Challenges of Irradiance-mode Spectral Response Measurements

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Abstract — Irradiance-mode spectral response measurements of solar cells are important because they provide a direct, reliable and accurate route for determination of the short circuit current ($I_{sc}$) of solar cells under air mass 1.5 standard reference spectrum. In this work, a monochromator-based approach was combined with a light emitting diode (LED) array-operated system based on an integrating sphere design to obtain the irradiance-mode SR curves for a variety of cells, including large-area cells with dimensions up to 155 mm. Challenges associated with these measurements, including light uniformity, collimation issues and light bias effects are discussed. $I_{sc}$ calculations using this approach and intercomparison with other laboratories confirm the accuracy of the outlined methodology.

Index Terms — spectral response, irradiance, integrating sphere, photovoltaic cells.

I. INTRODUCTION

The spectral responsivity (SR) measurement of a photovoltaic (PV) solar cell can be performed in either the power mode or the irradiance mode, and each measurement can be either a relative or an absolute measurement [1], [2]. Power-mode measurements require the knowledge of the monochromatic beam's radiant power, typically obtained using a calibrated, SI-traceable reference photodetector. For the irradiance mode, the irradiance or incident power per unit area of the monochromatic beam is required. Irradiance can be determined by fully illuminating (i.e., overfilling) a uniform, apertured-photodetector with a collimated incident monochromatic radiation and then dividing the measured beam power by the exposed area of the detector. The absolute SR in power mode has SI units of $A \, W^{-1}$, whereas the absolute SR in irradiance mode is reported in units of $A \, m^2 \, W^{-1}$.

Irradiance-mode SR measurements are generally difficult to perform for two reasons: 1. A very spatially-uniform monochromatic beam that can fully illuminate a test cell with areas ranging from $4 \, cm^2$ to over $200 \, cm^2$ over a large wavelength range is very challenging to produce in the lab. 2. The irradiance measurement itself requires linear standard reference detectors with precision apertures, mapped surface uniformity and calibration data. Due to these two main challenges, most secondary testing laboratories perform power-mode SR measurements and report external quantum efficiencies (EQE) normalized to 1. However, the more accurate and viable route for obtaining the $I_{sc}$ of a solar cell is achieved by using the irradiance-mode SR curve of the cell, since the lack of spatial uniformity of the cell responsivity or presence of metal fingers on the front surface of the cell can lead to systematic differences between the underfilled power responsivity measurements and the overfilled irradiance responsivity measurements.

This work discusses a solution for obtaining the irradiance-mode SR data of a given cell from the power-mode SR data by combining the traditional monochromator-based techniques with a light emitting diode (LED) approach. Discrete irradiance-mode SR measurements with one or multiple LEDs can be combined with SR curves obtained through the power-mode method to construct the overall curve representing the entire device response. Challenges associated with obtaining uniform monochromatic beams that overfill entire cells with dimensions up to 12 cm by 12 cm are discussed and the effects of material nonuniformity and beam collimation are further elucidated.

II. SYSTEM DESCRIPTION

The monochromator-based system which has been discussed in detail elsewhere[1] consists of a dual light source: A 150 W...
xenon (Xe) light source and a 250 W quartz tungsten halogen (QTH) light source, the former for the spectral range of 300-nm to 605 nm and the latter for the spectral range > 605 nm. The broadband light from these sources pass through order-sorting filters and a mechanical chopper for light modulation. The modulated monochromatic light that exits the monochromator illuminates the sample at a local spot and induces the cell to output an ac current which is detected by a lock-in amplifier. A dc operated light source also illuminates the cell simultaneously in order to provide light bias and push the cell to operate in the linear regime [3]. The dc generated photocurrent is separated from the ac signal by a transimpedance amplifier. A small portion of the monochromator’s light output is directed towards a sandwich Si/Ge monitor detector, whose response is also measured by a lock-in amplifier. The irradiance scale is transferred onto the sphere system by use of a calibration procedure where a reference photodiode detector with an exceptionally uniform area and a measured aperture size is mounted at the location of the test plane and its irradiance spectral response is transferred onto the monitored detectors.

III. FINDINGS

A. Light Output Uniformity

The irradiance uniformity at the integrating sphere’s test plane was measured while operating a select few LEDs on the mounted plane of the input port. Fig. 2 shows the result of this uniformity mapping for one LED as the percentage of uniformity with respect to the most intense spot in that plane (near the (6 cm, 8 cm) location coordinates). This data reveals that for the entire 15 cm by 15 cm mapped area (xy points represent the location of the center of the detector used for mapping), the nonuniformity is lower than 1.8 %. A similar behavior was observed for LEDs of other wavelengths. This excellent level of illumination uniformity allows for very accurate irradiance-mode SR measurements, even on larger solar cells.

B. Spectral Responsivity Measurements

As described above, power-mode measurements are generally performed in the underfilled configuration. When testing crystalline PV products such as mono-Si solar cells, the overall shape (or even the magnitude) of the spectral response curve will generally stay the same no matter where the location of the illuminated spot is across the surface of the cell. In cases such as this, the irradiance-mode SR measurements with the LED system need only be done with a select few number (sometimes even a single LED) of LEDs. Once these few irradiance-mode SR data points are obtained, the SR curve for the entire device can be constructed by an appropriate scaling factor so that the monochromator-obtained curve passes through these few points. Fig. 3 shows an example of this process for a crystalline Si solar cell. A single scale factor was used to construct the SR curve and indeed the curve does pass.
Fig. 4. (Inset) Variations in power-mode SR data across the area of a polycrystalline Si solar cell. (main) LED-based irradiance-mode SR data (symbols), and a simple-averaged monochromator-based SR curve scaled by a single factor (curve).

through all the individually-obtained LED data points. From this SR curve, the short circuit current of the cell, $I_{sc}$ under air mass AM 1.5 global irradiance spectrum, $E_{AM1.5}$ is obtained from:

$$I_{sc} = \int R_{i, \text{irrd\ mode}}(\lambda) \cdot E_{AM1.5}(\lambda) \, d\lambda,$$

where $R_i$ is the irradiance-mode SR. The short circuit current calculated using this method agrees to better than 1 % with other primary calibration techniques on several cells that have been tested in our laboratory. Currently, our total expanded uncertainty for this process is less than 0.8 %. More notes on the uncertainty analysis can be found in reference 1.

It has been observed that in addition to magnitude variations of the spectral response signal across the surface of the cell, the overall shape of the SR curve could also significantly change depending on the location of the illuminated beam. This behavior has been typically observed with polycrystalline or amorphous PV materials such as poly-Si solar cells [5]. An example of a cell with this behavior is shown in the data of Fig. 4 inset with a series of power-mode SR curves obtained at different locations across the surface of the cell. The differences are particularly significant in the near infrared (IR) range closer to the band gap of the material and are likely due to spatial distribution of defects or quality of the crystalline regions. In a case like this, the overall irradiance-mode SR curve for the entire cell is best constructed by the LED measurement system with the maximum number of LEDs available for the measurement. This is shown in the main part of Fig. 4 with all 33 LEDs. Also plotted is a simple-averaged SR curve from the data of the inset figure, scaled by a single factor, for the purpose of observing whether the curve will pass through all the LED points. Although a reasonably good agreement is observed in this case, however, this may not occur in general and the best method for obtaining the irradiance SR curve is likely a combination of interpolated LED- and the monochromator-obtained data.

C. Beam Collimation Issues

During the course of LED-based measurements with the integrating sphere setup, it was observed that the level of the collimation of the monochromatic probing beam influenced the SR measurements. For example, if the cell is exposed to the completely diffuse light at the opening of the integrating sphere, the SR data are different from the case where the cell is pulled farther back from the sphere, or exposed to a more collimated light by use of collimating optics. The reason for this effect, which is presented in Fig. 5 for a 2 cm by 2 cm Si reference solar cell is because the directional or cosine response of this cell is different from the reference detector’s cosine response used for the calibration of the system. Since variations in the cosine response of different cells are typical, care must be taken with regard to this angular mismatch. If the capability to measure the wavelength-dependent angular response of a cell does not exist or deemed too tedious of a task, the most innocuous approach to determine the SR curve of a cell is to perform the measurements under a more direct illumination with a projected or collimated source (as opposed to diffuse) presenting a narrower field of view for the cell under test.

D. Light Bias Effects

It has been observed that light bias can affect the spectral response measurement of solar cells. Previous results indicated that the overall shape and magnitude of the spectral response curve can change, depending on the light bias intensity and its spectral composition[6]. The exact nature of this effect is
currently not well understood but it is likely related to interfacial defects and recombination phenomena affecting the effective lifetimes of mobile charge carriers in the device. Fig. 6 shows an example of this light bias dependence in a poly-Si solar cell with the amount of light bias indicated by the dc photocurrent magnitude generated in the cell when exposed to the source. This plot indicates that a significant shift in the responsivity of the cell occurs between very low levels of light bias (≈ 0.01 W m⁻² or 10⁻⁵ Sun equivalent) to levels on the order of 50 W m⁻². Further increase in the light bias intensity did not result in a further shift in the shape of the SR curve, indicating that the device operates in the linear regime beyond a few percent of the sun intensity.

Furthermore, it was additionally observed that this light bias dependence also significantly depends on the pulsed monochromatic beam’s intensity. When the probing beam’s intensity is relatively high, the additional light bias effect is minimal, but when the overall pulsed beam intensities are low, the light bias effect can be significant, as shown in Fig. 6. In general, if the goal of the spectral response/EQE measurement is to provide the responsivity of the cell at near standard reporting conditions, then it will suffice to supply enough light bias intensity to make sure the cell is operating in the linear part of the current vs. intensity regime, provided the linearity is maintained all the way up to standard reporting conditions (i.e., 1000 W m⁻²). This could simply be a few percent of the SRC intensity. However, theoretically, if the cell has a significant amount of nonlinearity all the way up to the SRC conditions, then the light bias must also be intense at the levels of the SRC. More details related to the light bias dependence in solar cells will be discussed in a future correspondence.

IV. SUMMARY

Absolute differential SR measurements in irradiance-mode can be accomplished by combining the power-mode monochromator-based measurements with an LED-based system such as the one described in this work. Good illumination uniformity and narrow spectral emission characteristics of the LEDs allow for accurate determination of the irradiance-mode SR data which can be combined with monochromator data to construct an accurate SR curve representing the cell under test. Issues related to irradiance nonuniformity, beam collimation, light bias and others can present significant challenges to the SR measurements.

REFERENCES


