



Designation: E1021 – 06

Standard Test Method for Spectral Responsivity Measurements of Photovoltaic Devices¹

This standard is issued under the fixed designation E1021; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

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

1.2 *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 Relating to 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

E1328 Terminology Relating to Photovoltaic Solar Energy Conversion

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.

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 Multi-junction 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 and in Terminology E1328.

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.

3.2.8 *quantum efficiency, n*—number of collected electrons per incident photon at a specific wavelength in percent units.

3.2.9 *reference photodetector, n*—a photodetector used to quantify the amount of light in monochromatic beam.

3.2.10 *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, $m \cdot s^{-1}$,
 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, $A \cdot W^{-1}$,
 ε —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, J·s,
 I —current, A,
 I_{mc} —monitor photodetector current during calibration, A,
 I_{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, $A \cdot W^{-1}$,
 λ —wavelength, nm or μm ,
 λ_o —a specific wavelength, nm or μm ,
 M —spectral mismatch parameter,
 P —monochromatic beam power reaching the photodetector, W,
 ϕ —power of the monochromatic beam or irradiance of the monochromatic beam, W or $W \cdot m^{-2}$,
 q —elementary charge, C,
 Q —external quantum efficiency,
 R_{iq} —absolute spectral responsivity for irradiance mode, $A \cdot m^2 \cdot W^{-1}$,
 R_{pd} —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 Methods

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 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 between one third and one half of normal end use operating conditions intended for 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. Overall spectral response of a test device with substantial spatial non-uniformity of response should be performed in irradiance mode.

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

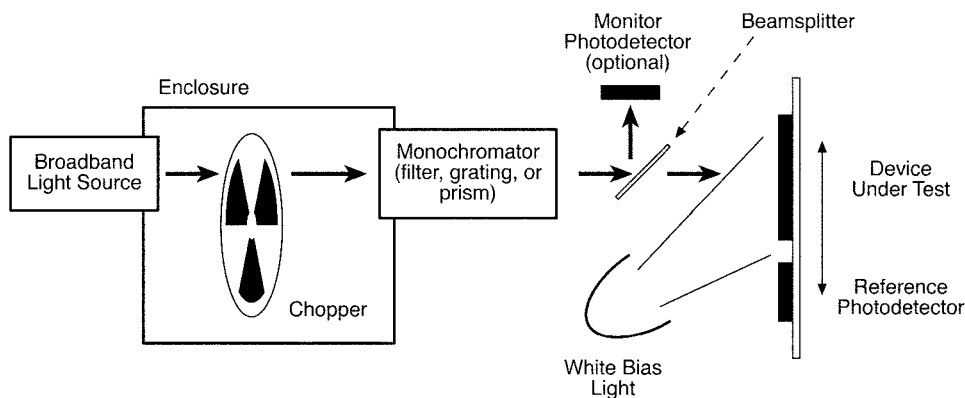


FIG. 1 Example of Spatial Placement of Optical Components for Spectral Responsivity Measurement

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.

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, one can compute the internal quantum efficiency of a device.

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 techniques⁵, 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.

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	Reference 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		Nonuniform	Smaller	Nonuniform	Absolute	D
Irradiance	Power		(reference photodetector calibration not valid)				
Irradiance	Irradiance	Smaller			(reference photodetector calibration cannot be used)		

NOTE 1—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.