A versatile light-emitting-diode-based spectral response measurement system for photovoltaic device characterization

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Abstract: An absolute differential spectral response measurement system for solar cells is presented. The system couples an array of light emitting diodes (LEDs) with an optical waveguide to provide large area illumination. Two unique yet complementary measurement methods were developed and tested with the same measurement apparatus. Good agreement was observed between the two methods based on testing of a variety of solar cells. The first method is a lock-in technique that can be performed over a broad pulse frequency range, The second method is based on synchronous multi-frequency optical excitation and electrical detection. An innovative scheme for providing light bias during each measurement method is discussed.

1. Introduction

The measurement of the spectral responsivity (SR) of a solar cell - which quantifies the wavelength dependency of the cell's photocurrent when normalized for the optical power of the incident monochromatic radiation - is essential in photovoltaic (PV) device characterizations [1]. Cell spectral responsivity, for example, is used to calculate quantum efficiency [2], which indicates the cell's conversion efficiency as a function of wavelength. The absolute determination of the SR of a solar cell, if done under appropriate conditions, can be used to predict the short circuit current, I_{sc}, of the cell under any given irradiance spectrum, including the standard air mass 1.5 (AM 1.5) solar spectrum [2-4]. The relative (or absolute) SR data of PV cells can be used to adjust for spectral differences between the actual illumination source versus the spectrum assigned to a standard or reference source [5-7]. Furthermore, the SR measurements are often used as a diagnostic tool to help understand the performance limitations of the PV device or identify defective areas of a cell. Finally, SR curves can be used in modeling and simulations to provide important physical quantities such as the charge carrier diffusion length or for studying of bandgap defect densities within the active layer of the device [1]. These physical parameters are an important indication of the quality of the semiconductor material comprising the active layer.

The most widely accepted method for measuring the SR of solar cells is the differential spectral responsivity (DSR) approach [3,6,8] which allows for introduction of a light bias during the measurement. In this technique, a small modulated (quasi)monochromatic light beam and a more intense steady-state white light source (the light bias) illuminate the solar cell, producing a small AC signal superimposed on a larger DC current. The AC current is amplified and detected using a lock-in technique. A monitor photodetector is typically used to measure the power of the monochromatic beam at each wavelength, either simultaneously with the cell measurements, or if not possible, during a second wavelength scan. The significance of the use of light bias has been described previously, particularly for certain types of solar cells [8].

Monochromatic illumination of the cells can be performed using a variety of techniques. Two common approaches are: 1. A monochromator-based method, where an incandescent or a discharge lamp (such as Xe arc lamps) provides the broad-spectrum input light source to the monochromator [9] and 2. A filter-based method where interference filters with bandwidth of roughly 20 nm to 50 nm are placed in front of a broad-spectrum light source to provide a quasi-monochromatic beam that can be used to expose a large area [8]. Each technique has its advantages and limitations and they have been described previously [3,6-11]. A common disadvantage of both systems is the reliance on light sources such as xenon or quartz-halogen lamps. These sources are very susceptible to aging effects, possess inherent instability and noise, have very limited power output or sharp peaks over certain regions of the spectrum that create nongaussian line shapes and produce nonuniform illumination at the exit plane [10]. All these issues increase the cost and maintenance of the system and can impact the accuracy of the measurements. In the last several years, some research groups have explored other ways of achieving monochromatic illumination, including by using a tunable laser source [12] and using light emitting diodes (LEDs) for SR, solar simulation and other types of PV characterization [13-18]. The use of LEDs is of particular interest and is the subject of this paper.

Advancements in LED technology over the last decade have contributed to an enhancement of their radiant intensity and availability at different spectral wavelengths. LEDs offer: increasing selection of available wavelengths, simple Gaussian emission curves, superior output stability, ease of operation, and lifetimes that are at least an order of magnitude longer than conventional optical sources, and therefore merit consideration as an alternative quasi-monochromatic radiation source for spectral response measurements of solar cells and detectors.

In this paper, the design and operation of a large-area, differential spectral response measurement system based on LED arrays coupled to a tapered optical waveguide is decribed. The measurement apparatus can illuminate an area of 25 cm by 25 cm or more with reasonable uniformity. Furthermore, the system can perform two unique types of SR measurements without any hardware changes. Each measurement method, in addition, can be conducted with or without light biasing. These LED based measurements can be robustly implemented on a variety of solar cell technologies and photodetectors. Cells and detectors of different sizes can be tested while achieving the desired overfill illumination. Measurements can be conducted using multiple intensities and pulsing schemes.

The first method, shown in Figure 1a, is a lock-in technique that is conceptually very similar to the traditional monochromatic-based systems that employ a mechanical chopper. The difference is a pulsed electrical signal is applied to one LED (in an array of 32) at a time; the other LEDs (or broad-spectrum white LEDs) are either temporarily turned off or turned on and maintained under DC current to provide a light bias. A computer-controlled sweep algorithm controls the LED drivers, a lock-in amplifier and a pulse generator and automatically sequences through each LED in the array. The AC signal generated across the solar cell or detector due to the pulsing LED is recorded. Each of the LEDs is pulsed at 40 Hz; allowing 10 s per LED has been found to be a suitable test interval. Thus, if using all 32 LEDs, the measurements process can be completed in 5 to 6 minutes.

The second technique is referred to here as the Fourier Transform (FT) method [18]. For this method, the LED drivers are used to pulse all 32 LEDs at the same time, but each with a slightly different frequency (as shown in Fig. 1b and 2). The time-dependent signal generated by the solar cell as a result of these concurrent pulsed illuminations is detected in the frequency domain using a signal analyzer. The SR of the solar cell over all wavelengths is determined over the comparatively short time interval of 4 s or less.

2. Experimental Setup

Within the test apparatus, individual LEDs are mounted in a grid-pattern on a water-cooled aluminum base plate. For this study, a total of 32 single-wavelength LEDs, and a few broad-spectrum white LEDs were used. As depicted in Figure 1, the LED plate is placed at the inlet aperture of a light guide, while the test cell or reference detector is mounted at the outlet aperature. Computer-controlled LED drivers regulate the current supplied and the pulse frequency of each individual LED. The tapered light guide is constructed of aluminum with an inlet aperture of 7.6 cm by 7.6 cm and an outlet aperture of 30.5 cm by 30.5 cm. The guide's total length is 5 m. The interior surface of the light guide is lined with highly polished aluminum sheets. The light guide is used to promote better mixing of light rays through multiple specular reflections and to yield more uniform optical power delivery over a large area. Details on the test apparatus are provided in Reference 16. In this earlier publication, notably, the performance of the test apparatus when used as a solar simulator is reported.

Figure 1a depicts the experimental system configuration used for the lock-in-based SR measurement. A function generator sequentially triggers each LED driver to apply a pulsed current to the corresponding LED at a user-selected frequency (typically 40 Hz). With regard to the light biasing, two schemes are possible. In one scheme, a set of higher-powered broad-spectrum white LEDs are used. These white LEDS are operated under constant DC current, to illuminate the device under test (DUT) concurrently with the quasi-monochromatic light from each pulsed individual LED. In the second scheme, one LED is operated in pulsed mode while the LEDs at the other wavelengths are operated in a DC current mode. Once the data from a given pulsed LED is collected, the pulsing LED is switched to DC operation, and the next LED in the queue temporarily toggles from DC to pulsed operation. The AC photocurrent signal generated in the solar cell is measured by the lock-in amplifier as a voltage signal across a 50 Ω sense resistor. The function generator provides the external reference signal for the lock-in measurement. A variable-range power supply that can sink a DC current of at least 500 mA and apply an external voltage in the range of 0 V to 30 V is used to handle the large DC currents generated by the constant bias lights, and also to maintain a potential difference of $\approx$ 0 V (short circuit conditions) across the solar cell. The latter state is verified and monitored by a digital multi-meter (DMM) placed directly across the cell. The current sinking and the voltage biasing are needed, because the DC current across the sense resistor, especially for larger cells and larger light biases, gives rise to a large potential drop across the cell which needs to be balanced out by an applied voltage (to maintain a zero voltage across the DUT). The entire operation is automated by a computer program with a sweep algorithm that sequentially pulses each LEDs (such as from shortest to longest wavelength) and records the photoresponse measured by the lock-in amplifier, with or without the light bias. Two sequential sweeps are performed, one with a NIST-calibrated photodetector for determination of the monochromatic light intensity and the other on the solar cell to determine its short circuit current density.

Figure 1b highlights the hardware and operating features of the second spectral response measurement method. For this method, the LED drivers are operated in a "strobe" mode (as opposed to the "trigger" mode use for first method). In this mode, a repeating strobe current profile command is sent to each LED driver channel, resulting in a unique pulsing profile for each LED. For these measurements, 32 pulsed signals in the frequency range of 102 Hz to 195 Hz in regular steps of 3 Hz are applied to the LEDs. The photocurrent signal generated by the reference detector and the DUT are determined using a signal analyzer that measures the root mean square (RMS) voltage drop across the sense resistor. Higher-harmonic voltage signals are generated at frequencies greater than 200 Hz but are ignored because of occurring outside the relevant data range (100 Hz-200 Hz). DC-operated bias lights may be used in this configuration as well. When light biasing is used, the voltage source is used to maintain the DUT's current output at short circuit conditions.

Figure 2 shows a typical dataset captured by the signal analyzer's frequency scan when implementing the second SR measurement method. The measurement process requires 4 seconds to complete. The currents supplied to LEDs are individually adjusted so that each LED's output intensity at the exit plane of the light guide is approximately 70 mW/m^2 as determined by a calibrated reference detector. This approach provides reliable, noise-free data. With regard to the post-measurement analysis, the raw data is imported into a computer program and the peak centers and the value of the V_{rms} signals are extracted using a peak-finding algorithm, and matched to the excitation frequency of the LEDs. By performing the measurement on both the reference photodiode and the solar cell, the absolute response of the cell is determined.

3. Findings and discussion

3.1 Spectral response measurements of photodiodes

The first test to verify our experimental approach in measuring the spectral response of devices using the two LED-based methods was to perform each procedure on two or more nominally similar photodiodes (PD), one used as the reference and the second used as the test specimen The reference PD was calibrated previously by the NIST Sensor Science Division using standard protocols [19] for determining the SR (a monochromator-based method). As part of the LED-based SR measurement methods, the calibrated PD is mounted on an optical breadboard at the exit plane of the light guide, and its AC photocurrent generated in response to the sequential pulsing of the LEDs (lock-in method) or from exposure to all of the synchronized LEDs (FT method) is measured. The calibrated PD is then replaced by the test PD (same exact XYZ location) and the same measurement is repeated. In order to establish the SR of the test PD, an *effective* spectral response $\overline{SR}(\lambda)$ for the calibrated PD is first determined from the true monochromatic $SR(\lambda)$ due to the quasi-monochromatic nature of the LED emission. This very small correction is obtained from:

$$\overline{SR}(\lambda) = \frac{\int_{\lambda 1}^{\lambda 2} SR(\lambda) I_{LED}(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda 2} I_{LED}(\lambda) d\lambda} \quad (1)$$

where $I_{LED}(\lambda)$ is the irradiance of the LED as a function of wavelength and it typically has a well-behaved Gaussian shape. The spectral irradiance of each LED is measured at the exit plane of the light guide by using a NIST-calibrated spectroradiometer [16] with a wavelength resolution of 1 nm in the UV-Vis range. From this effective SR for each LED, the power or the intensity (when the light overfills the detector) of the quasi-monochromatic light is determined. The ratio of the measured current (or current density) of the test PD to the optical power (or intensity) determined using the reference PD yields the absolute value of the spectral response of the test detector. The effective emission wavelength for each LED is determined by matching the effective SR value to the λ it corresponds to on the true SR curve of the detector. It should be mentioned that for most LEDs, this value is usually close to the center emission peak, as determined by a Gaussian fit to the irradiance data.

Figure 3a shows the lock-in-measured SR of 4 nominally identical test PDs as compared with the calibrated detector's response. In Fig. 3b, the SR curves using the Fourier measurement method on one test detector is compared to the calibrated PD. Excellent agreement is achieved with both techniques for all LEDs, hence confirming the validity and accuracy of both measurement techniques. We note that the lock-in technique is inherently less susceptible to sources of noise and hence provides a slightly more accurate and stable signal. Because the data shown in Fig. 3b using the FT method is obtained in only 4 s while providing exceptional agreement with the SR determined using the traditional monochromator-based method, this technique has great potential for fast throughput, as is needed for in inline manufacturing tests. Furthermore, these results, reveal that LEDs present a reliable light source to obtain accurate spectral data of devices while not requiring any sophisticated mathematical corrections [17,18], such as singular value decomposition to account for the finite emission bandwidth of the LEDs.

3.2 Solar cell spectral response

Measurement of the spectral responsivity of solar cells can also be performed using both methods. The main difference between the SR measurements on solar cells and photodiodes is the preference to apply a light bias for solar cell measurements. The light bias should be a constant source, ideally similar to that of the sun in terms of intensity and spectral shape. Although the photodiode SR can be obtained with non-pulsed monochromatic light, the solar cell measurements require a pulse or modulated illumination so that the monochromatically excited photocurrent can be distinguished from the background dc current caused by the bias light. As noted earlier, two forms of light bias are available: 1. using all the non-pulsing LEDs to provide a light bias for the pulsing LED in an automated fashion, and 2. using a few white LEDs that are illuminated for the duration of the measurement.

Figure 4a compares the normalized irradiance spectra of a white LED with that of a synthesized spectrum comprising all of the LEDs. The normalized AM 1.5 spectrum is also provided for reference. The LED-synthesized spectrum can be made to mimic the sun very well over this range; however, the 32 LEDs in the current setup cannot provide an intensity close to that of the sun (1000 W/m^2). Also, toggling the LEDs from the constant current mode to the pulse mode during the sweep introduces some inherent instability in the measurement (see next section). On the other hand, the white LEDs are readily available in the market, have tremendous optical power and are very stable. Although they lack emission in the IR part of the spectrum, white LEDs can provide a good substitute for a stable, powerful light bias.

Figure 4b shows the data obtained on a crystalline Si reference cell with dimensions 2 cm by 2 cm. Results from using the lock-in LED sweep method with the two light bias schemes discussed above, and data obtained using the FT method with white LEDs for light bias are included. The two methods using white LEDs as light bias are in excellent agreement, while the lock-in method with all-LED light bias shows reasonably good agreement with the white LED measurements. The amount of the DC light bias current for all 3 types of measurements was approximately 2 mA. It is noted that when using more powerful white LEDs, this AC measurement can be performed with as high as 70 mA of DC light bias current while maintaining good stability for the lock-in amplifier. The observed fluctuations in the data are mostly caused by spatial nonuniformity in the illumination plane (as discussed in the section below). Because the reference PD and the solar cell have different sizes (1 cm^2 vs 4 cm^2 in area) along with the measurements being performed using an overfill illumination, a small error is introduced in estimating the effective intensity of light on the solar cell. This error is minimized by making multiple measurements with the calibrated detector, and then propagating the standard deviation within the calculation of the cell's spectral response – see the error bars on the data. The other source of error, in particular for the all-LED light bias scheme, is the inherent instability in the operation of the LEDs when toggled successively between constant current mode and pulsed mode. This effect is discussed in more detail below.

With the good agreement observed using both measurement methods to determine the absolute spectral response, the short circuit current density, J_{sc}, under AM 1.5 standard test conditions can be calculated using:

$$J_{sc} = \int_{280\text{ nm}}^{4000\text{ nm}} I_{AM1.5}(\lambda) SR_{cell}(\lambda) d\lambda \qquad (2)$$

where $I_{AM1.5}(\lambda)$ is the standard AM 1.5G solar irradiance, and $SR_{cell}(\lambda)$ is the spectral response of the tested solar cell. Performing this calculation on the data obtained in Fig. 4b, we predict a J_{sc} = 29.6 mA/cm^2, or a short circuit current (I_{sc}) of 118.4 mA, which is within 6 % of the certified value of 125.6 mA. The small difference is likely due to errors introduced from the illumination nonuniformity and also due to the lack of LEDs with light emission below 370 nm.

SR measurements carried out on a variety of PV device types and sizes yield excellent agreement between the two techniques and with published absolute SR curves. The J_{sc} derived using the SR measurements, moreover, is comparable to the measured short circuit current density. For example, Fig. 5 compares the SR of the crystalline Si cell discussed above with a cadmium telluride (CdTe) cell and an IR-filtered Si cell. It is noted that although some cells, such as the Si device of Fig. 4b, did not show a significant change in behavior with light bias, other types of cells – such as the CdTe cell shown here – revealed a strong dependence upon the application of light bias. The effect of light bias on certain types of solar cell technologies has been investigated previously [8].

3.3 Spatial light uniformity and LED stability

Two operating parameters investigated for their effect on the SR measurements include the illumination uniformity at the exit plane of the light guide and the stability of the LEDs during both pulsed and constant-current operation. Figure 6a shows a map of the spatial uniformity of the integrated light intensity (All LEDs) at the exit plane of one of the light guides, as measured by a calibrated spectroradiometer. The total irradiance nonuniformity over the 20 cm × 20 cm area is approximately 10 %. The nonuniformity of individual LEDs, however, can be higher, as described extensively in a previous paper[16]. To summarize, local cold (low intensity) and hot (higher intensity) spots were observed throughout the illuminated plane indicating that the light mixing with the current light guide design has its limitations. Nonetheless, for solar cells on the order of a few centimeters, such as the standard 2 cm × 2 cm reference cells, the current set up allows for the ideal "overfill" illumination [3] of the entire cell area. The uncertainties due to intensity variations can be estimated by multiple measurements using the reference detector. A standard deviation can be determined for the SR curve, as discussed earlier. Overfill illumination of cells up to 6 inches in dimensions are also possible, and will be briefly described in the next section.

Fig. 6b shows the measured pulsed and steady-state light stability, and repeatability, of a typical LED, as evaluated using a fast photodiode. The straight curve shows the response of an LED (AC photocurrent) toggled between the pulse ON to pulse OFF states at a given pulse frequency over an interval of about 80 s. Each operation reaches stability typically in less than 5 s after the command signal is sent. The curves reveal a very stable and repeatable pattern after many minutes of operation, as long as the LED's operating temperature is maintained at a relatively constant value. For the results reported here, the LEDs were operated at 15 °C via their water-cooled mounting plate (see Fig. 1). The dashed curve shows the same LED toggled between a steady-state mode (DC current) and pulsed mode. In this case, the pulsed state shows a current transient and a small exponential decay before reaching steady values. Also, the nature of the transient varies slightly between multiple repetitions. This slight inherent instability, which is likely due to temperature fluctuations inside the LED, can cause slight fluctuations in spectral response data, if the second scheme of providing a light bias (all-LED light bias) is employed (see Fig. 4b). Although acceptable, the authors recommend that in order to reduce measurement uncertainties, a given LED should either be operated in pulse-only mode or constant-current mode when performing spectral response measurements. Ideally, it is best to have multiple numbers of each LED so that one set can be operated in pulse mode only, and all other ones can be used to provide a steady-state light bias in the shape of any spectrum that is desired.

3.4 Large-area solar cells

In order to show that spectral response measurements of large area solar cells are possible with the light guide set up, preliminary measurements on a 15 cm (6 in) × 15 cm mono-crystalline reference solar cell were performed. The results of these measurements are shown in Fig. 7. Since the area to be illuminated is very large and contains nonuniformities, the calibrated reference diode is first used to obtain multiple measurements of the monochromatic light intensity in the x-y plane where the cell is eventually placed. This intensity mapping was achieved in a relatively short amount of time using the FT method. Afterwards, the cell photocurrent density was measured (no light bias), and an absolute SR was determined, with the error bars reflecting the variations in monochromatic light power across the cell. This data is shown with filled circles in Fig. 7.

In a second measurement, the exit port of the light guide was blocked with a dark screen that had a small mm-sized aperture at its center. A condensing lens assembly was used to form a small focused spot (≈ 2 mm) onto the cell. Since this small spot underfills the calibrated PD, and its x-y position is fixed, its optical power for each LED wavelength is measured. This time, the solar cell was placed in front of the light spot, and the cell's photocurrent at multiple x-y locations was measured. The data was then used to calculate a spectral response for each position of the cell, and the average of those measurements is shown with filled squares in Fig. 7. The error bars which incorporate the variations of the photogenerated current at different locations across the cell point to spatial nonuniformity of the solar cell material. The two measurements mostly agree within the margin of error (except for a few wavelengths around the maximum peak of the curve), although the source of uncertainty is different for each. Therefore, large-area overfill measurements are possible with the apparatus, and show consistency with small spot measurements. For other types of cells such as polycrystalline, thin film or organic devices, large-area material nonuniformity or cell defects, along with the need for a light bias, and issues with spatial uniformity of the light source can all play a nontrivial role in large-area SR measurements. These factors are currently under investigation at NIST, and the findings will be discussed in a future correspondence.

4. Conclusions

Absolute differential spectral responsivity measurements of small and large-area solar cells having different technologies have been demonstrated using an LED-coupled light guide test apparatus. Measurements can be made over the wavelength range of 370 nm to 1200 nm. The measurements were performed using the lock-in and FT techniques, which were shown to yield the same result for variety of devices. The LED-obtained SR data were compared with traditional monochromator-based measurements and found to be in excellent agreement. Furthermore, a scheme for providing light bias during the measurement using LEDs were evaluated and found to yield nearly identical spectral response curves. Complete SR measurements were performed using the FT in as short a time as four seconds, while more accurate measurements using a lock-in technique required 5 to 6 minutes. The results described here confirm that LEDs have achieved technologically viable status in order to be incorporated into a variety of electro-optical characterization methods.

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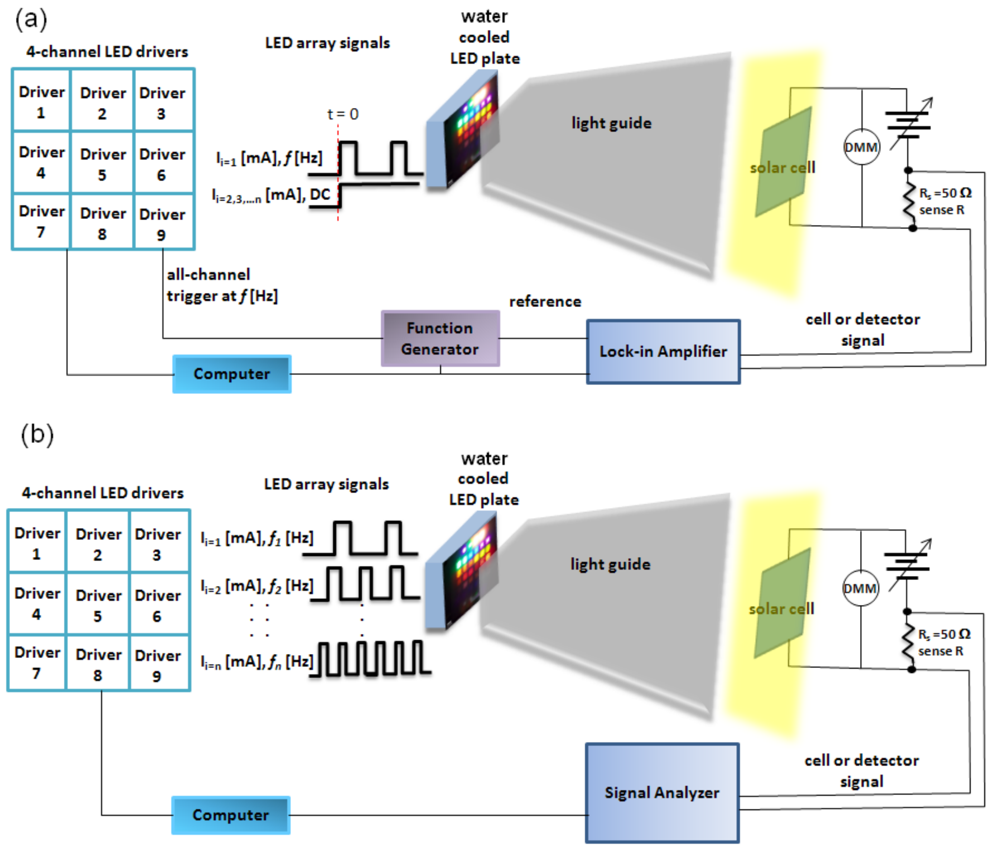

Fig 1. Hardware and operating features of (a) the lock-in based SR measurement method and (b) the Fourier-based SR measurement method

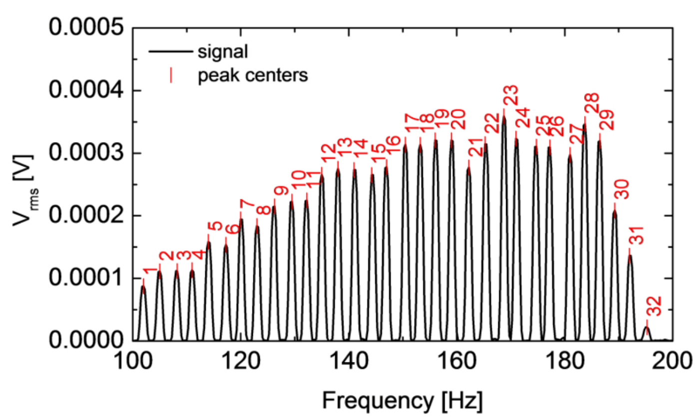

Fig 2. The frequency spectrum of the LEDs pulsed at the different frequencies. An example of data obtained by the fast Fourier method

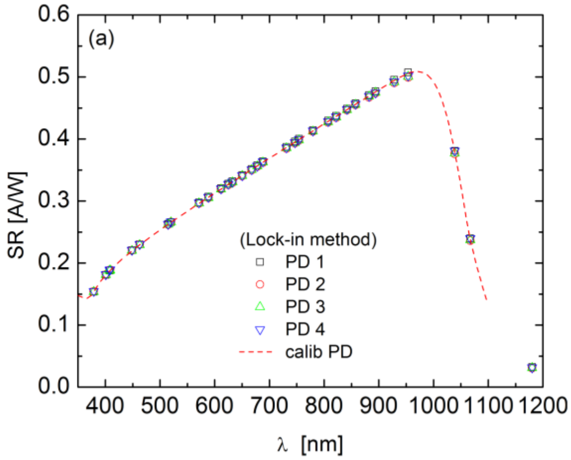

Fig 3. (a) The spectral response measurement of 4 photodiodes (PD) of the same model using the LED lock-in method and comparison of the results with a NIST-calibrated PD of the same kind. The percent difference between the LED data and the calibrated PD data is less than 1 % for most data points (b) The FT method of obtaining the spectral response of the same PD. The percent differences are mostly less than 2 % with a few points showing up to a 6 % difference.

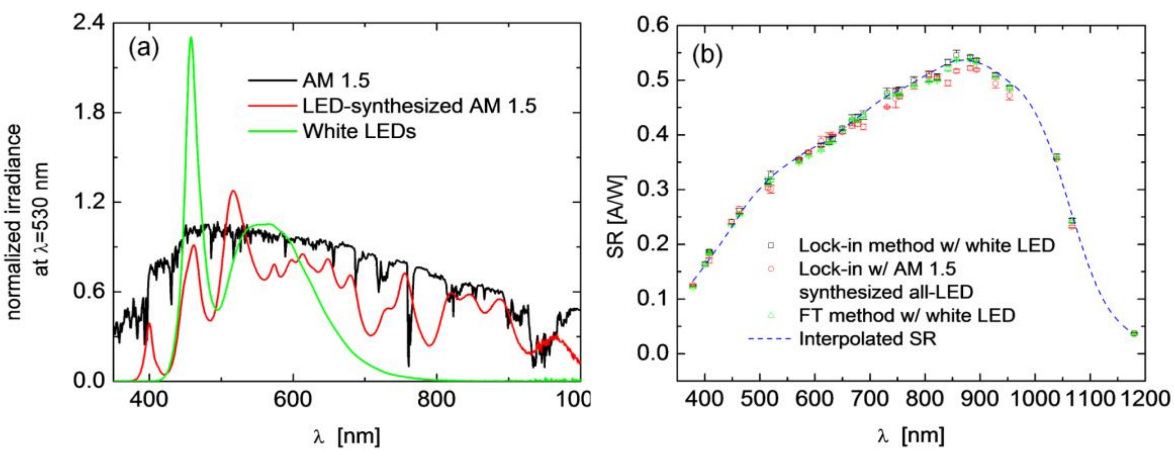

Fig 4. (a) The normalized irradiance of white LEDs, and an all-LED-synthesized AM 1.5 spectrum used as sources of light bias for SR measurements of solar cells. The AM 1.5 spectrum is also shown for comparison. (b) The SR of a reference Si cell obtained under various conditions as labeled.

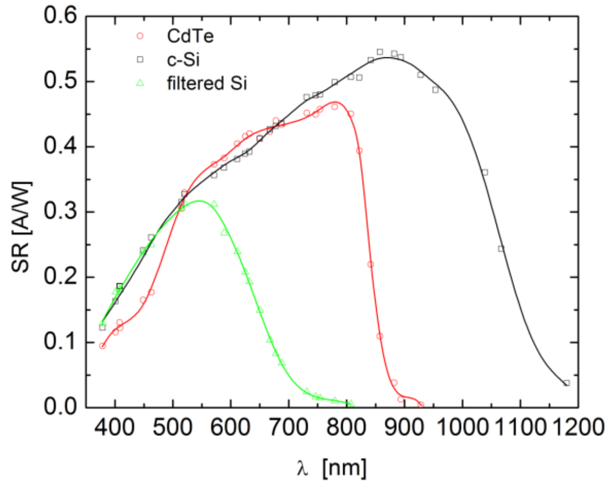

Fig 5. Lock-in LED-based measurement of the SR of a few PV device types. Solid curves are mathematical interpolations through measured data for guide to the eye.

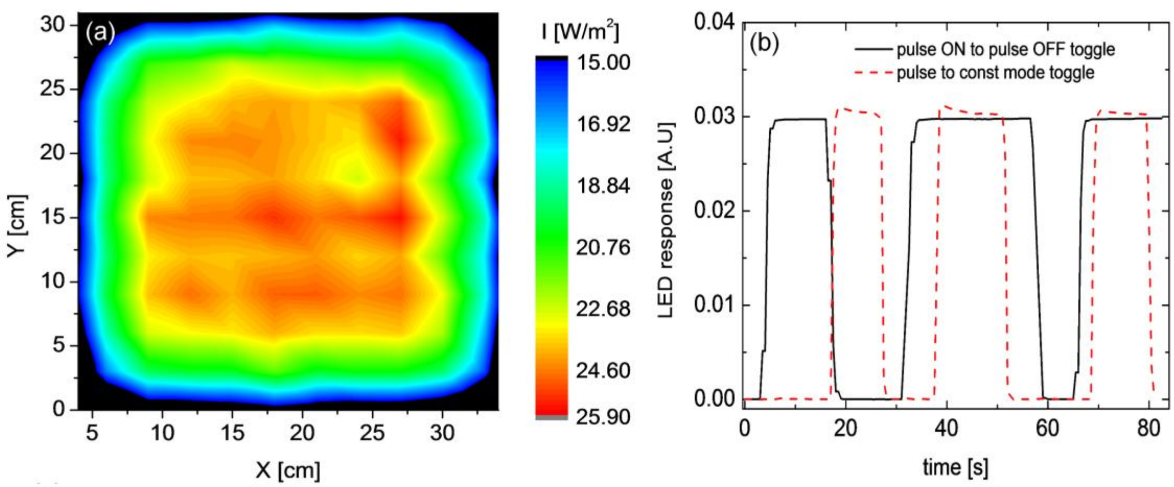

Fig 6. (a) Total irradiance uniformity contour map at the exit plane of a tapered light guide. (b) LED signal stability and repeatability as monitored by a fast photodiode.

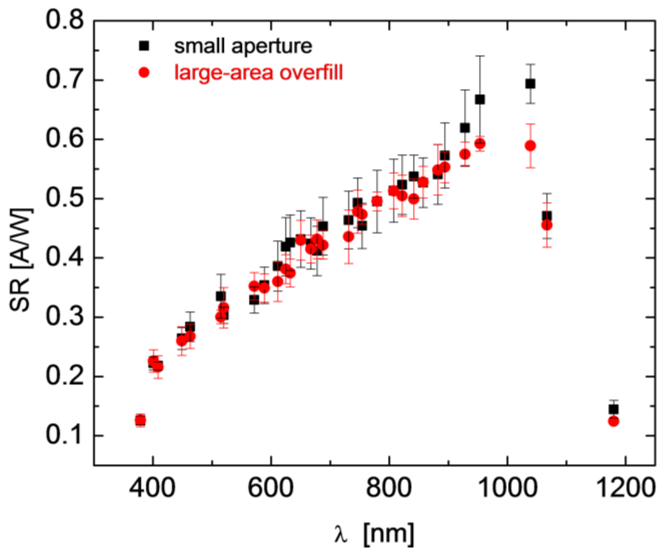

Fig 7. Large-area spectral response measurements of a 15 cm mono-Si solar cell using an underfill and an overfill approach.