APPLICATION NOTE

The Spectral Mismatch Factor

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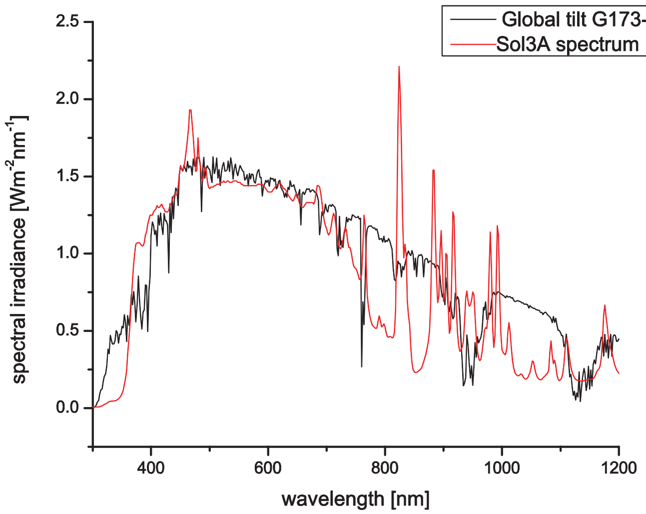

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A reference solar cell is calibrated when its short-circuit current is known with respect to an internationally accepted set of test conditions called the Standard Test Conditions (1 Sun or 1000 W/m2 of AM1.5G and a cell temperature of 25°C). The 5800 K plasma in a Xenon-arc lamp simulates the AM1.5G spectrum well, but a quartz tungsten halogen (QTH) lamp can also be adequate. In the (indoor) reference cell method for calibrating an unknown solar cell, a reference solar cell is used to adjust the intensity of a solar simulator until the short-circuit current produced by the reference cell is equivalent to its calibrated short-circuit current. One might then assume that the simulator is set to 1 Sun, i.e., that the total irradiance (at least where the reference cell is located) is 1 Sun, and that to calibrate an unknown test cell one can simply replace the reference cell by the unknown cell and measure its short-circuit current. This is only the case if the reference and the unknown solar cells exhibit identical spectral responses or that the simulator spectrum perfectly matches the reference spectrum AM1.5G. The latter would be highly unlikely since the reference spectrum is calculated using a numerical model of the atmosphere-sunlight interaction given theoretical values for barometric pressure, precipitable water, ozone content, etc. It is also often the case that the respective spectral responses of the reference and unknown solar cells don't quite match. These spectral mismatches lead to a kind of measurement error called spectral mismatch error that is quantified by the spectral mismatch factor . If this factor is known, it can be used to correct a solar cell's electrical performance under simulated sunlight to the reference condition of AM1.5G. We will derive an expression for M that will allow us to relate the spectrally corrected short-circuit current I^{t}_{stc} to its measured value I^{t}_{sim}, or

$$I^{t}_{stc}=\frac{I^{t}_{sim}}{M}$$

The short circuit current produced by an unknown test cell under standard test conditions (STC) can be expressed as the integral of the product of the cell's absolute spectral response $S_t(\lambda)$ and the reference spectral irradiance $E_{stc}(\lambda)$

$$I^{t}_{stc}=A_t\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_t(\lambda)d\lambda \qquad (1)$$

where A_t is the area of the test cell, and λ_1 and λ_2 cover the spectral range of the test cell. The fractional error between the test cell's short-circuit current under the simulator I^{t}_{sim} and its short-circuit current under the reference spectrum I^{t}_{stc} is

$$F=\frac{I^{t}_{sim}}{I^{t}_{stc}}=\frac{\int_{\lambda_1}^{\lambda_2} E^{*}_{sim}(\lambda)S_t(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_t(\lambda)d\lambda} \qquad (2)$$

where $E^{*}_{sim}(\lambda)$ is the absolute spectral irradiance of the solar simulator and $S_t(\lambda)$ is the spectral response of the test cell. (The latter can be relative since it appears in the numerator and denominator.) Note that area A_t algebraically cancels.

We can form a similar ratio with the currents produced by the reference cell in response to the reference and simulator spectra I^{ref}_{stc} and I^{ref}_{sim} respectively. In the reference cell method, the intensity of the simulator is adjusted until the reference cell's short-circuit current equals its short-circuit current under reference conditions or $I^{ref}_{sim}=I^{ref}_{stc}$. Then the ratio of the two can be set to 1, and

$$\frac{I^{ref}_{sim}}{I^{ref}_{stc}}=1=\frac{\int_{\lambda_1}^{\lambda_2} E^{*}_{sim}(\lambda)S_{ref}(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_{ref}(\lambda)d\lambda} \qquad (3)$$

So that

$$1=\frac{I^{ref}_{sim}\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_{ref}(\lambda)d\lambda}{I^{ref}_{stc}\int_{\lambda_1}^{\lambda_2} E^{*}_{sim}(\lambda)S_{ref}(\lambda)d\lambda} \qquad (4)$$

If we multiply (2) and (4) we get

$$F=\frac{I^{t}_{sim}}{I^{t}_{stc}}=\frac{I^{ref}_{sim}}{I^{ref}_{stc}}\frac{\int_{\lambda_1}^{\lambda_2} E^{*}_{sim}(\lambda)S_t(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_t(\lambda)d\lambda}\frac{\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_{ref}(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E^{*}_{sim}(\lambda)S_{ref}(\lambda)d\lambda} \qquad (5)$$

or

$$\frac{I^{t}_{sim}}{I^{t}_{stc}}=\frac{I^{ref}_{sim}}{I^{ref}_{stc}}M \qquad (6)$$

where

$$M=\frac{\int_{\lambda_1}^{\lambda_2} E_{sim}(\lambda)S_t(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_t(\lambda)d\lambda}\frac{\int_{\lambda_1}^{\lambda_2} E_{stc}(\lambda)S_{ref}(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{sim}(\lambda)S_{ref}(\lambda)d\lambda} \qquad (7)$$

Then from (6) we get the important relation

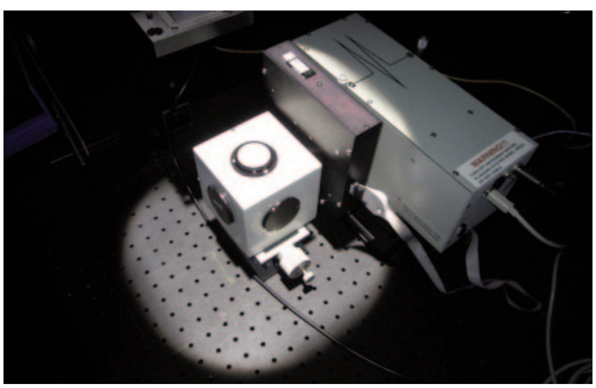
$$I^{t}_{stc}=\frac{I^{t}_{sim}}{M}\frac{I^{ref}_{stc}}{I^{ref}_{sim}} \qquad (8)$$

or if we adjust the simulator so that $I^{ref}_{sim}=I^{ref}_{stc}$ we get the simple relation that

$$I^{t}_{stc}=\frac{I^{t}_{sim}}{M}$$

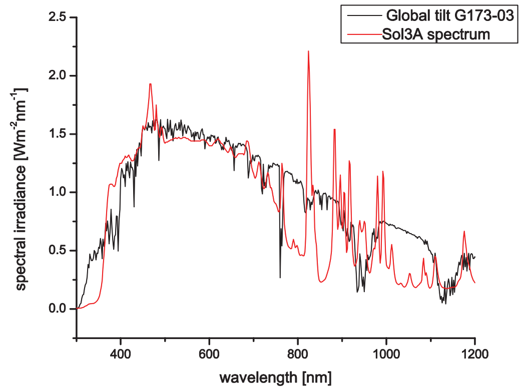
The expression in (8) relates the performance of the test solar cell under the simulator, i.e. in the laboratory, to its performance under the reference conditions. This is the expression that we were ultimately after. Note that in (7) the expression for M only requires the relative simulator spectrum $E_{sim}(\lambda)$ and the relative reference and test cell spectral responses $S_{ref}(\lambda)$ and $S_t(\lambda)$ since they all occur in the numerator and denominator, i.e. multiplicative factors cancel so that only the shapes of the curves matter. Another important feature of the spectral mismatch factor as it is defined in (7), is that if $S_t(\lambda) = S_{ref}(\lambda)$ over a wavelength range that covers the spectral response of the test cell, then $M \rightarrow 1$ (the same is true if $E_{sim}(\lambda) = E_{stc}(\lambda)$). Although the preceding analysis was performed using the short-circuit current, it equally applies to any current produced by the test cell at any bias voltage. In fact, each I-V data point (of the I-V curve) should be corrected by the spectral mismatch factor as is recommended in the ASTM standard E948 before deriving the electrical performance parameters.

Instead of regarding the spectral mismatch factor as a current correction factor, an alternative way to interpret M is the fractional amount by which to adjust the intensity of the solar simulator. The value of M will be greater than one ($M > 1$) if the simulator produces too much light in the spectral region of the test cell, and the simulator should be turned down accordingly. The reverse situation is that M will be less than one ($M < 1$) if there is too little light in the spectral region of the test cell, and the simulator should be turned up by the same factor. So either the I-V data is corrected or the simulator is adjusted by the spectral mismatch factor. The general rule of thumb is to select a reference cell and/or source spectrum such that the mismatch factor satisfies $0.98 \leq M \leq 1.02$.



Shown is the spectroradiometer in position at the center of the simulator beam to measure the spectrum of our 8 inch Sol3A solar simulator.

At the Newport TAC – PV Lab the solar simulator spectrum $E_{sim}(\lambda)$ is measured with an absolute spectroradiometer pictured above. The instrument is based around an Oriel® Cornerstone™ 130 (CS-130) scanning grating monochromator, a 4 inch integrating sphere (Model 70672) to introduce light into the monochromator. Light was detected after the exit slit of the monochromator with either the UV enhanced silicon or the IG (InGaAs) versions of the Newport 818 Series of Low Power Detectors. The UV model is used for scanning from 300 to 1200 nm; and the IG model is used from 1100 to 1550 nm. The two radiometry scans are then stitched together to make one extended scan. The instrument is calibrated with a NIST spectral irradiance standard according to the ASTM standard G138 entitled "Standard Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance." A typical scan is shown in the following figure.



Shown is a typical Sol3A™ spectrum measured using the described spectroradiometer against the reference spectrum (global tilt) as tabulated in ASTM G173-03 (available at http://rredc.nrel.gov/solar/spectra/am1.5/) Note the characteristic peaks of Xenon starting at 800 nm.

The spectral response of the test solar cell is measured using an instrument also based around an Oriel CS-130 monochromator called the IQE-200™ available from Newport Corporation. It is shown below.

The Oriel IQE-AC family of automated solutions for measuring PV spectral response

	Devices Under Test			
Reference Cells	m-Si	CdTe	OPV	CIGS
m-Si	1.000	1.041	1.089	0.975
m-Si KG5	0.917	0.954	0.997	0.899
GaAs	0.997	1.035	1.085	0.978
	Spectral Mismatch Factor M			

The table above (calculated using the above solar simulator spectrum) indicates by how much the choice of reference cell with respect to the device under test matters and how significant the spectral error will be if it's not chosen carefully. For example, choosing a KG5 filtered mono-crystalline silicon reference cell to measure a CIGS sample would introduce more than 10% measurement error. Measuring an OPV sample against a GaAs reference cell can result in 8.5% error. The spectral mismatch factor can eliminate the errors associated with any combination of reference cell and DUT material per the expression in (7) and/or from any source of light that deviates from the standard AM1.5G reference spectrum.

Newport Corporation

Worldwide Headquarters
1791 Deere Avenue
Irvine, CA 92606

(In U.S.): 800-222-6440
Tel: 949-863-3144
Fax: 949-253-1680

Email: sales@newport.com

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Visit Newport Online at: **www.newport.com**

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