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Solar Cell Spectral Response Measurement Errors Related to Spectral Band Width and Chopped Light Waveform

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SOLAR CELL SPECTRAL RESPONSE MEASUREMENT ERRORS RELATED TO SPECTRAL BAND WIDTH AND CHOPPED LIGHT WAVEFORM

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ABSTRACT

An error in a spectral response measurement of a solar cell can occur when the response of the solar cell varies over the spectral range of the beam but is assumed to be the response at a single wavelength. It depends on the spectral shape and width of the beam that is incident on the solar cell. This analysis predicts the magnitude of the error for a variety of solar photovoltaic cells measured with monochromatic light sources of approximately 10-nm bandwidth. It also shows that, although these errors can be substantial at certain wavelengths, their consequences are relatively small for performance measurements that use the spectral response information to set solar simulator intensity. The error caused by use of too few monochromatic beams to characterize a cell's spectral response is illustrated. Bias errors related to the waveform of the chopped, monochromatic light are also discussed.

INTRODUCTION

Spectral response characteristics of photovoltaic cells are used to understand physical mechanisms of devices and to calculate the spectral mismatch correction factor (M) [1] used to set solar simulator intensity for performance measurements. Error sources encountered in spectral response measurements include beam spatial intensity and spectral non-uniformities [2], irregular signal waveforms due to chopped light beams, calibration source uncertainty, and assumptions regarding the spectral width of the monochromatic beam used. Errors can occur when a device's response to the monochromatic beam varies over the beam's spectral range, but is reported for the center of that range.

How Beam Spectral Width Causes Measurement Error

A solar cell's response to light of a single wavelength is its spectral response at that wavelength multiplied by the intensity of the light. Its response to a real, polychromatic source is the sum of these products for all wavelengths in the source spectrum. If the actual irradiance and device spectral response profiles are symmetrical around the center wavelength, then the currents generated from light on each side of the center are equal, and their sum is equivalent to the current that the device would generate if illuminated by a single-wavelength source of the same intensity. When measuring a device with real light sources, it is commonly assumed that this symmetry exists. It sometimes does not (see Figs. 1 and 2). In such cases, a signal measured during a test can lead to an erroneous conclusion.

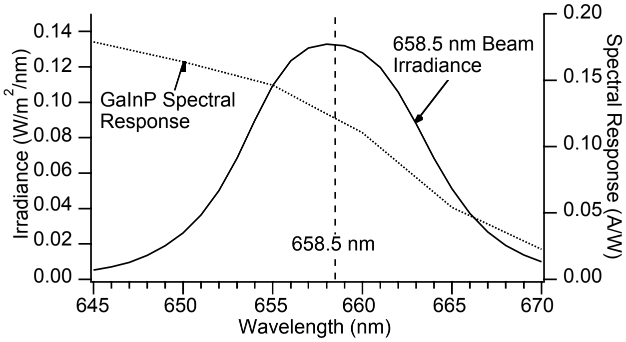

Fig. 1. The profile of the monochromatic beam generated by a xenon arc lamp source projected through a 660-nm bandpass filter. A 6.2% error in the spectral response measurement results.

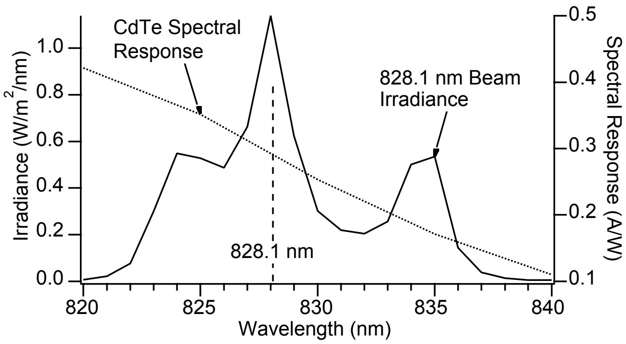

Fig. 2. Light from the same xenon arc lamp source projected through a 825-nm bandpass filter produces this asymmetric beam profile. A 3.4% error in the spectral response measurement results. The strong xenon emission lines cause the beam asymmetry.

PRACTICAL EXAMPLES AND ERROR MAGNITUDES

The measurement produced by a practical system can be simulated by integrating the monochromatic light spectrum multiplied by a test cell's spectral response and divided by the beam's total power. The error can be quantified by comparing this result to the original spectral response information. This author made this comparison using the spectra of 42 monochromatic light beams used in NREL's Photovoltaic Cell and Module Performance Characterization Laboratory's Filter QE System. The beam spectra were measured using an Optronic Labs OL750 spectroradiometer with 1-nm bandpass and 1-nm resolution (bandpass is 2 nm in the 1100-1600 -nm region). Comparisons use spectral response data measured by another system employing a tungsten source (no strong emission lines) and a grating monochrometer with 3-nm bandpass and 5-nm resolution as a baseline.

The wavelength of a monochromatic beam can be reported as the center of its filter's passband, the wavelength of peak filter transmission, the wavelength of the strongest beam component, or some weighted average of the beam contents. For this analysis, the wavelength that bisects the integrated beam power is the center wavelength. Table 1 lists beam center wavelengths, beam widths, and some errors expected while measuring the spectral response of the solar cells in Fig. 3. Additional error estimates for broader beams are also provided to show the effect of using monochromatic beams of twice the width of the NREL system's beams.

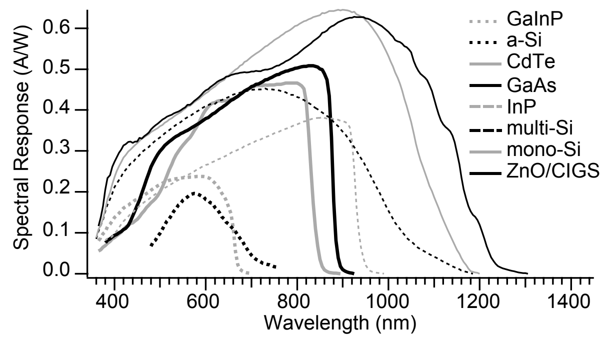

Fig. 3. The spectral response characteristics of the test cells considered in this study.

Table 1. Predicted spectral response measurement errors with wavelength and beam width of monochromatic beams associated with the errors. Errors smaller than 1% or at wavelengths where quantum efficiency is less than 5% are omitted. FWHM means Full-Width Half-Maximum, the width of the beam profile at half its height. Asterisks (*) in the beam width column indicate that the strong xenon emission lines are too strong for the FWHM designation to be meaningful. The second section shows errors for simulated beams of twice the width of the beams in the NREL system. Errors are in percent units. The slope (percent per nm) of the spectral response at the wavelength indicated is in parentheses.

Wavelength (nm)	Beam Width (FWHM, nm)	GaInP	a-Si triple middle cell	CdTe	GaAs	InP	Multi-Si	Mono-Si	ZnO/ CIGS
365.3	10.2							7.3 (2.2)	1.9 (3.3)
381.0	9.8					-1.3 (1.1)	1.3 (2.8)		
658.4	11.2	6.2 (-5.9)							
824.0	*			2.7 (-3.8)					
828.1	*			3.4 (-6.8)					
850.4	11.2			-14 (-11)					
881.5	*				-14 (-13)				
926.5	11.2					1.9 (-7.9)			
978.6	*						-1.1 (-1.2)		
381.0	19.6	-1.2 (2.3)				2.7 (1.1)	1.3 (2.2)		3.9 (2.8)
400.2	18.8	1.2 (0.9)					1.5 (1.0)		
420.8	20.1								1.0 (0.2)
479.6	15.6				1.1 (1.1)				
499.2	16.2			-1.2 (1.0)					
539.1	19.7		1.1 (1.2)						
639.5	24.4	1.8 (-0.9)							
658.4	22.4	12 (-5.9)							
697.5	12.8		-2.4 (-2.7)						
823.2	*			1.7 (-3.7)					
824.0	*			7.0 (-3.8)					
828.1	*			6.0 (-6.8)					
850.4	22.3			-34 (-11)					
881.5	*				-23 (-13)				
926.5	22.3					4.1 (-7.8)			
978.6	*						-2.0 (-1.2)		
1023.6	20.3						-1.2 (-1.3)		
1052.2	12.4							1.1 (-1.6)	

For nominal 10-nm monochromatic beams, the errors encountered are generally equivalent to those that would occur if the center wavelength was off by 1 nm. For nominal 20-nm beams, errors can be roughly twice as large. Fig. 4 illustrates the context of the large error predicted for the GaAs cell measurement. The error due to beam and spectral response asymmetry is a small addition to the error caused by undersampling the spectral response curve.

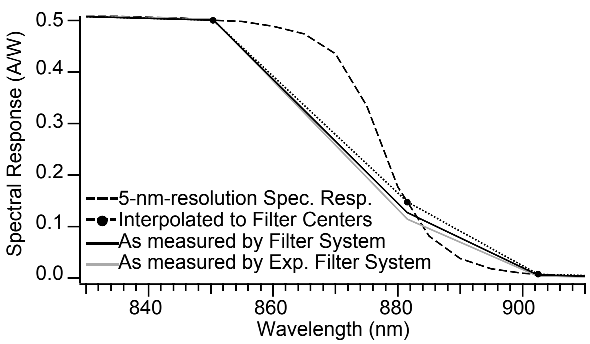

Fig. 4. A section of the spectral response curve for a GaAs solar cell illustrating two kinds of errors incurred when using monochromatic beams. By undersampling the response curve, the total response in the 850-900 -nm region is underestimated. Errors related to measurement beam spectral width also contribute.

SIGNIFICANCE

To the person interpreting spectral response data to determine qualitative physical characteristics of solar cells, most of these errors might not be significant. However, they may be significant to researchers performing quantitative analysis, especially that which pertains to band edges. To researchers using the data to calculate M to set the intensity of a solar simulator, most of these errors have little impact on performance measurement uncertainty, as shown below.

Effect on Performance Measurements

Calculations of spectral mismatch correction factors using spectral response data with and without these errors show small errors due to the relatively large errors in spectral response at specific wavelengths. Table 2 lists the spectral mismatch correction factors that would be used with the specified reference cells to set the intensity of NREL's Spectrolab X-25 solar simulator or an ELH projector lamp to the Air Mass 1.5 Global [2] equivalent for these test cells (see Fig. 3). The spectra of the light sources are shown in Fig. 5. M is calculated for a reference cell of similar spectral response characteristics as the test cell. M is calculated for the same spectral range for each comparison.

Table 2: Error in M due to predicted errors in test-cell spectral response for different test sources. Columns A and B show errors for nominal 10-nm beams in NREL's Filter QE System. Columns C and D show errors for simulated beams with twice the spectral bandwidth. Columns A and C show the errors due to sampling the spectral response curve at the center wavelengths of NREL's filters. Columns B and D show the error actually expected for measurements using these beams.

Test		Hi-res	Error in M (%)			
Spectrum	Test Cell	M	A	B	C	D
X25	GaInP	1.107	0.05	0	0.05	-0.04
Pr. Lamp	GaInP	0.985	0.21	0.31	0.20	0.39
X25	a-Si Mid	0.967	-0.38	-0.39	-0.44	-0.41
Pr. Lamp	a-Si Mid	1.197	-0.28	-0.28	-0.37	-0.40
X25	CdTe	1.028	0.09	0.18	0.09	0.30
Pr. Lamp	CdTe	1.118	0.02	0.04	0.02	0.05
X25	GaAs	0.988	0.77	0.81	0.77	0.81
Pr. Lamp	GaAs	1.023	0.52	0.63	0.53	0.69
X25	InP	1.008	0.09	0.09	0.10	0.09
Pr. Lamp	InP	0.969	0.21	0.22	0.21	0.21
X25	multi-Si	1.000	0.01	0.03	0	0.02
Pr. Lamp	multi-Si	1.050	-0.01	-0.02	0	-.01
X25	mono-Si	0.999	0.02	0.03	0.01	0.01
Pr. Lamp	mono-Si	0.992	0.01	0	0.02	-0.01
X25	ZnO/CIGS	1.020	-0.02	-0.02	-0.03	-0.04
Pr. Lamp	ZnO/CIGS	0.985	0.01	0.01	0.02	0.01

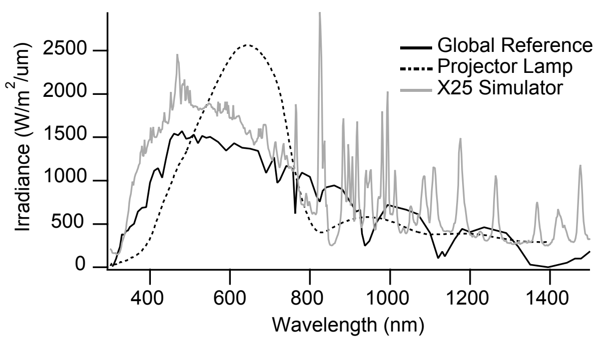

Fig. 5. The spectra used to generate the results listed in Table 2 plotted with the Global Reference Spectrum [3], for which M is calculated.

Table 2 shows that the error caused by measuring the spectral response of a solar cell with too few beams, as illustrated in Fig. 4, can be substantial. Small additional errors usually occur due to the asymmetry of the beams. Most errors are less than one fifth the uncertainty generally claimed for solar cell performance measurements at NREL [4].

BEAM WAVEFORM EFFECT ON SYSTEM CALIBRATION

To reduce noise in spectral response measurements, lock-in amplifiers or electrical filters are used to measure signals produced by a chopped light beam. The signal produced has a trapezoidal waveform, with sloped sides due to the gradual interruption of the light beam by the chopper. Electrical filters and lock-in amplifiers commonly measure the amplitude of the sinusoidal (fundamental) component of this waveform, which is not the same as the peak magnitude. If the calibration device and test device signals are both measured with similar instruments, then this error is equivalent during calibration and measurement, and it does not propagate to the results.

However, if the calibration device is an electrically calibrated pyroelectric radiometer, for example, the peak magnitude of the monochromatic light is measured. This instrument uses a pyroelectric thermal sensor with a resistive element on one side, while the other side is exposed to the beam to be measured. The signal to the resistive element is adjusted to be 180° out of phase from the light beam and of a magnitude so that the sensor experiences no thermal changes and therefore produces no signal. The beam's power is considered to be equivalent to the power being provided to the resistive heater, which the instrument measures and reports.

If not taken into consideration, this factor can contribute to a substantial reduction in spectral response measurements. The error is 10% for a square wave if the test device's instrumentation reports the RMS amplitude, and it rises as the signal cut-on and cut-off become more gradual. Because this error applies to all wavelengths equally, it appears as a multiplicative factor in both the numerator and denominator of the spectral mismatch correction factor equation; therefore it has no impact on solar simulator performance tests [1]. It can be avoided by computing and applying the appropriate waveform factor or by using a different calibration device.

CONCLUSIONS

An intense light source, in conjunction with narrow-bandwidth interference filters, can generate monochromatic beams for spectral response measurements that have the advantages of large beam size and high light intensity. This analysis shows that for performance measurements of solar cells, use of 10-nm bandwidth filters contributes small errors related to the source spectral profile itself. Chopper configuration in measurement systems can cause bias errors in spectral response measurements when certain calibration procedures are employed, but such errors have no effect on performance measurements. Other error sources are likely to dominate in spectral response measurements [5].

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