Fast and Reliable Spectral Response Measurements of PV Cells Using Light Emitting Diodes

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Abstract — **We present a measurement system for absolute differential spectral responsivity of solar cells based on high-powered LED arrays coupled to an optical light guide capable of large area illumination. Two different measurement techniques were developed and tested with the same measurement apparatus on a variety of solar cells. The first method is an individual LED lock-in technique that can be performed over a broad frequency range. The second method is based on synchronous multi-frequency optical excitation, called the Fourier transform (FT) technique, using the LEDs and detection with a spectrum analyzer. A scheme for providing light bias using the LEDs during either measurement scheme is discussed.**

Index Terms — **solar cells, spectral responsivity, light emitting diodes, Fourier transform.**

I. INTRODUCTION

The measurement of the spectral responsivity (SR) of a solar cell, defined as the ratio of the photocurrent generated by the cell to the optical power of the incident radiation over a wavelength range, is essential in photovoltaic (PV) device characterizations [1]. 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 desired standard air mass 1.5 (AM 1.5) criteria [2-4]. The relative SR data of cells are used in obtaining a calibration spectral mismatch factor when solar cells are tested indoors under artificial lighting conditions when the power conversion efficiency is expected to be reported with respect to the standard reference spectrum [5-7].

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 low-power modulated (quasi) monochromatic light beam and a more intense steady-state broad-band light source (the light bias) illuminate the solar cell, producing a small AC current superimposed on a larger DC current. The AC current is amplified and detected using a lock-in technique. The significance of the use of light bias has been described previously, particularly for certain types of solar cells [8].

In this paper, we describe the design and operation of a large-area, differential spectral response measurement system based on LED arrays coupled to a tapered hollow optical light pipe that can illuminate an area of 25 cm by 25 cm or more. Furthermore, the LED system can be utilized to perform two unique types of SR measurements with light bias without additional broad-spectrum sources. We demonstrate the feasibility of using the FT technique to reduce by a factor of 100 or 1000 the time duration for the spectral responsivity measurements over conventional measurement techniques.

II. EXPERIMENTAL SETUP

A wide variety of LEDs were chosen to construct the spectrally tunable source. These LEDs are available under many different wavelengths but have weaker outputs at certain wavelengths. These LEDs were mounted on a square water-cooled aluminum heat sink plate with a surface area of 8.9 cm × 8.9 cm as shown in Figure 1. On this plate, 30 LEDs were mounted. Additional high power LEDs (2 whites, 1 blue and 1 green) made by a different manufacturer, were mounted near the top edge. All the LEDs are powered by computer-controlled LED drivers. Each of these current drivers could drive 4 LEDs. A total of 8 current drivers were dedicated to operate the 32 monochromatic LEDs. These LEDs were operated in pulsed mode. The white LEDs were operated in dc current mode as sources of light bias. The LEDs were mounted at the opening of the light guide setup.

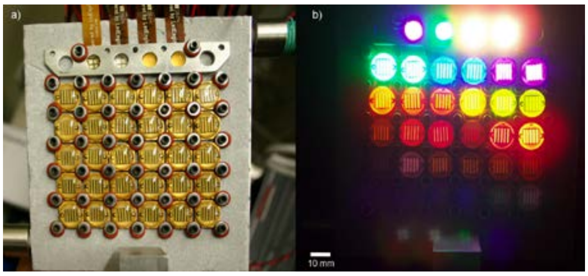

Fig. 1 (a) LED matrix heat sink/mount with built-in water circulating channels. (b) The same LED plate in operation under a small current to each LED. The LEDs on the second row from the bottom emit most of their radiation in the NIR region and hence appear very faint to the human eye. The bottom row LEDs in the infrared are completely invisible to human eye.

The tapered light guide shown in Figure 2 performs two functions: (1) Creating uniform irradiance from an extended source such as typical high power multiple arrays of LEDs, and (2) Allowing multiplexing of different wavelengths. The inside surfaces of the light guide are front surface mirrors with reflectivity of 98% from a wavelength of $\approx$ 500 nm to $\approx$ 750 nm. The light guide length and ratio of the input-to-output apertures were optimized so that the output irradiance will meet a certain uniformity tolerance. More details related to the construction and testing of the light guides can be found in reference 9.

Fig. 2 Assembled light guides using front surface reflecting stainless steel. The four 5-m-long light guides are shown, each with 7.6 cm by 7.6 cm input and 30.5 cm by 30.5 cm output openings. The rear opening of the light pipe is shown on the right side of the picture.

III. LED OPERATIONAL MODES

The LEDs were operated in two modes for the spectral responsivity measurements as shown in Fig 3. The first method, shown in Fig. 3a, is a lock-in technique that is the same as the traditional monochromatic-based systems employing mechanical choppers. A function generator is used to trigger a specified LED driver channel which can then apply a pulsed current signal source to an LED at a given frequency (typically 40 Hz). During the measurement, light bias is provided by DC current sourcing of a few "white" LEDs. The entire measurements allows for each of the 32 LEDs to be sequentially pulsed and photocurrent of the cell to be measured.

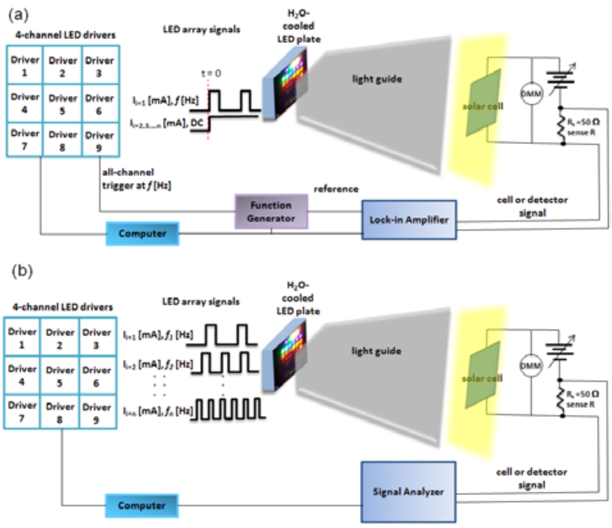

Fig. 3 (a) Schematics of the lock-in based technique and (b) the Fourier-based method of our large-area SR system

A single sweep at a pulsing frequency of 40 Hz over 32 LEDs can be performed in about 5 min total duration at roughly 10 s per LED.

In the second technique, shown in Fig. 3b, which we refer to as the Fourier Transform method, the LED drivers are used to pulse all 32 LEDs at the same time, but each with a slightly different frequency. The time-dependent signal generated in the solar cell as a result of these concurrent pulsed illuminations are detected in the frequency domain by use of a signal analyser; which allow determination of the SR of the solar cell over all wavelengths at a nominally short time of 4 s or less.

Figure 4 shows a typical dataset captured by the signal analyzer frequency scan which is accomplished in 4 seconds. In this example, the currents supplied to LEDs are individually adjusted so that each LED's output intensity at the exit plane of the light guide is roughly 70 mW/m^2, regardless of its total output power or efficiency. The pulse frequencies are chosen in the range of 100 Hz to 200 Hz separated by steps of 3 Hz. Therefore, higher order harmonics of these signals are outside this range and can be ignored. For data analysis, the raw data are imported into a computer program and the peak centers and the value of the V_{rms} signals are extracted using a peak-finding feature, 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 can be determined.

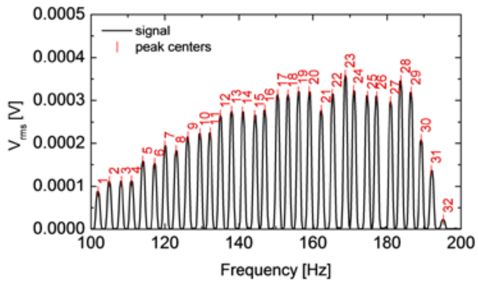

Fig. 4 The frequency spectrum of the LEDs pulsed at the different frequencies. An example of data obtained by the fast Fourier method

IV. LIGHT-BIASED SPECTRAL RESPONSIVITY MEASUREMENTS OF SOLAR CELLS

The spectral responsivities of solar cells should be performed with biased radiation. For these measurements, we either synthesized an approximate AM 1.5 spectrum using the non-pulsed LEDs of the lock-in method, or simply used powerful white light LEDs as sources of light bias. The white LEDs are readily available in the market, have tremendous optical power and are very stable and we found that although they lack emission in the IR part of the spectrum, they can provide a good substitute for a stable powerful light bias.

The spectral responsivity of a crystalline Si reference cell 2 cm by 2 cm using the lock-in LED sweep method is shown in Figure 5 with the two light bias schemes discussed above, and also shown is the data obtained using the FT method with white LEDs for light bias. For these measurements, first a calibrated reference Si diode is placed under the illumination in order to obtain the optical flux at each LED wavelength, then, the diode is replaced by the actual solar cell. 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 other two measurements. The amount of the DC light bias current for all 3 types of measurements was approximately 2 mA. We note that using more powerful white LEDs, we have been able to do this AC measurement with as high as 70 mA of DC generated current with good stability for the lock-in amplifier. The observed fluctuations in the data are mostly caused by spatial non uniformity in the illumination plane. Since the reference photodiode and the solar cell have different sizes (1 cm^2 vs 4 cm^2 in area) and the measurement is done under overfilled illumination conditions, a small error is introduced in estimating the effective intensity of light on the solar cell. We account for this by making multiple measurements with the calibrated detector, and propagating the standard deviation through the calculation of the spectral response; which is shown by error bars on the data.

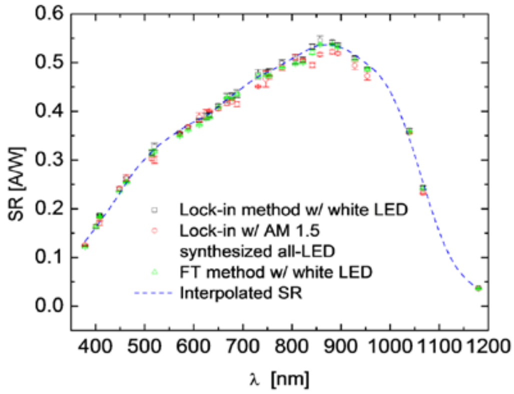

Fig. 5 The SR of a reference Si cell obtained under various conditions as labelled.

SR measurements on a variety of PV device types and sizes using both techniques were performed, and we found excellent agreement between the two techniques with absolute SR curves consistent with published results, and a J_{sc} prediction matching the measured short circuit current density of that type of cell. Fig. 6 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 the Si device did not show a significant change of behavior with light bias, other types of cells such as the CdTe cell shown here revealed a strong dependence upon application of light bias. The effect of light bias on certain type of solar cell technologies has been investigated previously [8].

V. CONCLUSIONS

We have demonstrated absolute differential spectral responsivity measurements of small and large-area solar cells of different variety based on a LED-coupled light guide over the wavelength range of 370 nm to 1200 nm. The measurements were performed using two different but complementary techniques that were shown to yield the same result for Si and a variety of other cells. The LED-obtained SR data were compared with monochromator-based measurements with excellent agreement. Using the FT technique, complete SR measurements were performed in as short a time as four seconds, while more accurate measurements using a lock-in technique were performed over a broad pulsing frequency range. Our results described here confirm that LEDs have achieved technologically viable status in order to be incorporated into a variety of electro-optical characterization methods, and that the FT technique has the promise for use as a factory in-line technique for rapid SR measurements.

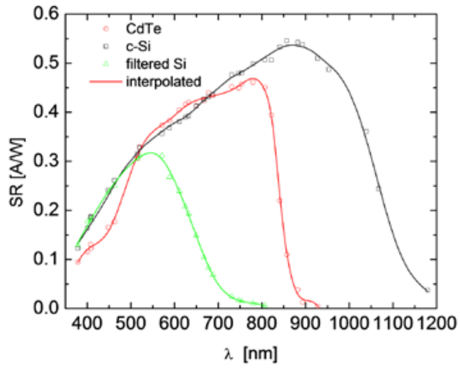

Fig. 6 Lock-in LED-based measurement of the SR of a few PV device types. Solid curves are mathematical interpolations through measured data for guide to the eye.

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