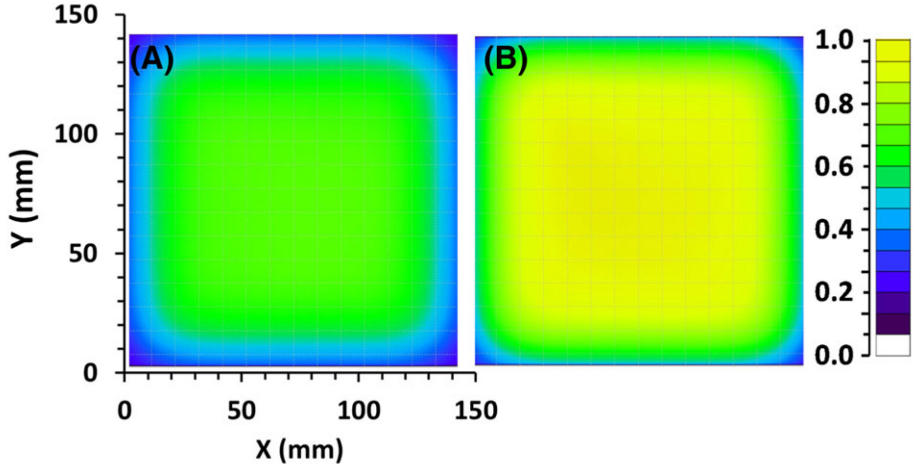

FIGURE 8 Irradiance plots for A, an isolated two-module array and B, a two-module array including LED contributions from neighbouring hexagonal units. The irradiance values have been normalised to the maximum value across both plots [Colour figure can be viewed at wileyonlinelibrary.com]

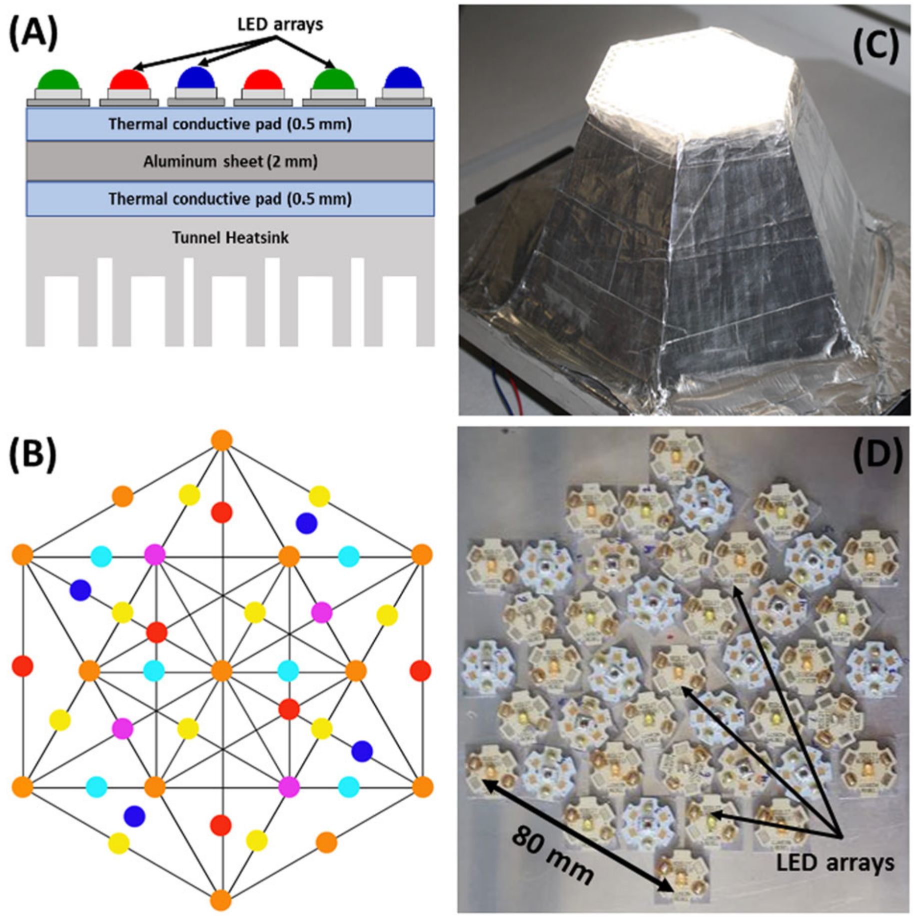

FIGURE 9 The prototype LED hexagonal unit cell. A, Schematic of the individual LED module. B, The corresponding model LED layout within the hexagonal unit cell highlighting the positions of the six LED colours. The colour code of each individual LED colour is the same as is given in Figure 4. C, Final fabricated prototype LED hexagonal solar simulator assembly with reflective concentrator and diffusors in place. D, Physical layout of LED modules within hexagonal unit cell on the aluminium heat sink [Colour figure can be viewed at wileyonlinelibrary.com]

hexagonal module is necessarily constrained by the boundary of the solar simulator. However, the uniformity of the central region of the hexagonal module must still meet the requirements for a large area simulator, resulting in uniformity areas of 20, 32, and 46 cm^2 for Class A, B, and C, respectively.

4.3 | LED solar simulator prototype module temporal instability

The stability in light intensity distribution measured at 30-second intervals is shown in Figure 12A demonstrating that there is no drop

TABLE 2 The spectral match characteristics of the LED solar simulator module

Wavelength Interval, nm	% AM 1.5G Irradiance	% Total Irradiance	% Spectral Match	Class
400-500	18.41	14.83	80.55	A
500-600	19.91	21.81	109.54	A
600-700	18.37	19.36	105.39	A
700-800	14.92	16.09	107.84	A
800-900	12.46	10.61	85.15	A
900-1100	15.93	17.30	108.6	A

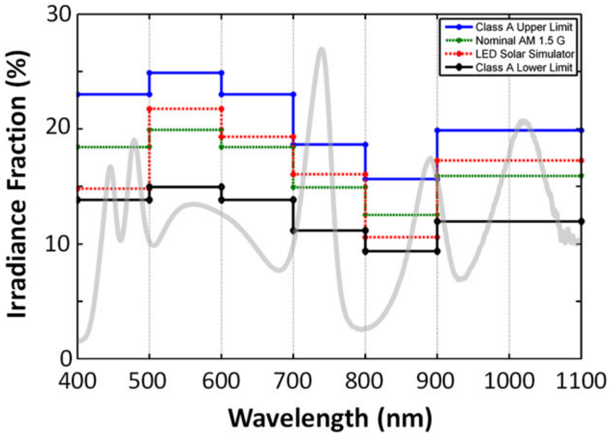

FIGURE 10 Spectral match characteristics of the LED solar simulator to AM1.5G and Class A upper and lower limits as a function of wavelength. The pale grey line illustrates the spectral emission of the LED hexagonal solar simulator assembly across the wavelength intervals [Colour figure can be viewed at wileyonlinelibrary.com]

in the light intensity over the measurement period and the spectral shape does not change. Figure 12B plots the long-term stability of the solar simulator over a 3-hour period, demonstrating that the system has a stability of better than 0.2% over a time period that is significantly longer than the time required to collect a single J-V measurement (~ 1-2 minutes) and well within the ±2% requirement for Class A classification.

4.4 | LED solar simulator prototype module benchmarking

The final stage in the characterisation of the LED solar simulator was to compare its performance against that of a standard solar simulator under device testing conditions. The ultimate application of this design is for large area printed organic photovoltaic devices, and consequently a standard OPV cell (5-mm^2 P3HT: PCBM 1:1) was used to benchmark the new LED system against an existing Xenon lamp-based solar simulator.

Figure 13 shows the current-density (J-V) curves for the OPV devices in the dark and under illumination using the two solar simulator systems. The device parameters are presented in Table 3.

The short circuit current mismatch between the two systems is extremely small (0.55%), showing that the as-designed LED solar simulator provides an excellent cost-effective alternative to commercially available simulators.

4.5 | Calculated spectral mismatch correction

The standard electrical performance test for a photovoltaic (PV) device is to measure the current-density voltage (J-V) characteristic of the device while illuminated with simulated sunlight.[25] These measurements are conducted under standard test conditions where a simulated AM 1.5 spectrum is used as a light source.[26] Since no solar simulator spectrum can 100% match the AM1.5 spectrum in its intensity distribution features, a spectral mismatch correction factor (MM) is essential to correct the performance parameter of the PV device and provide a practical way to identify the uncertainty in the J-V measurements.[21] A standard silicon reference photodiode calibrated at a national standards laboratory, such as National Renewable Energy Laboratory, is the most convenient device that can be used to study the spectral mismatch of the solar simulator. To estimate the value of mismatch factor (MM), we use the following equation[27]:

$$MM = \frac{\int E_r(\lambda)S_r(\lambda)d\lambda}{\int E_t(\lambda)S_r(\lambda)d\lambda} \times \frac{\int E_t(\lambda)S_s(\lambda)d\lambda}{\int E_r(\lambda)S_s(\lambda)d\lambda} \tag{2}$$

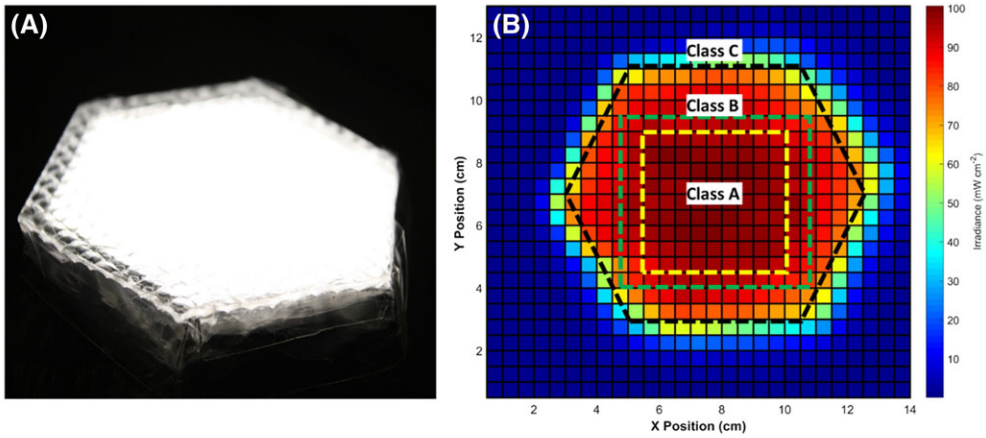

FIGURE 11 A, Illumination of the LED solar simulator at the sample test plane. B, 2D irradiance distribution map as measured by the 5 mm × 5 mm calibrated ocean optics spectrometer at a source—sample test plane distance of 140 mm. The yellow, green, and black contour lines represent the Class A, B, and C uniformity classification areas of 20, 36, and 65 cm^2, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

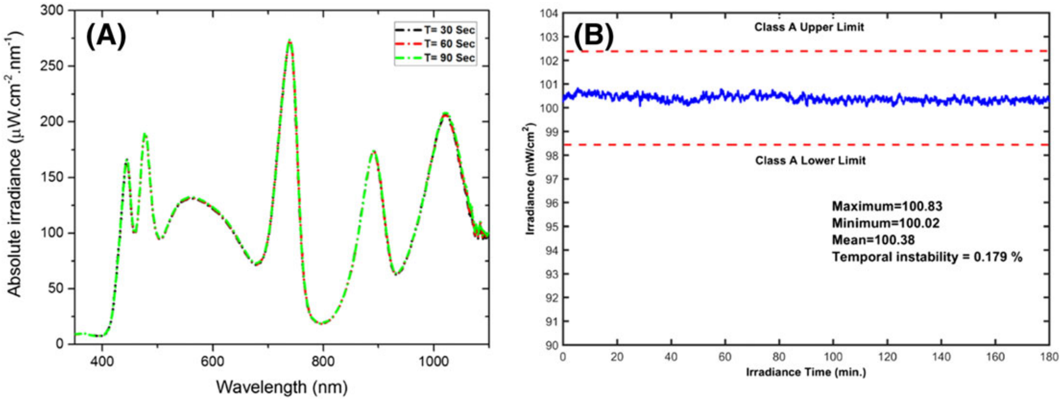

FIGURE 12 A, Spectral irradiance of the LED solar simulator measured at 30-second intervals. B, Long-term instability response for LED solar simulator utilizing a 200-millisecond data sampling and acquisition time. The system was stabilised for 60 seconds prior to the measurements [Colour figure can be viewed at wileyonlinelibrary.com]

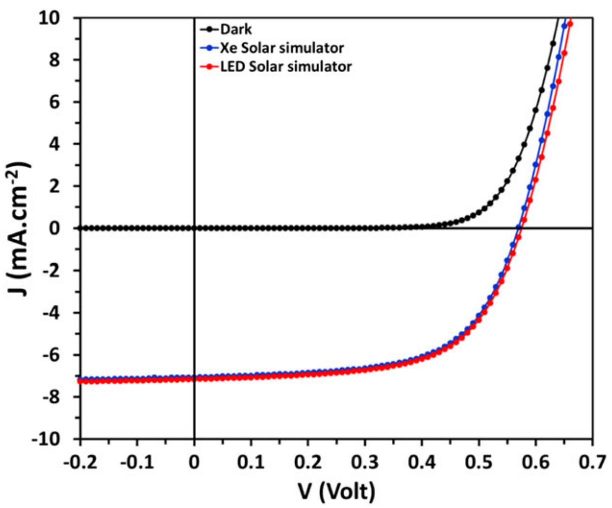

FIGURE 13 Current-density (J-V) curves for a P3HT:PCBM OPV device both in the dark and under illumination using the LED and Newport Oriel Sol3A Class AAA, 300 W Xenon (MODEL: 91160A) solar simulator at 80 and 77 mW/cm^2, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

where S_r (λ) is the spectral response function of the reference cell, E_r (λ) is the AM 1.5G spectrum, S_t (λ) is the spectral response function of the test cell, and E_s (λ) is the spectrum of the solar simulator.

The MM factor is applied to correct the intensity of an irradiance with a nonstandard spectrum to the intensity required with the standard spectrum, so that a test device will produce the same current under both light irradiances. If the value of the mismatch factor is M > 1, the output intensity of the of the solar simulator should be reduced by the same factor, and if M < 1 the intensity of the solar simulator should be increased by the same factor, in order to put more power in the region of spectral response of a test cell.

Practically, a calibrated reference cell like Newport Oriel, MODEL: 91150 V or any equivalent traceable cell can be used to adjust the simulator to an equivalent one sun short circuit current as would be measured at AM1.5G. This process simplifies the calculation for the mismatch factor. The spectral response for the reference Si cells and tested Si cell are shown in Figure 14.

A set of spectral response curves for organic and silicon solar cells are shown in Figure S8, and the measured and theoretically calculated

TABLE 3 The device parameters for a P3HT: PCBM OPV device under LED and Xenon lamp illumination

Solar Simulator System	Efficiency, %	V_{OC}, Volt	J_{SC}, mA/cm^2	Fill Factor
Xenon lamp solar simulator	2.48	0.570	7.072	0.615
LED solar simulator	2.53	0.575	7.15	0.614

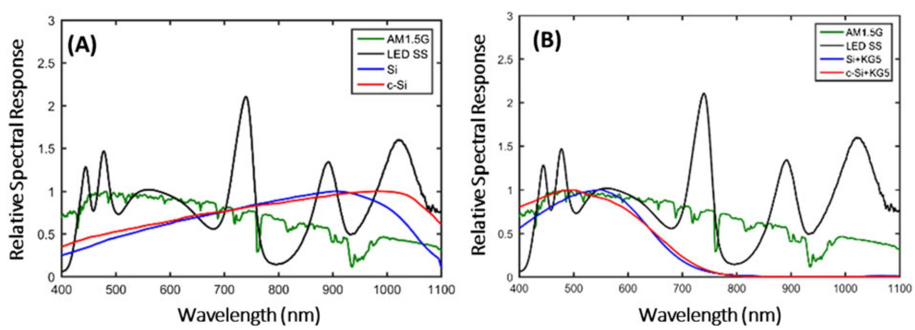

FIGURE 14 A, The relative spectral response of Si test cell against Si calibrated reference cell over wavelength range 400 to 1100 nm (Newport, MODEL: 91150 V). B, The relative spectral response of Si + KG5 test cell versus silicon calibrated reference cell of KG5 filter (infinity PV: 400-800 nm) [Colour figure can be viewed at wileyonlinelibrary.com]

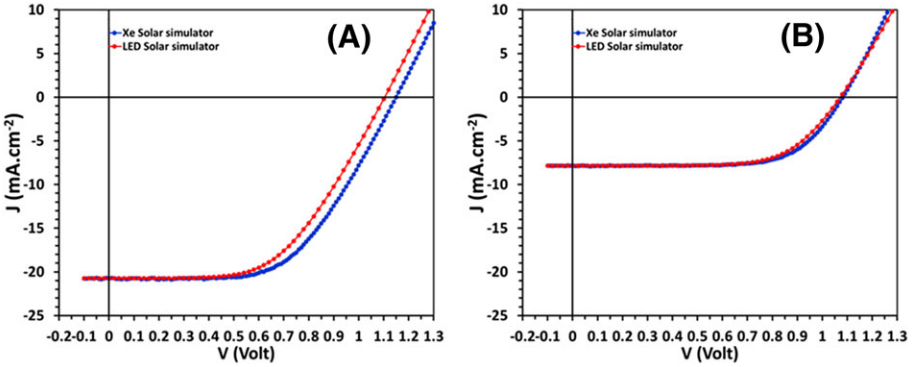

FIGURE 15 Current-density (J-V) curves for A, silicon cell and B, Si cell +800-nm cut-off KG5 optical filter, both under illumination from the LED and Newport Oriel Sol3A Xenon lamp solar simulators [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Summary of LED solar simulator and Newport Oriel Sol3A solar simulator test results for a selective Si cell. These data are the averages for three consecutive tests under each illumination condition

Electrical Parameters	Solar Simulator Systems			
	Oriel Sol3A solar simulator		LED solar simulator	
	Si	Si + KG5	Si	Si + KG5
J_{SC} (mA/cm^2)	20.8	7.82	20.7	7.85
V_{OC} (Volt)	1.14	1.09	1.10	1.07
Fill factor	0.596	0.663	0.538	0.659
Efficiency (%)	12.56	5.67	12.3	5.55

spectral mismatch factors are listed in Table S2. Figure 15 displays JV curves recorded from a silicon cell under 400 to 1100 nm illumination from Xenon arc and LED solar simulators in panel (A) and the same cell with optically filtered (KG5) 400 to 800 nm illumination in panel (B). Table 3 summarises the experimental data.

The LED solar simulator produces less emission between 780 and 820 nm than the Xenon lamp, and this is exhibited in Figure 15 as this wavelength region overlaps with the strongest absorption region of the Si cell and thus causes a considerable spectral mismatch, especially evident in the V_{OC} values. Conversely, for the KG5 filtered Si cell, there is slight drop in the fill factor value related to mismatch in the spectral range between 600 and 650 nm (Table 4).

5 | CONCLUSIONS

The design and implementation of a hexagonal module LED solar simulator have been presented. The class AAA LED solar simulator was designed in accordance with the standards of ASTM E-927-10 to measure the I-V characteristics of solar cells. This simulator uses a novel configuration of LED modules positioned in a hexagonal geometry designed to allow multiple modules to be tessellated into larger areas. Optical modelling confirms that the combination of low cost of components and a tessellating modular design of this LED solar simulator allow for upscaling to any desired illumination area. An initial prototype consisting of a single hexagonal module has been fabricated and demonstrated Class AAA spectral match, spatial uniformity, and temporal stability at one sun intensity across the wavelength range of 400 to 1100 nm.

ACKNOWLEDGEMENTS

This research was supported by the Priority Research Centre for Organic Electronics, University of Newcastle. The work was also performed in part at the Material's Node of the Australian National Fabrication Facility, which is a company established under the National Collaborative Research Infrastructure Strategy to provide nano- and micro-fabrication facilities for Australia's researchers. A. Al-Ahmad gratefully acknowledges the Higher Committee for Education Development in Iraq (HCED-Iraq) for providing his PhD scholarship.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Al-Ahmad AY, Holdsworth J, Vaughan B, et al. Modular LED arrays for large area solar simulation. *Prog Photovolt Res Appl*. 2018;1–11. https://doi.org/10.1002/pip.3072