Designation: E1021 – 15

# Standard Test Method for Spectral Responsivity Measurements of Photovoltaic Devices[1]

## 1. Scope

1.1 This test method is to be used to determine either the absolute or relative spectral responsivity response of a single-junction photovoltaic device.

1.2 Because quantum efficiency is directly related to spectral responsivity, this test method may be used to determine the quantum efficiency of a single-junction photovoltaic device (see 10.10).

1.3 This test method requires the use of a bias light.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E772 Terminology of Solar Energy Conversion
E927 Specification for Solar Simulation for Photovoltaic Testing
E948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight
E973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell
E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
E1125 Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum
E1362 Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells
E2236 Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules
G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

## 3. Terminology

3.1 *Definitions*—Definitions of terms used in this test method may be found in Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *chopper, n*—a rotating blade or other device used to modulate a light source.

3.2.2 *device under test (DUT), n*—a photovoltaic device that is subjected to a spectral responsivity measurement.

3.2.3 *irradiance mode calibration, n*—a calibration method in which the reference photodetector measures the irradiance produced by the monochromatic beam.

3.2.4 *monitor photodetector, n*—a photodetector incorporated into the optical system to monitor the amount of light reaching the device under test, enabling adjustments to be made to accommodate varying light intensity.

3.2.5 *monochromatic beam, n*—chopped light from a monochromatic source reaching the reference photodetector or device under test.

3.2.6 *monochromator, n*—an optical device that allows a selected wavelength of light to pass while blocking other wavelengths.

3.2.7 *power mode calibration, n*—a calibration method in which the reference photodetector measures the power in the monochromatic beam.

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[1] This test method is under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sources and is the direct responsibility of Subcommittee E44.09 on Photovoltaic Electric Power Conversion.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.8 *reference photodetector, n*—a calibrated photodetector with a known spectral responsivity over a wavelength range and used to quantify the amount of light in a monochromatic beam.

3.2.9 *spectral bandwidth, n*—the range of wavelengths in a monochromatic light source, determined as the difference between its half-maximum-intensity wavelengths.

3.3 *Symbols:*

3.3.1 The following symbols and units are used in this test method.

$A$—illuminated device area, $m^2$,

$c$—speed of light in vacuum, 299792458 $m \cdot s^{-1}$,

$CV_{Mi}$—monitor photodetector calibration value for irradiance mode, $A \cdot m^2 \cdot W^{-1}$,

$CV_{Mp}$—monitor photodetector calibration value for power mode, $A \cdot W^{-1}$

$\varepsilon$—small wavelength interval, nm or µm,

$E_o$— reference total irradiance, $W \cdot m^{-2}$,

$E_o(\lambda)$—reference spectral irradiance, $W \cdot m^{-2} \cdot nm^{-1}$ or $W \cdot m^{-2} \cdot \mu m^{-1}$,

$E_M$—monochromatic source irradiance, $W \cdot m^{-2}$,

$Err$—fractional error in measurement, dimensionless,

$h$—Planck's constant, $6.62606957 \times 10^{-34} J \cdot s$,

$I$—current, A,

$I_{mc}$—monitor photodetector current during calibration, A,

$l_{mt}$—monitor photodetector current during test, A,

$I_{sc}$—solar cell short-circuit current, A,

$I_o$—$I_{sc}$ under $E_o(\lambda)$, A,

$J_{sc}$—solar cell short-circuit current density, $A \cdot m^{-2}$,

$K_i$—relative-to-absolute spectral responsivity conversion constant for irradiance mode, $A \cdot m^2 \cdot W^{-1}$,

$K_p$—relative-to-absolute spectral responsivity conversion constant for power mode, $A \cdot W^{-1}$,

$\lambda$—wavelength, nm or µm,

$\lambda_o$—a specific wavelength, nm or µm,

$M$—spectral mismatch parameter,

$P$—monochromatic beam power reaching the photodetector, W,

$\varphi$—power of the monochromatic beam or irradiance of the monochromatic beam, W or $W \cdot m^{-2}$,

$q$—elementary charge, $1.602176565 \times 10^{-19}$ C,

$Q$—external quantum efficiency dimensionless or percent,

$R_{ia}$—absolute spectral responsivity for irradiance mode, $A \cdot m^2 \cdot W^{-1}$,

$R_{pa}$—absolute spectral responsivity for power mode, $A \cdot W^{-1}$,

$R_{ir}$—relative spectral responsivity for irradiance mode, dimensionless,

$R_{pr}$—relative spectral responsivity for power mode, dimensionless,

$SR$—spectral responsivity, $A \cdot W^{-1}$ or $A \cdot m^2 \cdot W^{-1}$.

3.3.2 Symbolic quantities that are functions of wavelength appear as $X(\lambda)$.

## 4. Summary of Test Method

4.1 The spectral responsivity of a photovoltaic device, defined as the output current per input irradiance or radiant power at a given wavelength, and normally reported over the wavelength range to which the device responds, is determined by the following procedure:

4.1.1 A monochromatic, chopped or pulsed beam of light is directed at normal incidence onto the cell. Simultaneously, a continuous white light beam (bias light) is used to illuminate the DUT at irradiance levels intended for end use operating conditions of the device. See Fig. 1.

4.1.2 The magnitude of the ac (chopped) component of the current at the intended voltage is monitored as the wavelength of the incident light is varied over the spectral response range of the device.

4.2 Measurement of the absolute spectral responsivity of a device requires knowledge of the absolute beam power or irradiance produced by the monochromatic beam. The total power or irradiance of the monochromatic beam incident on the device is determined by the reference photodetector (see 6.1). The absolute spectral responsivity of the device can then be computed using the measured device photocurrent and the power or irradiance of the monochromatic beam.

4.3 The choice of power versus irradiance mode may depend on the spatial non-uniformity of the test device or the incident monochromatic beam. Overall spectral response of a test device with substantial spatial non-uniformity of response should be performed in irradiance mode with a monochromatic beam of high spatial uniformity.

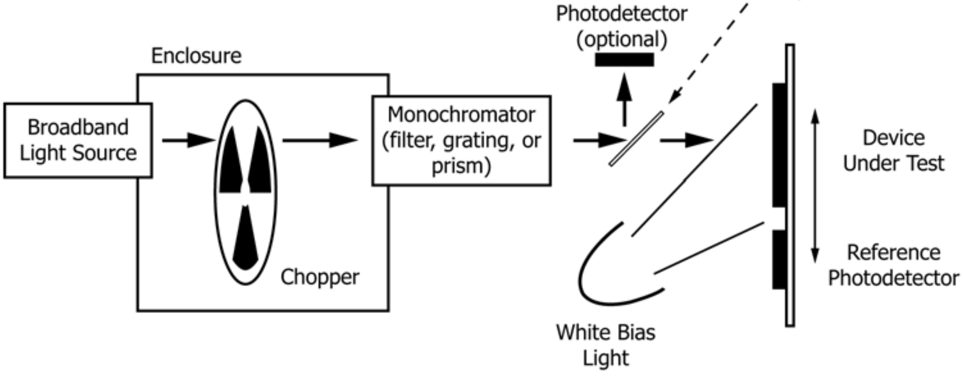

FIG. 1 Example of Spatial Placement of Optical Components for Spectral Responsivity Measurement

4.4 The test procedure can be adapted to provide absolute or relative spectral responsivity measurements, depending on the calibration device used, its calibration mode and the relative sizes of the calibration device, the monochromatic beam size, and the device being measured.

## 5. Significance and Use

5.1 The spectral responsivity of a photovoltaic device is necessary for computing spectral mismatch parameter (see Test Method E973). Spectral mismatch is used in Test Method E948 to measure the performance of photovoltaic cells in simulated sunlight, in Test Methods E1036 to measure the performance of photovoltaic modules and arrays, in Test Method E1125 to calibrate photovoltaic primary reference cells using a tabular spectrum, and in Test Method E1362 to calibrate photovoltaic secondary reference cells. The spectral mismatch parameter can be computed using absolute or relative spectral responsivity data.

5.2 This test method measures the differential spectral responsivity of a photovoltaic device. The procedure requires the use of white-light bias to enable the user to evaluate the dependence of the differential spectral responsivity on the intensity of light reaching the device. When such dependence exists, the overall spectral responsivity should be equivalent to the differential spectral responsivity at a light bias level somewhere between zero and the intended operating conditions of the device. Depending on the linearity response of the DUT over the intensity range up to the intended operating conditions, it may not be necessary to set up a very high light bias level.

5.3 The spectral responsivity of a photovoltaic device is useful for understanding device performance and material characteristics.

5.4 The procedure described herein is appropriate for use in either research and development applications or in product quality control by manufacturers.

5.5 The reference photodetector's calibration must be traceable to SI units through a National Institute of Standards and Technology (NIST) spectral responsivity scale or other relevant radiometric scale.[3,4] The calibration mode of the photodetector (irradiance or power) will affect the procedures used and the kinds of measurements that can be performed.

5.6 This test method does not address issues of sample stability.

5.7 Using results obtained by this test method and additional measurements including reflectance versus wavelength, one can compute the internal quantum efficiency of a device. These measurements are beyond the scope of this test method.

5.8 This test method is intended for use with a single-junction photovoltaic cell. It can also be used to measure the spectral responsivity of a single junction within a series-connected, multiple-junction photovoltaic device if electrical contact can be made to the individual junction(s) of interest.

5.9 With additional procedures (see Test Methods E2236), one can determine the spectral responsivity of individual junctions within series-connected, multiple-junction, photovoltaic devices when electrical contact can only be made to the entire device's two terminals.

5.10 Using forward biasing techniques[5], it is possible to extend the procedure in this test method to measure the spectral responsivity of individual series-connected cells within photovoltaic modules. These techniques are beyond the scope of this test method.

## 6. Apparatus

6.1 *Reference Photodetector:*

6.1.1 The following detectors are acceptable for use in the calibration of the monochromatic light source:

6.1.1.1 Pyroelectric radiometer, and

6.1.1.2 Cryogenic radiometer, and

6.1.1.3 Spectrally calibrated photodiode, photodiode irradiance detector, or solar cell, calibrated in power or irradiance mode.

NOTE 1—A spectrally calibrated photodiode should have calibration data that includes the entire spectral response range of the device to be tested. If a part of the range is omitted, it will limit the spectral range of the results of this test, causing an error in computing the spectral mismatch parameter.

NOTE 2—A photodetector calibrated in power mode must have spatially uniform spectral responsivity over its photosensitive region. A photodetector calibrated in irradiance mode may have spatially non-uniform spectral responsivity characteristics, and must only be used with a uniform monochromatic beam larger than its surface area. See also Table 1.

6.1.2 The reference photodetector must have a known linear current versus incident light intensity ratio over the range of intensities and wavelengths of the monochromatic light source.

6.1.3 The reference photodetector's calibration must be traceable to SI units through a National Institute of Standards and Technology (NIST) spectral responsivity scale or other relevant radiometric scale.[3,4]

6.1.4 The uniformity of responsivity over the surface of the reference photodetector must be characterized if it will not be entirely illuminated (overfill illumination) by the monochromatic light beam. A photodetector with spatially uniform sensitivity is suitable for use in both power mode and irradiance mode measurements. Non-uniform detectors are suitable for use in irradiance mode with uniform light beams only. The non-uniformity of the incident radiation should be ideally better than ±2 %. For best results, use a photodetector with the best spatial response uniformity available. The spatial uniformity map of the reference detector are typically provided as part of the calibration documents for one or two wavelengths.

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[3] Larason, T. C., Bruce, S. S., and Parr, A. C., NIST Special Publication 250-41 Spectroradiometric Detector Measurements, Washington, DC, U.S. Government Printing Office, 1998. Also available at http://ois.nist.gov/sdm/

[4] Eppeldauer, G., Racz, M., and Larason, T., "Optical characterization of diffuser-input standard irradiance meters," SPIE Vol 3573, 1998, pp. 220-224.

[5] Emery, K. A., "Measurement and Characterization of Solar Cells and Modules," Handbook of Photovoltaic Science and Engineering, Chapter 16, pp. 701-747, Luque, A., and Hegedus, S., Eds., John Wiley & Sons, W. Sussex, U.K., ISBN 0-471-49196-9.

**TABLE 1**

| Reference Detector Design Mode | Rference Detector Calibration Mode | Beam Size Relative to Reference Detector | Beam Uniformity over Reference Detector Surface | Beam Size Relative to DUT | Beam Uniformity over DUT Surface | Type of Measurement that can be Performed | Case |
|---|---|---|---|---|---|---|---|
| Irradiance | Irradiance | Larger | Uniform | Larger | Uniform | Absolute | A1 |
| Irradiance | Irradiance | Larger | Uniform | Smaller | Nonuniform | Relative | A2 |
| Irradiance | Irradiance | Larger | Uniform | Smaller | Defined, Uniform | Absolute | A3 |
| Power | Power | Smaller | Nonuniform | Smaller | Nonuniform | Absolute | B |
| Power | Irradiance | Larger | Uniform | Larger | Uniform | Absolute | C1 |
| Power | Irradiance | Larger | Uniform | Smaller | Nonuniform | Relative | C2 |
| Power | Irradiance | Smaller | Uniform | Smaller | Defined, uniform | Absolute | C3 |
| Power | Irradiance | | Nonunifrom | Smaller | Nonuniform | Absolute | D |
| Irradiance | Power | (reference photodetector calibration not valid) | | | | | |
| Irradiance | Irradiance | Smaller | (reference photodetector calibration cannot be used) | | | | |

The kinds of measurements that can be performed depend on the calibration mode of the reference photodetector and the relationship between the size of the reference photodetector, DUT, and monochromatic beam. "Smaller" means the entire beam reaches the photosensitive surface of the reference detector or DUT. "Larger" means the entire detector or device is illuminated. "Uniform" means the part of the beam that intercepts the reference detector or DUT is uniform. "Defined" means the beam power is known because the irradiance is uniform over the area of an aperture placed between the source and the DUT. Where "absolute" measurement capability is indicated, it is implied that "relative" measurements can also be performed.

6.1.5 The reference photodetector's angular sensitivity must be compatible with the beam divergence angle of the monochromatic light source in 6.3.

6.1.6 The reference photodetector's frequency response must be known or invariant in the range of chopping frequencies to be used in the test.

6.1.7 If the reference photodetector has an aperture smaller than its photosensitive area, then irradiance and power mode calibrations can be converted to each other. If calibrated in irradiance mode, the aperture must have limited the monochromatic beam to the photosensitive region during the photodetector's calibration. If calibrated in power mode, the aperture must limit the monochromatic beam to the photosensitive region during use in irradiance mode.

6.1.8 The change in responsivity of the reference detector with wavelength over the bandwidth of the monochromatic light must be less than 1%. Avoid using a semiconductor based reference photodetector near its energy gap.

6.2 *Monitor Photodetector and Associated Optics (optional):*

6.2.1 The monitor photodetector can be a pyroelectric radiometer, a photodiode, or a solar cell.

6.2.2 Additional optical elements such as a beam splitter are needed to sample the light in the monochromatic beam and provide it to the monitor photodetector.

6.2.3 Monitor photodetectors should be calibrated by the reference photodetector and the transfer calibration data should be checked regularly through recalibrations, particularly after lamp changes, monochromator wavelength calibrations, filter replacements and other opto-mechanical adjustments to the system.

6.3 *Monochromatic Light Source:*

6.3.1 A variety of different laboratory apparatus are available for the generation of monochromatic light.[5] Grating monochromators coupled with tungsten, xenon or other light sources are most commonly used. Discrete and tunable continuous-wave lasers offer another source of monochromatic light. The wide range of wavelengths available coupled with the high optical quality of lasers renders them attractive. Light emitting diodes (LEDs) can also provide stable, monochromatic light over a range of discrete wavelengths in the visible and near-infrared regions. Another source is the use of narrow-bandpass optical filters in conjunction with a broad-spectrum light source such as tungsten. The wavelength range, spectral bandwidth, and wavelength increment must be consistent with the expected responsivity characteristics of the device to be tested.

6.3.2 The monochromatic light source shall be capable of providing wavelengths that extend beyond the response range of the device to be tested. When the measurement is intended to be used to compute the spectral mismatch parameter for a terrestrial spectrum, the monochromatic source wavelengths do not need to go below 300 nm.

6.3.3 The following characteristics for the monochromatic source are recommended. The test report must provide explanation for any deviation from these recommendations.

6.3.3.1 A minimum of 12 wavelengths within the spectral response range of the device to be measured is recommended.

6.3.3.2 All increments between wavelengths should be less than 50 nm. Additional wavelengths may be required in wavelength regions where the spectral responsivity changes substantially (more than 10 percent change between measured wavelengths) with small changes in wavelength, such as at the band gap in a direct band gap semiconductor.

6.3.3.3 The spectral bandwidth of the monochromatic light source should not exceed 20 nm for any wavelength used in the test.[6]

NOTE 3—In certain cases where the spectral bandwidth of the device under test is large (such as a typical Si solar cell), and the device shows a well-behaved (quantified) response with wavelength, it may be permissible to use light sources with spectral bandwidth larger than 20 nm. This includes most of monochromatic LEDs with bandwidths ranging from 15 to 65 nm. Potential errors due to use of larger bandwidth sources should be evaluated on a case by case basis. (Filter in front of LED as an option.)

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[6] Field, H., "Solar cell spectral response measurement errors related to spectral band width and chopped light waveform," *Proc. 26th IEEE Photovoltaic Specialists Conf.*, Anaheim, CA, 1997, pp. 471-474.

6.3.4 The presence of small amounts of light in the monochromatic beam at wavelengths other than the intended wavelength can cause substantial errors in the measurement. The magnitude of expected error can be determined from the following equation:

$$Err \cdot SR_{\lambda o} \cdot \O_{\lambda o} \cdot 2\varepsilon > \int_{0}^{\lambda_o - \varepsilon} SR(\lambda) \cdot \O(\lambda) \cdot d\lambda + \int_{\lambda_{o+\varepsilon}}^{\infty} SR(\lambda) \cdot \O(\lambda) \cdot d\lambda \quad (1)$$

where ε is 1.5 times the spectral bandwidth in 6.3.3.3, $\lambda_o$ is the wavelength of concern, *SR* is the spectral response of the test device, and φ is the power or irradiance of the monochromatic beam. The apparatus must be designed and tested to ensure that this requirement is met for a particular error level (0.005 is recommended). If a higher error level is used in the test, it must be noted in the test report. The error can be estimated by measuring a test device known to respond at a wavelength of concern with a filter that blocks that wavelength in front of the test device. In a grating monochromator system, this may require the use of order-sorting filters or a prism monochromator to attenuate stray light and higher-order wavelengths of the diffracted light. Stray light is a particular problem when making measurements in the ultraviolet region using tungsten sources or using a pyroelectric reference detector with bandpass filters.

6.3.5 Care must be taken to minimize scattered chopped light reaching the DUT. A non-reflective cavity enclosing the monochromatic light chopper (see 6.4), and the adjacent entrance or exit optics of the monochromatic light source can help minimize the modulation of stray light by the chopper. Monochromator entrance and exit slits should be non-reflective. Materials that appear black to the eye may actually reflect substantial amounts of infrared light. To evaluate the presence of stray light due to bias light modulated by the chopper, one can measure the signal produced by a DUT with bias light present but the lamp in the monochromatic source turned off (not shuttered).

6.3.6 The monochromatic light source shall be capable of providing a temporal stability of ±1 % during the calibration and measurement period unless a monitor photodetector is used, in which case ±10 % is acceptable. The temporal stability need only be maintained during the time needed for a complete cycle of measuring the signal from the DUT and measuring the signal from the reference photodetector and exchanging the positions of these two units (if applicable).

6.3.7 If the monochromatic beam spatial uniformity deviates more than ±2 % over the part of the beam intercepted by the device being tested, then the source is considered “nonuniform,” and the kinds of tests that can be performed are limited, according to Table 1.

6.3.8 It is recommended that the monochromatic light source be able to illuminate the entire area of the device to be tested. If it is not, at least two measurements of the spectral responsivity in different regions of the device are required (see 9.1.13 and 9.1.13.1).

6.3.9 The monochromatic source must illuminate the entire reference photodetector and be uniform over the detector’s photosensitive area if the photodetector has an irradiance-mode design.

6.3.10 An optical shutter may be used to interrupt the monochromatic beam to reduce delays involved with source and supply warm-up times during the test procedure (see 9.1.2 and 9.1.4). Such a shutter should be installed between the chopper and the test fixture to prevent chopped bias light from being interpreted as true signal.

6.3.11 The center wavelength of a bandpass filter should be measured preferably with a spectroradiometer in the test plane as opposed to measuring the filter transmittance.[6] If a monochromator is used, its wavelength calibration should be periodically checked.

6.4 *Monochromatic Light Modulation*—A rotating blade or other device used to modulate the monochromatic light source.

6.4.1 The chopper blades should be designed to minimize modulated stray light.

6.4.2 To minimize the modulation of room light or bias light, the chopper should be configured to be close to the monochromatic light source, or integrated within the monochromatic light source. If the chopper and filters are mounted at the exit of the monochromator, the filters should be between the chopper and the test device.

6.4.3 The radiant output of other monochromatic light sources such as LEDs can be electronically modulated by use of pulse-triggered current drivers.

6.5 *Bias Light Source*—A stable, dc light source used to illuminate the device during the measurement.

6.5.1 The bias light should emit radiation at wavelengths throughout the responsivity range of the device under test. A good choice is a tungsten lamp with a stable dc power supply to minimize temporal instability.

6.5.2 The light should be of sufficient intensity to ensure the DUT is operating in its linear response region. If the DUT is not linear, the bias light source should provide bias light over the intensity range of interest.

6.5.3 The bias source should contain no significant harmonics of the chopper frequency used with the monochromatic source. This can be achieved by using a well regulated, dc power supply for the bias light. Mechanical vibrations, either from the chopper or other sources, shall not be allowed to modulate the bias light.

6.5.4 Some bias sources can introduce a significant amount of noise in the measurement over a range of frequencies, creating instability in the data collection by the modulated current measurement instrument (see 6.6). If possible, the monochromatic light’s chopping frequency should be shifted away from such unwanted sources of noise.[7]

6.6 *Modulated Current Measurement Instruments*—A system to quantify the alternating current produced by the DUT, the monitor photodetector (if used) and (if appropriate) the reference photodetector.

6.6.1 A current-to-voltage converter, followed by a lock-in amplifier or true-root-mean-square (RMS) voltmeter can be used to detect the low-level, modulated current from the

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[7] Hamadani, B. H., Roller, J., Dougherty, B., Persaud, F., and Yoon, H. W., “Absolute spectral responsivity measurements of solar cells by a hybrid optical technique,” *Appl. Optics*, 52, 5184, 2013.

photovoltaic device. An analog-to-digital converter with digital filtering can also be used.

6.6.2 True-RMS voltmeters respond to both the ac and the dc components of the short-circuit current which then must be separated to determine the ac component. An acceptable method uses the square-root of the difference between the square of the signal and the background (or noise) signal.

6.6.3 Choice of current-to-voltage converter and other signal conditioning instruments must include consideration of the DUT operating voltage, and that both a low-level ac, as well as a high-level dc signal may be present.

6.6.4 The frequency response of the instrumentation must be known or invariant in the range of frequencies to be used by the chopper.

6.7 *Test Fixture*—A means to mount the device to be tested in a position to allow illumination by both the monochromatic and bias light sources.

6.7.1 The test fixture shall also allow the reference photodetector (see 6.1) to be illuminated by the monochromatic and the bias light sources (if the reference photodetector was calibrated with bias light) in the same plane as the photovoltaic device. Exception: if the monochromatic beam is smaller than the reference photodetector's sensitive surface, then the reference photodetector does not need to be in the same plane as the DUT.

6.7.2 The test fixture shall allow for temperature regulation of the DUT's junction to 25 ± 5°C or other temperatures of interest.

## 7. Preparation of Apparatus

7.1 Configure the apparatus according to Fig. 1.

7.2 Allow a warm-up time for the measurement equipment such as the lock-in amplifier, power supplies, etc., according to the manufacturer's recommendations. The light sources such as xenon or tungsten lights should also be turned on and allowed to stabilize prior to starting the measurement.

7.3 Select a chopping frequency that is compatible with the frequency response of the reference photodetector, test device, and modulated current measurement instrumentation. The frequency should not be an integer multiple of the ac line frequency. If a pyroelectric radiometer is used, the chopper frequency must be compatible with its instrumentation and calibration. If the reference photodetector requires unmodulated light, such as the case of a pyroelectric radiometer with internal chopper, turn the chopper off and ensure that it does not block the beam.

7.4 Configure equipment gains and ranges to optimize measurement accuracy while avoiding saturation by dc signals caused by the bias light.

7.5 Set time constants or integration periods on modulated current measurement instrumentation so that readings represent multiple periods of the chopper frequency. If the integration period is less than a chopper period, substantial errors will occur.

7.6 If multiple readings are made at each wavelength interval, it is recommended that the reading interval be set so that modulated current measurement instrumentation readings are independent of each other.

## 8. Hazards

8.1 *Precaution*—In addition to other precautions, appropriate steps must be taken to protect against the following hazards:

8.1.1 *Eye*—Light sources used, particularly if a laser is employed as the monochromatic light source (intensity) or if an arc lamp is used (ultraviolet, intensity).

8.1.2 *Electrical*—High voltages present when lasers or arc lamps are used.

8.1.3 *Bodily Injury*—The possibility of bulb explosion, if arc lamps are used. Light choppers when rotating at high speeds.

## 9. Procedure

9.1 The signals from the reference photodetector and DUT must be measured at all wavelengths. The order of measurement depends on the apparatus used. If there is no provision to mount the reference photodiode and the DUT at the same time, it is expedient to measure the reference photodiode at all wavelengths and then measure the DUT. The procedure is presented with this presumption, but it is also acceptable to measure both signals at a particular wavelength, change wavelengths, and measure them again. The sequence can vary from that presented here.

9.1.1 Mount the reference photodetector in the test fixture. Adjust temperature control equipment as appropriate.

9.1.2 Turn on or unblock the monochromatic light source.

9.1.3 Measure the source irradiance as a function of wavelength at a minimum of 12 wavelengths throughout the spectral response range of the device to be tested, using the reference photodetector output. The wavelengths used for the source irradiance and the DUT response measurements (see 9.1.11) must be identical.

9.1.3.1 If a monitor photodetector is employed, also measure the signal produced by the monitor photodetector while measuring the reference photodetector signal.

9.1.4 Turn off or block the monochromatic light source.

9.1.5 Measure the noise level at the reference photodetector output. Note the wavelengths, if any, for which the noise exceeds 1% of the weakest signal recorded in 9.1.3.

9.1.5.1 If present, also measure the signal produced by the monitor photodetector. Note the wavelengths, if any, for which the noise exceeds 1% of the weakest signal in 9.1.3.1.

9.1.6 Mount the device to be tested in the test fixture, set its temperature to 25°C or the temperature of interest, and connect it to the modulated current measurement instrumentation.

9.1.7 The DUT should be configured such that the chopped beam is incident on its photoelectrically active region. The preferred method is to illuminate the entire device with a uniform, monochromatic beam, thereby averaging out the spatial and spectral variations over the surface. If the device is not entirely illuminated, record the position of the monochromatic beam relative to device features such as gridlines.

9.1.8 Turn on the dc bias light and record the bias current in the device to be tested. Ensure that the bias light current does not saturate the signal conditioning equipment. If a resistor is used instead of a transimpedance amplifier, record the dc voltage at the DUT and check that it is not so large as to introduce unacceptable error.

9.1.9 Measure the output of the modulated current measurement instrumentation. This is the background signal level.

9.1.10 Turn on or unblock the monochromatic light source. Wait at least three time constants of the modulated current measurement instrumentation for the output reading to stabilize.

9.1.11 Record the output of the modulated current measurement instrumentation for each wavelength selected in 9.1.3.

9.1.11.1 If present, record the output of the monitor photodetector, while measuring the signal produced by the DUT.

9.1.12 Note the wavelengths, if any, for which the output of the modulated current measurement instrumentation in 9.1.11 relative to the background signal recorded in 9.1.9 represents a signal-to-noise ratio greater than 1%.

9.1.13 If the monochromatic beam does not illuminate the entire DUT, repeat step 9.1.11 with the monochromatic and bias light illuminating another region of the DUT.

9.1.13.1 If sets of measurements taken at different regions on the DUT reveal variation in spectral responsivity that exceeds twice the expected repeatability, then average multiple measurements that represent the entire device surface.

9.1.14 Turn off or block the monochromatic light source.

9.2 *Optional*—Measure the absolute responsivity of the DUT at one wavelength by illuminating it with a second monochromatic light source of known intensity or power (such as a laser) while measuring its response to this light.

9.2.1 If the DUT has a linear operating range, ensure that the power density of the light source is within the linear operating range.

## 10. Calculation of Results

10.1 *Absolute versus Relative Spectral Responsivity*—Whether absolute spectral responsivity can be calculated depends on the apparatus available and the relative sizes of the monochromatic beam, the reference photodetector, and the DUT (see Table 1).

10.2 If the reference photodetector is calibrated in irradiance mode and the monochromatic beam is smaller than its photosensitive area (Table 1 case D), convert the calibration data to power mode by dividing the calibration data by the area of the aperture used. Example: 1.0 × 10-5 A·m$^2$·W$^{-1}$ translates to 0.5 A·W$^{-1}$ if the aperture area is 2.0 × 10$^{-5}$ m$^2$.

10.3 Determine the power in the monochromatic beam or the irradiance produced by the monochromatic beam reaching the reference photodetector for every wavelength in 9.1.3. Depending on the apparatus used, apply one or the other of the following:

10.3.1 Determine the power, $P$, (Table 1 cases B, D) in the monochromatic beam at each of the wavelengths in 9.1.3. If the reference photodetector is a photodiode, divide its current readings by its wavelength-specific spectral responsivity calibration factors.

10.3.2 Determine the irradiance level (Table 1 cases A, C) produced by the monochromatic beam, $E_M$, at each of the wavelengths in 9.1.3. If the reference photodetector is a photodiode, divide its current readings by its wavelength-specific spectral responsivity calibration factors.

10.4 Determine the power in the monochromatic beam or the irradiance produced by the monochromatic beam reaching the DUT for every wavelength in 9.1.3 using the determinations in 10.3.

10.4.1 For cases A3 and C3, the power is the irradiance level, $E_M$, (determined in 10.3.2) times the area of the aperture defining the beam reaching the DUT: $P = a{\cdot}E_M$.

10.5 Determine the spectral responsivity of the DUT using one of the following:

10.5.1 If a monitor photodetector is not used, divide each of the DUT modulated current measurement instrumentation readings, $I$, by the corresponding power, $P$, or irradiance, $E_M$, level.

$$R_{ir}(\lambda) = I(\lambda)/E_m(\lambda)\ (\textit{irradiance mode}) \tag{2}$$

$$R_{pr}(\lambda) = I(\lambda)/P(\lambda)\ (\textit{power mode}) \tag{3}$$

10.5.2 If a monitor photodetector is used, compute the monitor photodiode calibration factors, $CV_{Mi}$ or $CV_{Mp}$, according to Eq 2 or Eq 3, as appropriate, for every wavelength in 9.1.3.

$$CV_{Mi}(\lambda) = I_{mc}(\lambda)/E_m(\lambda)\ (\textit{cases}\ A1, A2, C1, C2) \tag{4}$$

$$CV_{Mp}(\lambda) = I_{mc}(\lambda)/P(\lambda)\ (\textit{Cases}\ A3, B, C3, D) \tag{5}$$

10.5.3 Multiply each of the modulated current measurement instrumentation readings, $I$, by the corresponding monitor photodetector calibration factor, $CV_{Mi}$ or $CV_{Mp}$, and divide by the corresponding monitor photodetector current, $I_{mt}$.

$$R_{ir}(\lambda) = I(\lambda){\cdot}CV_{Mi}(\lambda)/I_{mt}(\lambda)\ (\textit{irradiance mode}) \tag{6}$$

$$R_{pr}(\lambda) = I(\lambda){\cdot}CV_{Mp}(\lambda)/I_{mt}(\lambda)\ (\textit{power mode}) \tag{7}$$

NOTE 4—If the instrumentation used to measure the signal from the photodetector is not the same as that used to measure the signal from the DUT, then the effect of the signal waveform must be considered. Multipy $I$ by a factor to convert the reading units (for example, RMS) to those used in $E_M$ (for example, peak-to-peak) prior to performing the calculation in Eq 1.

10.6 If the apparatus and relative monochromatic beam, reference photodetector, and DUT sizes comply with Table 1 cases A1, A3, B, C1, C3, or D, then the spectral responsivity calculated in 10.5 is the absolute spectral responsivity, $R_{ia}$ or $R_{pa}$, of the DUT. Otherwise (cases A2, C2), it is the relative spectral responsivity.

NOTE 5—Because absolute spectral responsivity depends upon the actual device area illuminated, any gridlines or contacts blocking the monochromatic light will affect the results.

10.7 For cases A2 or C2, normalize the relative spectral responsivity by dividing each value by the maximum spectral response.

10.8 If multiple measurements of spectral responsivity at each wavelength have been taken, average them to obtain the spectral responsivity at each wavelength.

10.9 If absolute spectral responsivity was not measured directly, then relative spectral responsivity can be converted to absolute spectral responsivity with a multiplicative constant, *K*. Due to potential non-linearities noted in 5.2, *K* may differ according to the method of its calculation.

10.9.1 The conversion constant can be obtained from the absolute spectral responsivity at a single wavelength $\lambda_o$ (see 9.2) by:

$$K_i = R_{ia}(\lambda)/R_{ir}(\lambda) \ (irradiance\ mode) \tag{8}$$

$$K_p = R_{pa}(\lambda)/R_{pr}(\lambda) \ (power\ mode) \tag{9}$$

10.9.2 Alternatively, if the short-circuit current of the DUT under a standard reference spectral irradiance has been measured according to Test Methods E948, E1036, E1125, or E1362, $K_i$ or $K_p$ can be calculated with:

$$K_i = I_o \div \int R_{ir}(\lambda)E_o(\lambda)d\lambda \ (irradiance\ mode) \tag{10}$$

$$K_p = \frac{I_o}{A} \div \int R_{pr}(\lambda)E_o(\lambda)d\lambda \ (power\ mode) \tag{11}$$

10.10 Absolute power spectral responsivity may also be converted to external quantum efficiency, with the dimensionless units of collected electrons per incident photon, using:

$$Q(\lambda) = \frac{hc}{q} \frac{R_{pa}(\lambda)}{\lambda} = 1.240 \times 10^{-6} \frac{R_{pa}(\lambda)}{\lambda} \tag{12}$$

for wavelength units in m. Replace the factor $1.240 \times 10^{-6}$ with 1.240 if the wavelength units are µm or 1240 if the wavelength units are nm.

10.10.1 For cases A1 and C1 of Table 1, the absolute spectral responsivity is in irradiance units. To determine external quantum efficiency, convert the absolute irradiance spectral responsivity to absolute power spectral responsivity by dividing by the area of the DUT and then apply Eq 12.

10.11 If desired, compute the expected current density under any spectral irradiance, such as those in Tables G173, according to:

$$J_{sc} = \frac{1}{A} \cdot \int R_{ia}(\lambda)E_o(\lambda)d\lambda \ (irradiance\ mode) \tag{13}$$

$$J_{sc} = \int R_{pa}(\lambda)E_o(\lambda)d\lambda \ (power\ mode) \tag{14}$$

Eq 13 and Eq 14 provide an absolute value for $J_{sc}$, which can be used to verify results for these parameters that are obtained using a solar simulator (see Test Method E948) and an area measurement. Substantial differences may occur when the DUT spectral responsivity is bias-light dependent.

## 11. Precision and Bias

11.1 *Interlaboratory Test Program*—An interlaboratory study of spectral responsivity measurements was conducted in 1992 through 1994. Seven laboratories performed three repetitions on each of ten solar cells circulated among the participants. The design of the experiment, similar to that of Practice E691, and a within-between analysis of the data are given in an ASTM Research Report.[8]

11.1.1 *Test Result*—Analysis of data from interlaboratory studies of spectral responsivity measurements is complicated by the lack of a single numerical result (see 10.5). This complication was overcome by performing a reference spectral mismatch parameter calculation according to Test Method E973 using the spectral responsivity data submitted by the participants. Because of the normalization inherent in spectral mismatch calculations, the precision information given below in percentage points is representative of relative spectral responsivity measurements.

11.1.2 *Precision (spectral mismatch parameter calculations; errors at specific wavelengths can be substantially higher):*

| | |
|---|---|
| 95 % repeatability limit (within laboratory) | 0.3 % |
| 95 % reproducibility limit (between laboratory) | 1.7 % |

11.2 *Bias*—The contribution of bias to the total error will depend upon the bias of each individual parameter used for the determination of the spectral responsivity. The procedures prescribed in these test methods are designed to reduce bias errors as much as is reasonably possible.

11.2.1 For relative spectral responsivity measurements, wavelength-independent bias errors cancel because of the normalization performed. However, bias errors which vary with wavelength (such as errors due to non-flat detector responsivity) will still introduce error into the final results.

11.2.2 For absolute spectral responsivity measurements, bias errors do not cancel out from normalization and therefore propagate directly into the final results. Of all possible sources of bias, two will most likely dominate the total error: photodetector calibration and the area measurements. Errors due to multiple reflections between apertures and detector surfaces can also occur when irradiance responsivity and power responsivity are converted to each other. Waveform-related errors can also occur when the modulated current measurement instrumentation is calibrated for square wave or sinusoidal signals and the measurement system produces trapezoidal waveforms (see 10.5).

## 12. Measurement Uncertainty

12.1 Measurement uncertainty is an estimate of the magnitude of systematic and random measurement errors that may be reported along with the measurement errors and the measurement results. An uncertainty statement relates to a particular result obtained in a laboratory carrying out this test method, as opposed to precision and bias statements which are mandatory

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[8] Available from ASTM International. Request Research Report No. RR:E44 – 1003.

parts of the method itself and normally derived from an interlaboratory study conducted during development of the test method.

12.2 It is neither appropriate for, nor the responsibility of, this test method to provide explicit values that a user of the test method would quote as their estimate of uncertainty. Uncertainty values must be based on data generated by a laboratory reporting results using the test method.

12.3 Measurement uncertainties should be evaluated and expressed according to the NIST guidelines[9] and the JCGM guide.[10]

12.4 Sources for uncertainty in spectral responsivity measurements can be divided into three broad categories: photocurrent measurements, radiant power measurements, and quality of the monochromatic light. Appendix X1 provides a list of potential sources of uncertainty.

12.5 Uncertainty in the measurement results obtained using this test method depend on the calibration uncertainties of the instruments used and the signal noise encountered during the test.

12.6 One can gather information describing the random uncertainty of a measurement result by repeating the measurement several times and reporting the number of measurements, and their range or standard deviation.

12.7 At the wavelengths noted in 9.1.5, 9.1.5.1, 9.1.12, results obtained using this test method have substantial additional uncertainty due to the poor signal to noise performance of the measurement system.

12.8 Uncertainty of test results at wavelengths near the bandgap of the monitor photodetector, reference photodetector, or DUT may be adversely affected due to the uncertainty of the device temperatures and the high temperature coefficient of spectral responsivity at such wavelengths.

12.9 Uncertainty of test results for individual wavelengths depends on the capabilities of the apparatus used. Calibrated reference photodiodes can have calibration uncertainties between 0.2 and 7.0%, depending on wavelength, which contributes to bias error in spectral responsivity measurements. Noise, spatial uniformity issues, and varying light intensities are likely to contribute random uncertainties between 1 and 5% to measurement results.

## 13. Report

13.1 *Device Under Test Description:*

13.1.1 *Suggested Items*—Data for the following items are suggested for the report: Semiconductor material(s), Semiconductor structure, Device/junction type, Dimensions, and Device Identification, Encapsulation or Anti-reflective coating.

13.2 *Reference Photodetector Description*—Describe the reference photodetector used for calibration using Type, Identification, Manufacturer, Calibration method, Calibration laboratory, Calibration date, and Calibration data.

13.2.1 Report the wavelengths of the test for which the reference photodetector does not have calibration data (see Note 1), if any, and note that this omission will introduce error in the spectral mismatch parameter if it is computed from the test data.

13.2.2 Report the current produced by the bias light on the reference photodetector, if any. Also report the wavelengths for which the background noise exceeded 1% of the signal as recorded in 9.1.5, and 9.1.5.1.

13.3 *Test Conditions:*

13.3.1 Data for the following items shall be provided to describe the conditions under which the test was performed: Monochromatic Light source, Monochromator, Bias light source, Date of test, Calibration method, Relative sizes of monochromatic beam reference photodetector, and DUT.

13.3.2 Report the wavelengths for which the background noise was greater than 1% as noted in 9.1.12.

13.3.3 Report monochromatic light source non-uniformity (see 6.3.7).

13.3.4 Report reference detector non-uniformity (see 6.1.4), if known.

13.3.5 Report the light chopping frequency and any knowledge available as to whether the DUT has transient response characteristics that may be slower than the frequency used.

13.3.6 If the instrumentation used to measure the signal from the photodetector is not the same as that used to measure the signal from the DUT, report the factor used to convert the reading units (for example, RMS) to those used in $E_M$ (for example, peak-to-peak) prior to performing the calculation in Eq 1. Also, report how the factor was determined.

13.3.7 *Unusual Conditions*—Report any observations of unexpected phenomenon or unusual conditions pertaining to the calibration or measurement.

13.4 *Test Results:*

13.4.1 Plot the relative or absolute spectral responsivity versus wavelength and also tabulate it as *X-Y* data pairs.

13.4.2 Report the current induced in the DUT by the light bias applied as recorded in 9.1.8.

13.4.3 Report the bias voltage induced in the DUT by the light bias applied if recorded in 9.1.8.

13.4.4 If desired by the user of the report, include the integral of the spectral responsivity with a reference spectral irradiance in the form of a short-circuit current or current density as calculated in 10.11.

13.4.5 Report the measurement uncertainty of the spectral responsivity results in 13.4.1.

## 14. Keywords

14.1 cell; irradiance; measurement; photovoltaic; quantum efficiency; radiant power; responsivity; solar; spectral; testing

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[9] Taylor, B. N., and Kuyatt, C. E., Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Tech. Note 1297, U.S. Government Printing Office, Washington, DC, 1994.

[10] Joint Committee for Guides in Metrology, Evaluation of measurement data — Guide to the expression of uncertainty in measurement, JCGM 100:2008, 2010 Corrected Version (available from http://www.bipm.org/en/publications/guides/gum.html).

# APPENDIX

## (Nonmandatory Information)

## X1. LIST OF POTENTIAL SOURCES OF UNCERTAINTY IN SPECTRAL RESPONSIVITY MEASUREMENTS

X1.1 *Photocurrent Measurements:*

X1.1.1 *Electrical instrumentation:*
X1.1.1.1 I-V conversion amplifier gain, linearity, noise, and offsets.
X1.1.1.2 Load resistor calibration, drift, and thermovoltages.
X1.1.1.3 Lock-in amplifier calibration, resolution, accuracy, waveform-to-sine wave correction, overloading, noise, dynamic range, time constant, and usage procedures.
X1.1.1.4 AC voltmeter gain, noise level offset, linearity, and time constant.

X1.1.2 *DUT:*
X1.1.2.1 Temperature.
X1.1.2.2 Time response to chopped light.
X1.1.2.3 Linearity.
X1.1.2.4 Bias light spatial uniformity.
X1.1.2.5 Monochromatic light spatial uniformity.
X1.1.2.6 Voltage bias.
X1.1.2.7 Bias light spectral irradiance.
X1.1.2.8 Sensitivity to polarized light.

X1.1.3 *Mechanical:*
X1.1.3.1 Movement of optics.
X1.1.3.2 Vibration.
X1.1.3.3 Chopped stray monochromatic light.

**X1.2** *Radiant Power Measurements:*

X1.2.1 *Filament or Xe arc light sources:*
X1.2.1.1 Irradiance fluctuations.
X1.2.1.2 Spectral irradiance variations with age and operating current.

X1.2.2 *Calibration:*
X1.2.2.1 Source polarization.
X1.2.2.2 Signal to noise ratio..
X1.2.2.3 Photodetector characteristics.
X1.2.2.4 Calibration drift with time.

X1.2.3 *Stray light:*
X1.2.3.1 Illumination differences between photodetector and DUT.
X1.2.3.2 Photodetector area different from DUT area.
X1.2.3.3 Photodetector field of view different from DUT field of view.
X1.2.3.4 Incomplete attenuation of unwanted orders in grating monochrometers.
X1.2.3.5 Pinholes in narrow bandwidth filters.
X1.2.3.6 Degradation of or insufficient blocking in narrow bandwidth filters.

X1.2.4 *Photodetectors and associated electronics:*
X1.2.4.1 Calibration, resolution, and accuracy.
X1.2.4.2 Gain, phase, offsets, and linearity.
X1.2.4.3 Temperature drift.
X1.2.4.4 Field of view changes.
X1.2.4.5 Photodetector degradation.
X1.2.4.6 Phtodetector spectral responsivity.

X1.2.5 *Pyroelectric radiometers:*
X1.2.5.1 Time constants.
X1.2.5.2 Microphonics.
X1.2.5.3 Signal to noise ratio.
X1.2.5.4 Phase angle adjustment.
X1.2.5.5 Waveform factor.
X1.2.5.6 Non-constant responsivity versus wavelength.

X1.3 *Quality of Monochromatic Light:*

X1.3.1 Wavelength bandwidth.

X1.3.2 Filter defects.

X1.3.3 Polarization variation with wavelength.

X1.3.4 Wavelength offset or error.

X1.3.5 Wavelength variation with laboratory temperature.

X1.3.6 Beam location variation with wavelength.

X1.3.7 *Beam larger than DUT:*
X1.3.7.1 Photodetector area versus DUT area.
X1.3.7.2 Beam spatial uniformity.
X1.3.7.3 Different photodetector and DUT positions.

X1.3.8 *Beam smaller than DUT and photodetector areas:*
X1.3.8.1 Partially shaded regions.
X1.3.8.2 Spatial variation of DUT spectral responsivity.

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