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# LIGHT-EMITTING-DIODE-BASED FOURIER-TRANSFORM SPECTRAL RESPONSE MEASUREMENT SYSTEM FOR PHOTOVOLTAIC CHARACTERIZATIONS

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**Abstract:** A system for measuring the absolute spectral responsivity of solar cells is described. The system uses higher-powered LED arrays that are coupled to an optical light guide that together provide large area illumination. Two different measurement methods were developed and tested using this measurement apparatus. The first method is an individual LED lock-in technique that can be performed over a broad frequency range. The second method, which uses a Fourier transform technique, is based on synchronous multi-frequency optical excitation of all the LEDs, coupled with detection by a spectrum analyser. Schemes for providing light bias using the LEDs during both measurement schemes are discussed. Spectral response measurements using both measurement methods are reported for a variety of solar cells.

**Keywords:** solar cells, spectral responsivity, light emitting diodes, Fourier transform.

## 1. 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 its full wavelength range of response 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 standard air mass 1.5 (AM 1.5) spectrum used for rating purposes [2-4]. The relative SR data of cells are used in obtaining a spectral mismatch factor. This factor is especially useful when testing solar cells and solar modules that have a different spectral response than the reference cell or module used to measure the incident irradiance. [5-7]. Notably, values for the relative SR can be determined from the absolute SR values, but not vice versa.

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. For this approach, 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. These two light sources cause the cell to produce 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].

To achieve monochromatic illumination of the cells, several methods have been undertaken to date. 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 needed for the operation of the monochromator 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.

In this paper, the design and operation of a large-area, differential spectral response measurement system that differs from those systems currently used for solar cell SR measurements is reported. The system places an array of LEDs at the inlet of a tapered optical light guide. The solar cell under test is mounted at the larger, outlet end of the optical guide. Each coupled LED array and guide can illuminate an area of 25 cm by 25 cm, or more. The LED-based system can be operated using two distinct approaches. For the first approach, only one LED is pulsed at a time in sequentially progressing through all of the LEDs in the array. For the second approach, all the LEDs are pulsed for the entire measurement interval, only now with the pulse frequency being different for each LED. For the first approach, the solar cell's AC current output is measured using a lock-in technique. For the second approach, a spectrum analyzer is used in combination with a Fourier Transform (FT) technique to determine the AC current created by each pulsing LED. In both cases, light bias is provided without requiring an additional broad-spectrum source. Results from using the LED-based system to measure the SR of several solar cells are reported.

The leading attributes of the SR measurement method include the potential for measurement system cost savings, the ability to measure full-size solar cells while offering the potential for scaling up to applications on mini and full size solar modules, and the comparatively fast means for measuring SR. On this last point, the LED-based SR measurements system, especially when applied using the FT technique, reduces by a factor of 100 to 1000 the time required to complete such measurements as compared to using conventional SR measurement techniques

## 2. EXPERIMENTAL SETUP

A wide variety of LEDs, most mounted in TO-66 packages, were chosen to construct the array, thus creating a spectrally tuneable source. These LEDs are available at many different wavelengths with some having weaker outputs than others. Each TO-66 LED is composed of 60 diode dies mounted on metal and ceramic heat sinks. Each diode assembly is covered with a double coated clear silicone and epoxy resin lens that provides a wide dispersion angle. The LED chip is circular and is roughly 11 mm in size. Excess edge metal of the TO-66 package was removed to allow closer mounting of the LED packages. These LEDs were mounted on a square water-cooled aluminium heat sink plate having a surface area of 8.9 cm × 8.9 cm, as shown in Figure 1. On this plate, 30 modified TO-66 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. The LED array is then positioned at the smaller opening of the light guide.

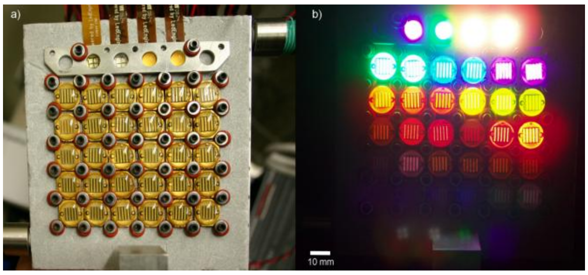


**Figure 1.** (a) LED matrix heat sink/mount with built-in water circulating channels. (b) The same LED plate in operation under a small current to each LED. The LEDs on the second row from the bottom emit most of their radiation in the NIR region and hence appear very faint to the human eye. The bottom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

The primary function of the tapered light guide shown in Figure 2 is to distribute, via multiple internal reflections, the spectral output generated by each LED as uniformly as possible over the entire exit plane of the light guide. The inside surface of the light guide is lined with thin, highly reflective stainless steel sheets that provide a reflectivity of 98% for wavelengths of ≈ 500 nm to ≈ 750 nm, and > 95% reflectively for wavelengths from ≈ 750 nm to ≈ 1800 nm. Using a ray tracing program, the light guide length and ratio of the input-to-output apertures were optimized to maximize the spatial uniformity of the total irradiance at the guides' exit plane. The assembled light guide is 5 meters long and has an input aperture of 7.6 cm × 7.6 cm and exit aperture of 30.5 cm × 30.5 cm.

**Figure 2.** Four assembled light guides using front surface reflecting stainless steel. The 5-m-long light guides are shown, each with 7.6 cm by 7.6 cm inlet apertures and 30.5 cm by 30.5 cm exit apertures. The exit apertures of the light pipe are shown on the right side of the picture.

## 3. LED OPERATIONAL MODES

The LEDs were operated in two modes for the spectral responsivity measurements,. The first method, shown in Fig. 3a, is a lock-in technique that is 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). At the same time, two light biasing schemes were explored. In one scheme, a set of high-powered broad-spectrum white LEDs were operated under constant DC current to illuminate the device under test (DUT) concurrent with the pulsed operation of each individual LED. An electrical pulse is applied to one LED (in an array of 32) at a time while the other LEDs (or broad-spectrum white LEDs) are turned on and maintained under DC current to provide a light bias. A computer-controlled sweep algorithm controlling 9 four-channel LED drivers, a lock-in amplifier

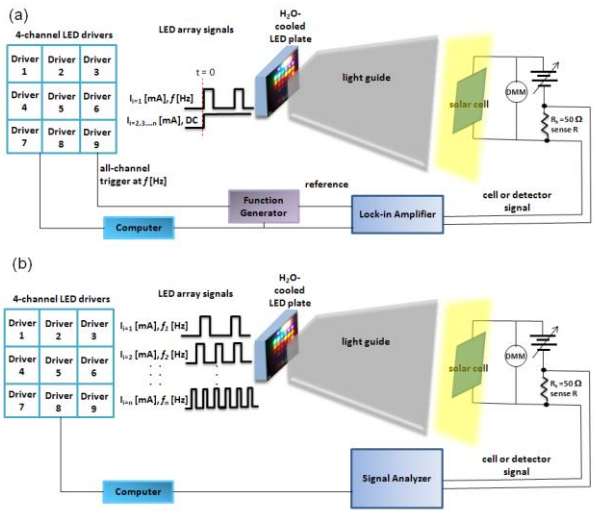


**Figure 3.** (a) Schematics of the lock-in based technique and (b) the Fourier-Transform based method of the LED large-area SR systems.

and a pulse generator automatically scans through the different LEDs and records the AC signal generated across the solar cell or detector due to the pulsing LED. The entire measurement with the each of the 32 LEDs is sequentially pulsed. A single sweep of the 32 LEDS, pulsing each at a frequency of 40 Hz, can be completed in about 5 min, or roughly at a rate of 10 s per LED.

In the second technique, shown in Fig. 3b, which is referred to as the Fourier Transform (FT) 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 signals 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. Using this approach, the SR of the solar cell is determined over all 32 wavelengths at a nominally short time of 4 s or less.

Figure 4 shows a typical dataset captured by the signal analyzer frequency scan when using the FT technique. 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 at roughly 70 mW/m$^2$, regardless of its total output power or efficiency. This approach provides more reliable and noise-free data collection. For data 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 a reference photodiode and a solar cell, the absolute spectral response of the cell can be determined.

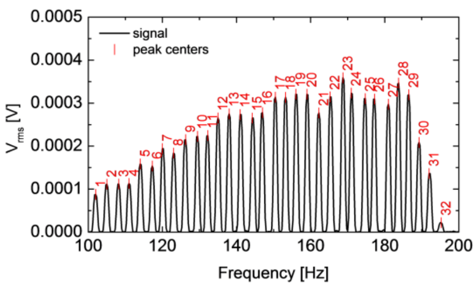


**Figure 4.** The frequency spectrum of the LEDs pulsed at the different frequencies. An example of data obtained by the fast Fourier method.

## 4. SPECTRAL RESPONSIVITY MEASUREMENTS OF PHOTODIODES

To verify the two LED-based methods, each procedure was conducted using a test photodiode (PD) and a nominally similar reference photodiode. The reference PD was calibrated in advance by the NIST Sensor Science Division using standard protocols (i.e., a monochromator-based method). When tested in the LED-based SR measurement system, the calibrated PD was mounted on an optical breadboard at the exit plane of the light guide. Its AC generated photocurrent due to sequential pulsing of the LEDs (lock-in method) or all LEDs synchronously (FT method) was measured as described in the previous section. Afterwards, the calibrated PD was replaced by the test PD (same exact XYZ location) and the same measurements were performed. In order to establish the SR of the test PD, an effective spectral response for the calibrated PD was determined by comparing the LED based results to the monochromatic measurement results. This step was needed due to the quasi- monochromatic nature of the LED emission.

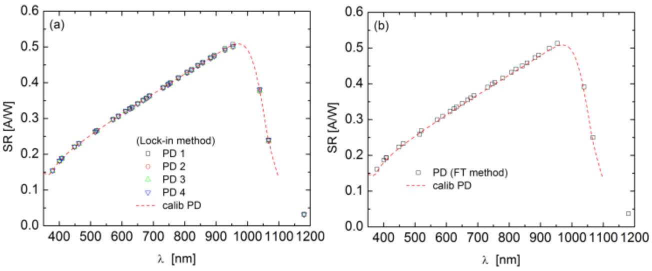


**Figure 5.** (a) The spectral response measurement of 4 photodiodes (PD) of the same model using the LED lock-in method and comparison of the results with a NIST-calibrated PD of the same kind. (b) The FT method of obtaining the spectral response of the same PD.

The spectral irradiance of each LED was measured at the exit plane of the light guide by using a NIST-calibrated spectroradiometer with a wavelength resolution of better than 3 nm. From this spectrum measurement for each LED, the power or the intensity (with the light overfilling 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) determines 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 wavelength it corresponds to on the true SR curve of the detector. For most LEDs, this value is usually close to the center emission peak as determined by a Gaussian fit to the irradiance data.

## 5. BIASED SPECTRAL RESPONSIVITY MEASUREMENTS OF SOLARCELLS

The spectral responsivities of solar cells should be measured while subject to biased radiation. Since the LEDs are used to provide the bias radiation, the agreement of the total LED output to the AM1.5 spectral irradiance must be determined. Figure 6a compares the normalized irradiance spectra of a white LED with that of a synthesized spectrum comprising all of the LEDs. The normalized AM1.5 spectrum is also provided for reference. The LED-synthesized spectrum can be made to mimic the sun very well over this range, but the 32 LEDs in our current setup are not intense enough to provide the spectral irradiance close to that of the sun (1000 W/m2). Also, toggling the LEDs from the constant current mode to the pulse mode during the sweep introduces some inherent instability in the measurement due to the hysteresis of the LED output. On the other hand, white LEDs are readily available in the market, have tremendous optical power and are very stable. And, although they lack emission in the IR part of the spectrum, they can serve as a stable, powerful bias light .

The spectral responsivity of a 2 cm by 2 cm crystalline Si reference cell, as measured using the lock-in LED sweep method and each of the light biasing schemes described above, is shown in Figure 6b. The SR data obtained using the FT method and white LEDs for the light biasing is included in the same Figure. The two measurements using the white LEDs for the light biasing yield excellent agreement. The lock-in method with all-LED light biasing shows reasonably good agreement with these other two measurements. The amount of the DC light bias current for all 3 measurements was approximately 2 mA. Measurements using more powerful white LEDs which created, DC generated currents as high as 70 mA. Even with this much higher DC signal, the lock-in amplifier technique was found to yield good stability and comparable SR results. The observed fluctuations in the SR data are mostly caused by spatial non uniformity in the illumination plane. Since the reference PD 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 uncertainty is introduced in estimating the effective intensity of light on the solar cell. This uncertainty is accounted by making multiple measurements with the calibrated detector, and propagating the standard deviation through the calculation of the spectral response. The resulting uncertainty is shown by the error bars on the plotted data.

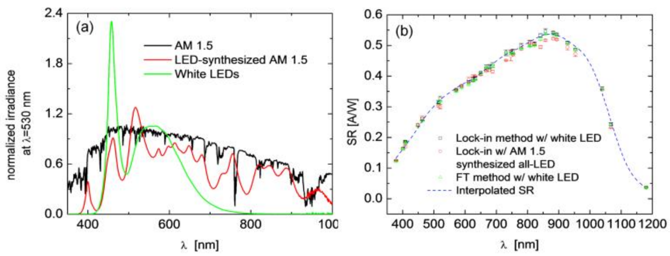

**Figure 6.** (a) **Light biasing options:** normalized irradiance of white LEDs and an all-LED-synthesized AM 1.5 spectrum . The normalized AM 1.5 spectrum is also shown for comparison. (b) The SR of a reference Si cell obtained under various conditions as labeled.

SR measurements on a variety of PV device types and sizes using both techniques were performed. Excellent agreement was observed between the two techniques with absolute SR curves consistent with published results, and a $J_{sc}$ prediction matching the measured short circuit current density. Fig. 7 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].

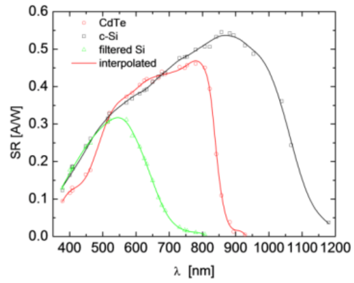

**Figure 7.** Lock-in LED-based measurement of the SR of a few PV device types. Solid curves are mathematical interpolations through measured data for guide to the eye.

## 6. CONCLUSIONS

Absolute differential spectral responsivity measurements have been successfully conducted on of a variety of small and large-area solar cells using 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. Furthermore, a scheme for providing light bias during the measurement using LEDs were also proposed and tested with good results. 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. 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, and that the FT technique has the promise for use as a factory in-line technique for rapid SR measurements.

## 5. REFERENCES


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