BS EN 60904-8:2014

BSI Standards Publication

Photovoltaic devices

Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device

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National foreword

This British Standard is the UK implementation of EN 60904-8:2014. It is identical to IEC 60904-8:2014. It supersedes BS EN 60904-8:1998 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee GEL/82, Photovoltaic Energy Systems.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2014

ISBN 978 0 580 79766 8
ICS 27.160

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 October 2014.

Amendments issued since publication

Date	Text affected

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 60904-8

August 2014

ICS 27.160

Supersedes EN 60904-8:1998

English Version

Photovoltaic devices - Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device (IEC 60904-8:2014)

Dispositifs photovoltaïques - Partie 8: Mesure de la sensibilité spectrale d'un dispositif photovoltaïque (PV) (CEI 60904-8:2014)

Photovoltaische Einrichtungen - Teil 8: Messung der spektralen Empfindlichkeit einer photovoltaischen (PV-)Einrichtung (IEC 60904-8:2014)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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Foreword

The text of document 82/822/FDIS, future edition 3 of IEC 60904-8, prepared by IEC/TC 82 "Solar photovoltaic energy systems" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60904-8:2014.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2015-03-12
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2017-06-12

This document supersedes EN 60904-8:1998.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 60904-8:2014 was approved by CENELEC as a European Standard without any modification.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu

Publication	Year	Title	EN/HD	Year
IEC 60904-3	-	Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data	EN 60904-3	-
IEC 60904-7	-	Photovoltaic devices - Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices	EN 60904-7	-
IEC 60904-9	-	Photovoltaic devices - Part 9: Solar simulator performance requirements	EN 60904-9	-
IEC 61215	-	Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval	EN 61215	-
IEC 61646	-	Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval	EN 61646	-
IEC/TS 61836	-	Solar photovoltaic energy systems - Terms, definitions and symbols	CLC/TS 61836	-
ISO/IEC 17025	-	General requirements for the competence of testing and calibration laboratories	EN ISO/IEC 17025	-

CONTENTS

PHOTOVOLTAIC DEVICES –

Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device

1 Scope

This International Standard specifies the requirements for the measurement of the spectral responsivity of both linear and non-linear photovoltaic devices. It is only applicable to single-junction devices. The spectral responsivity of a photovoltaic device is used in cell development and cell analysis, as it provides a measure of recombination and other processes occurring inside the semiconductor or cell material system.

The spectral responsivity of a photovoltaic device is used for the correction of the spectral mismatch if a PV device is calibrated in a setup where the measurement spectrum is different from the reference spectral irradiance data given in IEC 60904-3 and a reference device with a different spectral responsivity to the device under test is used. This procedure is given in IEC 60904-7.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

IEC 60904-7, *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*

IEC 60904-9, *Photovoltaic devices – Part 9: Solar simulator performance requirements*

IEC 61215, *Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval*

IEC 61646, *Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval*

IEC/TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

3 Marking

Each photovoltaic device should carry a clear and indelible marking. This marking should be cross-referenced against:

– name, monogram or symbol of the manufacturer;
– base material and type of photovoltaic device;

– type number or identification, if available;
– serial number, if applicable.

When the photovoltaic devices to be tested are prototypes of a new design and not from production, this fact shall be noted in the test report (see Clause 10).

4 Testing

4.1 General

The photovoltaic device shall be subjected to one of the procedures for spectral responsivity measurements defined in Clauses 7 to 9.

4.2 Special considerations

Preconditioning – Before beginning the measurements, the device under test shall be stabilized (if necessary) by an appropriate light soaking test procedure, as specified in IEC 61215 or IEC 61646. Different photovoltaic technologies may require different pre-conditioning procedures.

4.3 Measurement under white bias light

The procedures in Clause 7 and 9 require a white bias light being applied to the device under test during the determination of spectral responsivity. Under bias light conditions, not the spectral responsivity but rather the differential spectral responsivity is measured. The spectral responsivity can be determined from the differential spectral responsivity by taking the non-linearity into account based on a series of differential spectral responsivity measurements at bias light levels generating short-circuit currents in the device ranging from 5 % to 110 % of that at standard test conditions (see Clause 5). Most crystalline silicon solar cells have a differential spectral responsivity at a bias light generating 30 % to 40 % of their short-circuit current at standard test conditions that is identical to the spectral responsivity at standard test conditions. Therefore, the measurement should be performed with such bias light levels if the non-linearity of a crystalline silicon PV device is not determined. If the non-linearity is confirmed to be negligible, i.e. the differential spectral responsivity is constant within the irradiance range of interest, the differential spectral responsivity at a specific bias light level may be used. For details see Clause 5.

4.4 Applying a bias voltage to the device under test

Generally, the spectral responsivity of a photovoltaic device is measured at short-circuit conditions (zero bias voltage) of the photovoltaic device and used for the purposes of cell analysis and calculating the spectral mismatch.

In order to measure the spectral responsivity of the specimen under a specific voltage, a bias voltage may need to be applied. The bias voltage of the device shall be controlled by an external voltage source. If a bias voltage is applied it shall be specified in the report.

5 General description of spectral responsivity measurement

The spectral responsivity of a photovoltaic (PV) device is measured by irradiating it by means of a narrow-bandwidth light source at a series of different wavelengths covering its responsivity range, and measuring the short-circuit current and monochromatic irradiance at each of these wavelengths (formula 1), or short-circuit current and monochromatic light beam power (formula 2). The first type of measurement results in the spectral irradiance responsivity with the unit $A/W \cdot m^{-2}$. In order to determine the spectral responsivity as defined in IEC/TS 61836 this needs to be divided by the area of the device under test whereas the second type results directly in the spectral responsivity in the unit A/W.

In order to determine the output current of the device, the bias light as well as the monochromatic light should irradiate the entire area of the device uniformly. It is important to illuminate effectively the entire area of the device, as light not directly falling onto the active area may also contribute to the measured signal. If the spectral responsivity is used for the calculation of the spectral mismatch correction according to IEC 60904-7 the illuminated area during the measurement of the spectral responsivity should be identical to that during the measurement of the current-voltage characteristics. This is normally the entire device area. If not it should be suitably delimitated by an aperture.

In case the area of the device is larger than the respective beam sizes the latter should be scanned appropriately across the entire device area to provide a uniform illumination. If both beams are scanned, the scanning should be synchronous with the bias light always illuminating a spot larger than the monochromatic light.

The temperature of the device should be controlled.

The current density of the device under test at each wavelength is divided by the respective irradiances to give spectral responsivity.

$$s(\lambda) = I_{sc}(\lambda)/E(\lambda)/A \tag{1}$$

where:

$s(\lambda)$ is the spectral responsivity of the device under test at the wavelength λ;

$I_{sc}(\lambda)$ is the short-circuit current of the device under test at the wavelength λ;

$E(\lambda)$ is the irradiance of the light source at the wavelength λ;

A is the area of the device under test.

The area of the device under test shall be noted in the test report.

Alternatively, the short-circuit current $I_{sc}(\lambda)$ and the radiant power incident on the device $P(\lambda)$ may be measured. The spectral responsivity is then determined as:

$$s(\lambda) = I_{sc}(\lambda)/P(\lambda) \tag{2}$$

where:

$I_{sc}(\lambda)$ is the short-circuit current of the device under test at the wavelength λ;

$P(\lambda)$ is the radiant power incident on the device at the wavelength λ.

The determination of $P(\lambda)$ requires the measurement of the area of the device under test. This area shall be noted in the test report.

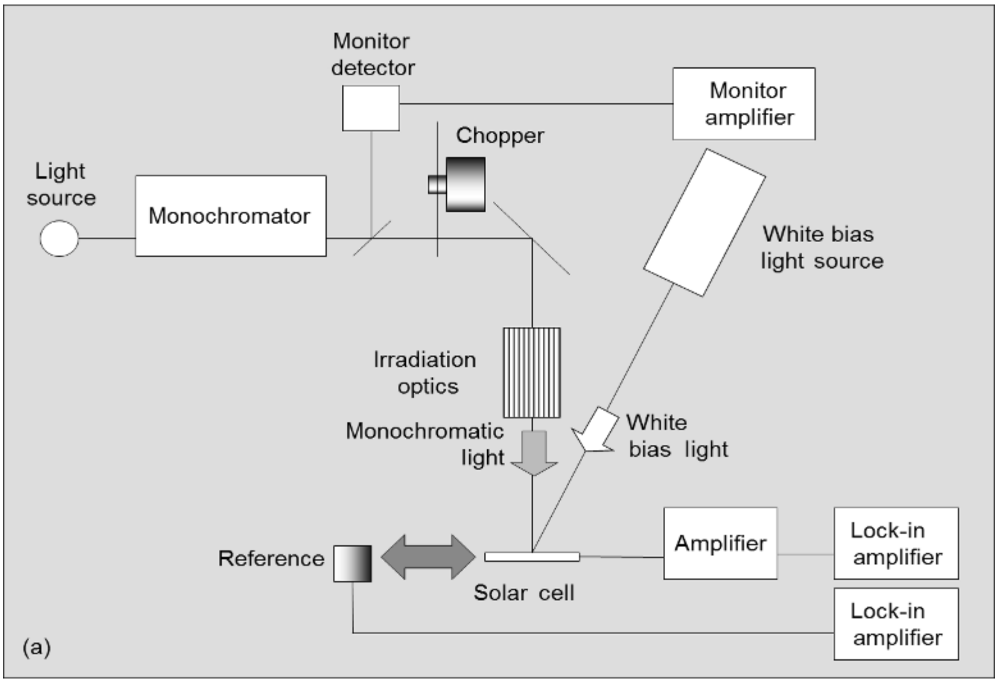
In practice (see Clauses 7 and 9) a small modulated signal originating from the monochromatic light is superimposed on a large bias signal originating from the white bias light. In such cases the evaluated quantities need to be treated as differential and a wavelength dependent differential spectral responsivity (DSR) $\tilde{s}(\lambda, E)$ is determined for a specific bias light irradiance E. The spectral responsivity at standard test conditions $s(\lambda)|_{STC}$ will equal the differential spectral responsivity only if the device is strictly linear. If the non-linearity is confirmed to be negligible, the differential spectral response at a specific bias light level may be used. For example, if the differential spectral response or the resultant spectral mismatch factor is constant within the bias light levels to generate the I_{sc} between 5 % and 110 % of standard test conditions, the differential spectral response at a bias level of 100 % of standard test conditions may be used. In all other cases the DSR shall be measured at a sufficient number of bias irradiances and the resultant spectral responsivity can be calculated or a specific bias light irradiance E_0 shall be found with $\tilde{s}(\lambda, E_0) \approx s(\lambda)|_{STC}$.

6 Apparatus

6.1 General

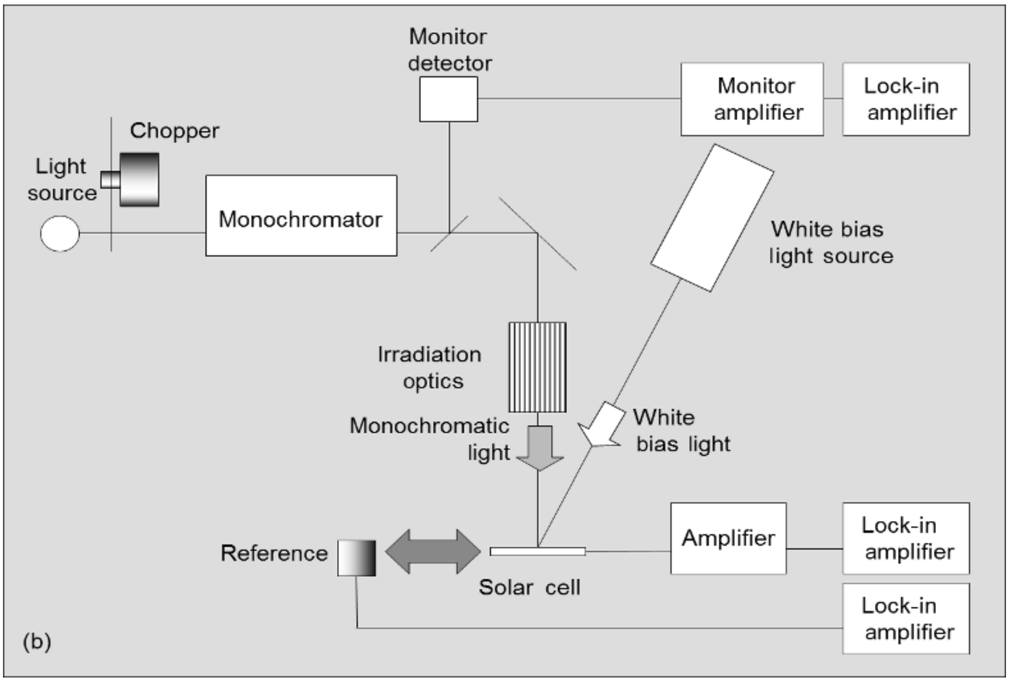
A spectral responsivity measurement system consists of a continuous (chopped or unchopped) or pulsed monochromatic light source, an optional beam splitting assembly with a monitor detector, a device stage able to hold the device under test, a reference device, an optional bias light assembly and electrical instrumentation. Figures 1(a, b) and 2(a, b) show examples of test arrangements for the measurement of the DSR of a solar cell.

If an optical chopper is used (Figures 1 and 2) care needs to be taken that no bias light reflected of the optical chopper reaches the test plane.



IEC 1171/14

Figure 1a) – Monochromator ahead of chopper



IEC 1172/14

Figure 1b) – Chopper ahead of monochromator

Figure 1 – Example block diagram of a differential spectral responsivity measuring instrument using a continuous light source and a grating monochromator

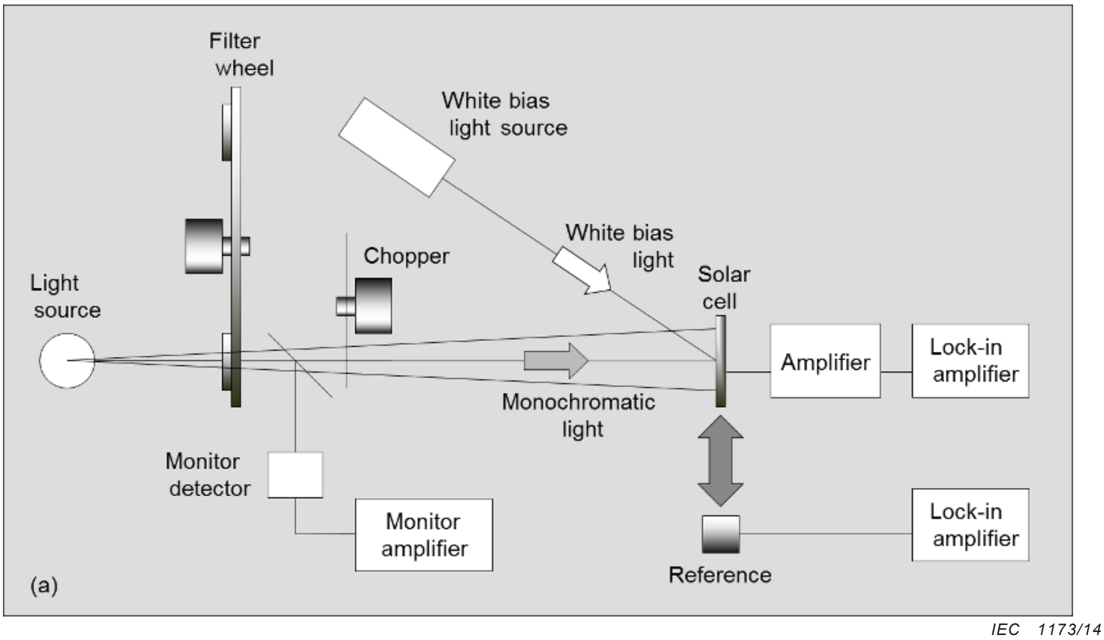


Figure 2a) – Filter ahead of chopper

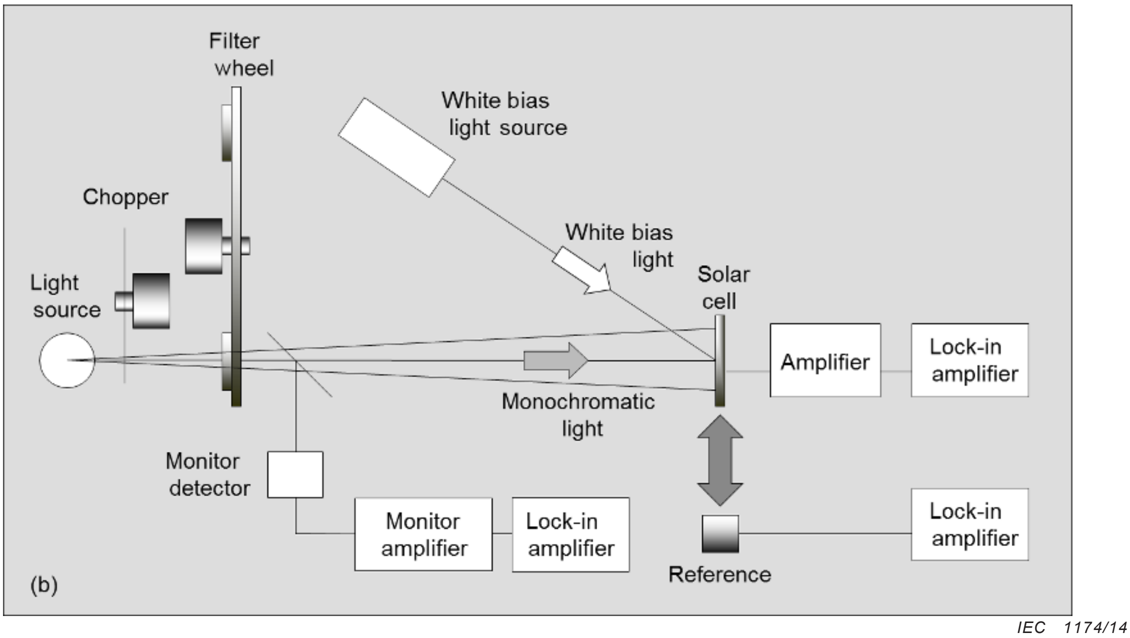


Figure 2b) – Chopper ahead of filter

Figure 2 – Example block diagram of a differential spectral responsivity measuring instrument using a continuous light source and bandpass filters

6.2 Monochromatic light source

The monochromatic light is usually generated by a light source and monochromator (for example a grating) or filter wheel with bandpass filters. The bandwidth (Full Width at Half Maximum, FWHM) of the monochromatic light should not exceed 20 nm for spectral responsivity measurements in the range between 300 nm and 1200 nm. In the range up to 3000 nm, the bandwidth should not exceed 50 nm.

The bandwidth of the monochromatic light should be chosen according to the fine structure of variation in the spectral responsivity of the device under test. Typically, a bandwidth (FWHM) of 10 nm – 15 nm is chosen for crystalline silicon cells or thin film solar cells.

The temporal light fluctuations caused by the lamp used for generating the monochromatic light and its power supply should be below 2 %. Spatial uniformity of the monochromatic light in the test plane should be better than ± 2 % determined according to IEC 60904-9. The spatial non-uniformity is especially relevant if the reference device and device under test deviate in their area or shape. It shall be considered within the uncertainty calculation. With a stable light source the reference and the device under test are normally measured consecutively in the same position and the non-uniformity is only relevant if the two are of different size. For sufficiently large area uniform illumination the reference and the device under test may be placed side-by-side and measured simultaneously thereby eliminating the effect of temporal fluctuations of the light source. Alternatively a beam splitting arrangement can provide two uniformly illuminated test planes for the test and reference devices.

NOTE This is analogous to the definition of simulator class A in IEC 60904-9.

6.3 PV device holder and temperature control

The PV device holder should provide the capability to make electrical connections to the device under test with good conductivity and to control the temperature of the device under test and the reference device. The temperature of the reference device and the device under test shall be measured or controlled to an accuracy of ± 1 °C with a repeatability of ± 0,5 °C. The temperature uniformity of the reference device and the device under test should be within ± 2 °C. If the temperature of the reference device differs by more than 2 °C from the temperature at which it was calibrated, the calibration value shall be adjusted to the measured temperature.

NOTE Temperature differences of the reference device between its calibration and its use for a measurement typically will have their largest effect near the band edge of the reference device.

6.4 PV device contacts

A four point connection (Kelvin contacts, i.e. separate contacts for current and voltage) to the device under test should be used in order to allow the measurement of the cell voltage during the spectral responsivity measurement. It shall be designed such that the contacts do not impede the temperature control of the device under test, especially in the case of cells with all contacts on the back side.

NOTE If the device under test has a low shunt resistance, the correct measurement of the cell voltage is of special importance.

6.5 Bias light

For most PV devices, it is sufficient to use tungsten lamps or lamp arrays to generate the constant irradiance bias light. The light bias should illuminate the entire area of the device under test. The spatial non-uniformity (as defined in IEC 60904-9) of the applied bias light in the test plane should be less than 10 %, corresponding to class C. One possible scanning approach is described in Clause 5.

6.6 DC measurements

a) Voltages and currents shall be measured to an accuracy of ± 0,2 % of the open-circuit voltage or short-circuit current, respectively. Voltages and currents shall be measured using independent leads from the terminals of the specimen (four (4) wire leads), keeping them as short as possible. If the device under test is a bare cell, the 4-wire connection should start at the bus bars.

   The connection method for cells should be carefully evaluated, as it may change the short-circuit condition of the cell due to resistive losses. Due to this effect, differences in spectral responsivity may occur.

b) Short-circuit currents produced by the bias light should be measured at zero voltage. Typically current to voltage converters (transimpedance amplifier) can be used. Alternatively an external shunt resistor can be used together with a variable bias voltage source to offset the voltage drop across it. The variable voltage bias may be omitted if the voltage drop across the device under test is less than 3 % of its V_{OC}.

NOTE For a crystalline silicon solar cell this corresponds to typically a bias voltage of less than 20 mV.

6.7 AC measurements in the presence of bias light

If the spectral responsivity is measured using chopped monochromatic light in addition to bias light, the alternating monochromatically generated current shall be separated from the steady state current generated by the bias light by using a lock-in amplifier or equivalent equipment. As above an IV converter or an external shunt resistor should be chosen such that the voltage across the test device is less than 3 % of the open-circuit voltage. Care shall be taken to ensure that the measurement device or amplifier is not saturated by the DC current generated by the bias light. The chopping frequency shall be included in the test report.

The chopping frequency should be chosen such that the cycle time is longer than the time constant of the device under test. Furthermore, the chopping frequency should be chosen such that it does not coincide with the power frequency or its harmonics.

Set the voltage across the cell to the desired value (either 0 V for short-circuit conditions or the desired voltage).

6.8 Reference device

The irradiance or the power of the monochromatic light can be measured by reference devices such as thermal radiometers, calibrated photodiodes or photovoltaic devices. Silicon photodiodes can be used for the wavelength range of 300 nm to 1 100 nm. Ge photodiodes, InGaAs photodiodes or other devices with lower band gaps and thermal detectors can be used over a longer wavelength range. Devices under test which have a spectral responsivity over a wide wavelength range might necessitate the use of two or more different reference devices to cover this wide range.

NOTE Thermal detectors may not generally be suitable as they have time constants longer than the cycle time of the chopped light.

In the case that more than one reference device is used to extend the wavelength range of the measurement system, special care needs to be taken to avoid artefacts in the wavelength region of overlap of the reference devices.

7 Measurement of spectral responsivity using a constant light source

7.1 General method with a grating monochromator or filter wheel

If the light source is temporally stable, in the first step the reference device is measured at all wavelengths under consideration. In the second step, it is replaced by the PV device under test.

If the spatial distribution of light is uniform, the reference device and the PV device can be mounted next to each other and can be measured simultaneously. The other provisions of 7.2 and 7.3 do still apply in this case.

NOTE Analogous for a beam splitting arrangement providing two uniformly illuminated areas (see 6.2).

7.2 Measurement of the reference device for setup calibration

7.2.1 Mount the reference device in the spectral responsivity measurement system. Connect it to the instrumentation. Set its bias voltage to the conditions used at its calibration.

7.2.2 Set the reference device temperature to 25 °C or the temperature given by its calibration certificate, and maintain within the recommended temperature range of the reference device.

7.2.3 Set the monochromatic light beam to the size appropriate for both the measurement of the reference device and the device under test.

It is important to illuminate effectively the entire area of the device, as light not directly falling onto the active area may also contribute to the measured signal. If the spectral responsivity is used for the calculation of the spectral mismatch correction according to IEC 60904-7 the illuminated area during the measurement of the spectral responsivity should be identical to that during the measurement of the current-voltage characteristics. This is normally the entire device area. If not it should be suitably delimitated by an aperture.

In case the area of the device is larger than the respective beam sizes the latter should be scanned appropriately across the entire device area to provide a uniform illumination. If both beams are scanned, the scanning should be synchronous with the bias light always illuminating a spot larger than the monochromatic light.

Special care shall be taken if the device under test is of different size in comparison to the reference device. In this case the smaller device should map the area of the larger device, (especially if the light beam is not uniform in irradiance) by measuring it at several positions. Spatial non-uniformity of the monochromatic light shall be considered explicitly in the determination of the final measurement uncertainty.

7.2.4 The bias light induced DC current $I_{\mathrm{ref,DC}}$ of the reference device shall have the same value as during its calibrations (usually low bias light for reference solar cells and no bias light for reference photodiodes).

7.2.5 Measure the output $I_{\mathrm{ref}}(\lambda, I_{\mathrm{ref,DC}})$ of the reference device as a function of the wavelength under monochromatic illumination. For the calculation of the irradiance of the monochromatic light the differential spectral responsivity of the reference device at the bias current level $I_{\mathrm{ref,DC}}$ as set in 7.2.4. shall be used.

In case of simultaneous measurement under a uniform light beam the measurement of the reference will be taken together with that of the device under test in 7.3.3. It is recommended to repeat the measurements with the positions of reference and device under test inverted and suitably average the results. In any case spatial non-uniformity of the monochromatic light shall be considered explicitly in the determination of the final measurement uncertainty.

7.3 Measurement of the device under test

7.3.1 Mount the device under test in the spectral responsivity measurement system. Connect it to the instrumentation. Set the bias voltage so that the voltage across the device under test corresponds to short-circuit conditions or to the required specific voltage.

7.3.2 Set the device temperature to 25 °C or the required temperature, and maintain within ± 1 °C.

If this is not possible for an inverted cell structure or a large area device, the temperature deviation should be noted in the test report.

7.3.3 Measure the complete wavelength dependent output $I(\lambda, I_{\mathrm{bias}}(E))$ under at least 5 different bias light irradiances E resulting in bias light generated short-circuit currents $I_{\mathrm{bias}}(E)$ ranging from 5 % and 110 % of the short-circuit current of the device under standard test conditions. Usually $I(\lambda, I_{\mathrm{bias}}(E))$ is measured with a lock-in-amplifier and $I_{\mathrm{bias}}(E)$ is measured with a multimeter in DC mode.

If the scanning approach as described in Clause 5 is used, the short-circuit current needs to be averaged along the scanning path.

7.3.4 Appropriate corrections for fluctuations of the light irradiance shall be applied if a monitor detector is used. If no monitor detector is used, verify the stability of the light for all wavelengths over the time of both measurements of reference device and device under test and include its variation in the uncertainty analysis.

7.4 Calculation of spectral responsivity

7.4.1 Determine the differential spectral responsivity $\tilde{s}\big(\lambda, I_{\text{bias}}(E)\big)$ for each wavelength and each bias light setting:

$$\tilde{s}\big(\lambda, I_{\text{bias}}(E)\big) = \frac{I\big(\lambda, I_{\text{bias}}(E)\big)}{I_{\text{ref}}\big(\lambda, I_{\text{ref,DC}}\big)} \cdot \tilde{s}_{\text{ref}}\big(\lambda, I_{\text{ref,DC}}\big) \tag{3}$$

where $\tilde{s}_{\text{ref}}\big(\lambda, I_{\text{ref,DC}}\big)$ is the given differential spectral responsivity of reference device.

7.4.2 Calculate the differential responsivity $\tilde{s}(I_{\text{bias}})$ for each bias light setting by integrating over all wavelengths:

$$\tilde{s}(I_{\text{bias}}) = \frac{\int_0^\infty \tilde{s}\big(\lambda, I_{\text{bias}}(E)\big) \cdot E_{\text{AM1.5G}}(\lambda)\, d\lambda}{\int_0^\infty E_{\text{AM1.5G}}(\lambda)\, d\lambda} \tag{4}$$

where $E_{\text{AM1.5G}}(\lambda)$ is the reference spectral irradiance distribution as defined in IEC 60904-3.

NOTE The irradiance E_{bias} is not known during the measurement. But the AM1.5G effective irradiance can be calculated afterwards: $E_{\text{bias}} = \int_0^{I_{\text{bias}}} \frac{1}{\tilde{s}(I)}\, dI$.

7.4.3 Calculate the responsivity $s(I_{\text{STC}})$ of the device under standard test conditions as:

$$s(I_{\text{STC}}) = \frac{I_{\text{STC}}}{\int_0^{I_{\text{STC}}} \frac{1}{\tilde{s}(I_{\text{bias}})}\, dI_{\text{bias}}} \tag{5}$$

where I_{STC} is determined by iteratively evaluating the integral in the denominator until it equals 1 000 W·m^{-2}.

Use the differential responsivity at the lowest bias level for the extrapolation to $I_{\text{bias}} = 0$. The lowest bias level should be approximately 50 W/m^2.

7.4.4 Then calculate the spectral responsivity $s\big(\lambda,\ I_{\text{STC}}\big)$ of the device under standard test conditions as:

$$s\big(\lambda,\ I_{\text{STC}}\big) = \frac{I_{\text{STC}}}{\int_0^{I_{\text{STC}}} \frac{1}{\tilde{s}(\lambda,\ I_{\text{bias}})}\, dI_{\text{bias}}} \tag{6}$$

This spectral responsivity can be used for the calculation of the spectral mismatch factor.

7.4.5 If necessary, the spectral responsivity may be interpolated as a function of the wavelength by appropriate methods (e.g. linear or spline). An estimate of the uncertainty shall be provided for the procedure.

7.5 Simplifications

7.5.1 If the measurements described in 7.3 cannot be performed at all bias light irradiances and at all wavelengths, then determine the bias light irradiance E_0 at which the differential spectral responsivity equals the spectral responsivity of the device under test using the following procedure. Measure the differential spectral responsivity $\tilde{s}(\lambda_i, I_{\text{bias}}(E))$ with a step width of 200 nm (i.e. for crystalline silicon at 3 to 5 different wavelengths λ_i) or at least at one wavelength λ_1 close to the maximal spectral responsivity at 3 to 5 different bias light irradiances E. The bias light irradiances shall result in bias currents I_{bias} ranging from approximately 5 % to approximately 110 % of the approximated $I_{\text{STC,approx}}$ of the device under test. Calculate the responsivity and the bias light level E_0 at which the measured differential responsivity $\tilde{s}(I_{\text{bias}})$ equals the calculated spectral responsivity $s(I_{\text{STC,approx}})$ according to the formulas of 7.4. Perform a differential spectral responsivity measurement at this bias light irradiance.

NOTE The approximated $I_{\text{STC,approx}}$ can be measured with a sun simulator without spectral mismatch correction.

7.5.2 If the measurements described in 7.5.1 cannot be performed, then determine the bias light irradiance E_0 at which the differential spectral responsivity equals the spectral responsivity of the device under test using the following procedure with white light instead of monochromatic light. Measure the differential white light responsivity $\tilde{s}(I_{\text{bias}}(E))$ at 3 to 5 different bias light irradiances E. These bias light irradiances shall result in bias currents I_{bias} ranging from approximately 5 % to approximately 110 % of the approximated $I_{\text{STC,approx}}$ of the device under test. Calculate the responsivity according to:

$$s\left(I_{\text{STC,approx}}\right) = \frac{I_{\text{STC,approx}}}{\int_0^{I_{\text{STC,approx}}} \frac{1}{\tilde{s}(I_{\text{bias}})}\, dI_{\text{bias}}} \,. \qquad (7)$$

Identify the bias light level E_0 at which the measured differential white light responsivity $\tilde{s}(I_{\text{bias}})$ equals the calculated white light responsivity $s\left(I_{\text{STC,approx}}\right)$. Perform a differential spectral responsivity measurement at this bias light irradiance.

For the white light responsivity it is recommended to use white light with a spectral match of at least Class B (as defined in IEC 60904-9) to the reference solar spectral irradiance distribution as defined in IEC 60904-3.

7.5.3 If the methods as described above cannot be used, then use a bias light level that generates approximately a short-circuit current of 30 % $I_{\text{STC,approx}}$ to 40 % $I_{\text{STC,approx}}$. The differential spectral responsivity so measured is assumed to equal the spectral responsivity at standard test conditions.

7.5.4 If this is not possible then use a bias light to give a minimum of 10 % of I_{sc} and verify that the monochromatically generated current in the device under test as function of wavelength does not vary by more than 2 % if the bias light irradiance is (a) reduced to 50 % and (b) increased by 50 %. If it varies more, then the two additional measurements should be included in the report.

8 Measurement of spectral responsivity under pulsed light

8.1 Additional apparatus

a) A pulsed light source, e.g. a Xenon flash lamp combined with interference filters.

b) For experimental set-ups, where simultaneous readings of the device under test and reference device are taken, no monitor is necessary.

c) Sufficiently fast data acquisition to measure the full pulse shape of the output signals from the reference device, the device under test and the monitor (where appropriate) is required for measuring the spectral responsivity using pulsed monochromatic light.

8.2 Test procedure

An example of a test arrangement for pulsed solar spectral responsivity measurement system is shown in Figure 3.

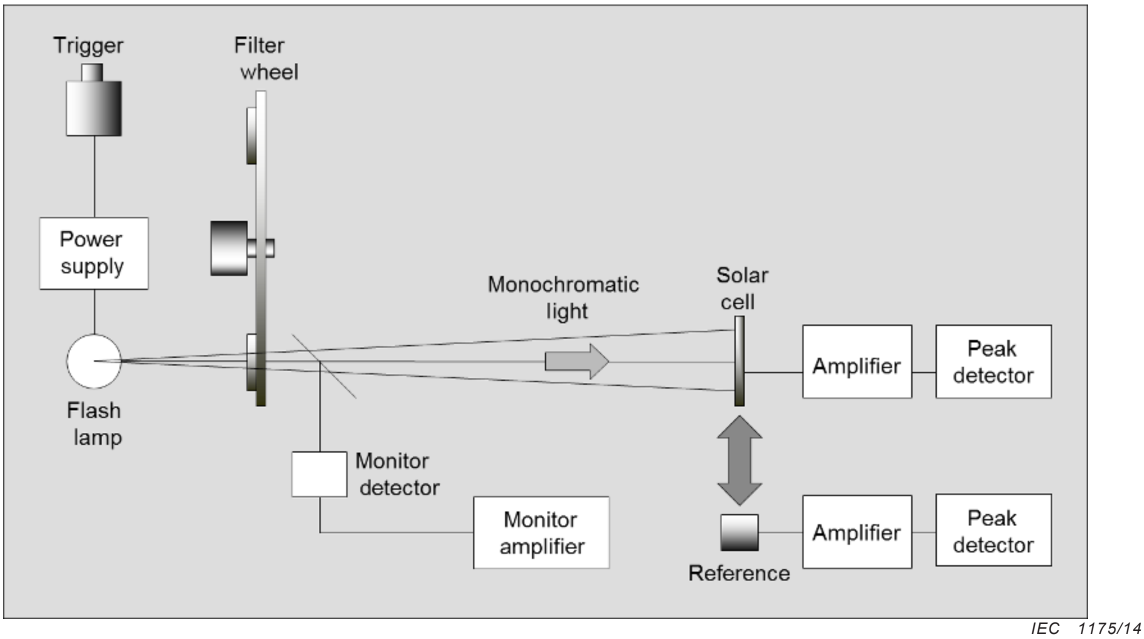


Figure 3 – Example block diagram of a spectral responsivity measuring instrument using a pulsed light source and bandpass filters

Apart from the change of light source and data acquisition system, the measurement method remains as given in 7.2 and 7.3, except that additional bias light is not required for this method.

The pulsed light method cannot be used on devices under test that have a response time that is slower than that of the pulse length in the given operating conditions. Therefore, it shall be verified that the ratio of the short-circuit currents of device under test and reference over the variation of the irradiance of the monochromatic light pulse is a constant. If not, one of the two devices may not be suitable for pulsed measurements.

9 Measurements of series-connected modules

9.1 General

When the spectral responsivity of a component cell in a series-connected PV module is to be measured, the following procedure can be used. The cell in the module to be measured is hereinafter referred to as the target cell.

9.2 Additional apparatus

A supplemental bias light source, which illuminates the whole area of the module, or one of the strings of the module divided by a bypass diode.

9.3 Test procedure

9.3.1 Mount the module in the spectral responsivity measurement system. Connect it to the instrumentation.

9.3.2 During the measurements the target cell shall be maintained at 25 °C (or other temperature) to an accuracy of ± 1 °C with a repeatability of ± 0,5 °C. Other parts of the module shall be maintained in thermal equilibrium to an accuracy of ± 1 °C with a repeatability of ± 0,5 °C.

9.3.3 Apply the supplemental bias light on all the cells in the module, and measure the I-V curve $I_1(V)$ of the module. Then shade the target cell from the supplemental bias light, and apply the white bias light to it. The irradiance of the white bias light and the supplemental bias light should be chosen so that the output current of the module is limited by the photocurrent of the target cell (Figure. 4), i.e. the white bias light plus the additional monochromatic light generate less photocurrent in the target cell than the worst cell in the remaining string or module generates for the applied light bias. If the circuit of the module is divided into strings by by-pass diodes, the cells in the string(s) without the target cell may be shaded instead of applying the supplemental bias light (Figure 5). Measure the I-V curve $I_2(V)$ of the module (Figure 6). The low voltage region shown by the dashed line in Figure 6, needs not be measured, because only $I_2(V)$ around the point B in the figure is necessary in the following procedure.

As a guideline to set the target cell to limit the output current of the whole module, it is recommended that the averaged irradiance of the target cell is smaller than that of other cells by at least 50 W·m^{-2}. For example, if the bias light of 50 W·m^{-2} is applied on the whole area of the target cell, the averaged irradiance of the supplement bias light larger than 100 W·m^{-2} is recommended. If the bias light of 1 000 W·m^{-2} is applied on the 1/10 area of the target cell, the averaged irradiance of the bias light is 100 W·m^{-2}. In this case, the averaged irradiance of the supplement bias light larger than 150 W·m^{-2} is recommended.

Measuring the low voltage region of the $I_2(V)$, shown by the dashed line in Figure 5, applies high negative voltage on the target cell, because the output current of the module is limited by the target cell. Care should be exercised when applying high negative voltage as the performance of the target cell of some materials may be permanently damaged.

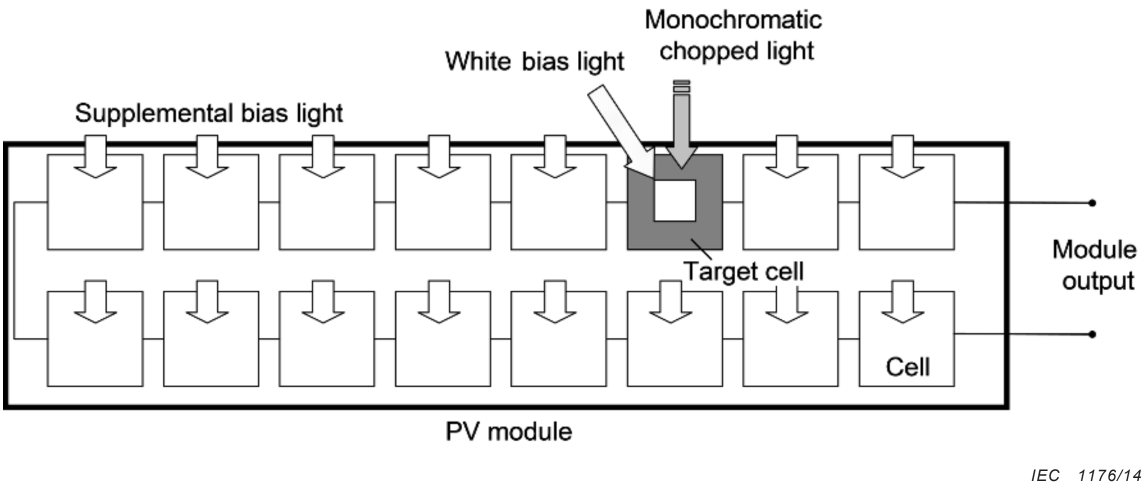


Figure 4 – Example of the measurement setup for the differential spectral responsivity measurement of a target cell in a PV module, where the supplemental bias light is applied on all the cells in the module other than the target cell

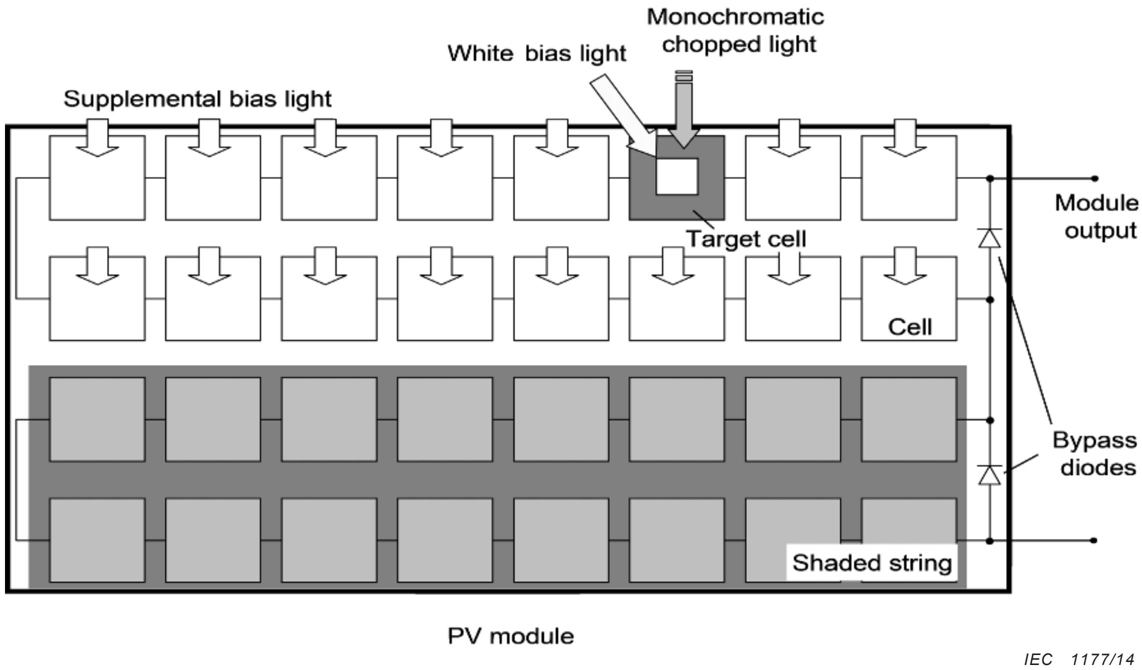


Figure 5 – Example of the measurement setup for the differential spectral responsivity measurement of a target cell in a PV module, where the supplemental bias light is applied on all the cells in a string of the module other than the target cell

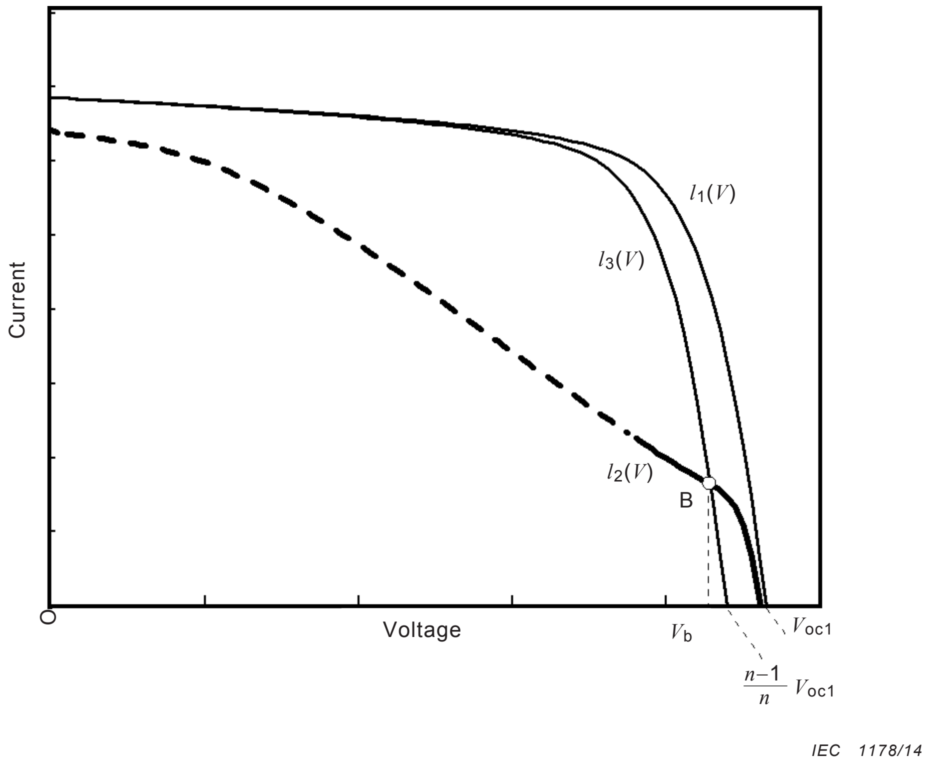


Figure 6 – Determination of the bias voltage V_b to set the voltage across the target cell to the short-circuit condition (see 9.3)

9.3.4 In order to set the voltage across the target cell to the short-circuit condition (zero bias voltage) apply bias voltage V_b as determined as follows. Firstly, calculate the total I-V curve $I_3(V)$ of the cells other than the target cell under the supplemental bias light by multiplying $I_1(V)$ by $(n–1)/n$ regarding the voltage by formula (8).

$$I_3(V) \equiv I_1(\frac{n}{n-1}V) \tag{8}$$

where n is the number of the component cells under the supplemental bias light in the module while measuring $I_1(V)$. Then V_b is determined as the voltage value of the graphical intersection (B in Figure 6) of $I_2(V)$ and $I_3(V)$. I-V curves may be interpolated in order to find the intersection. Apply the bias voltage to the module, which should put the voltage across the target cell to zero. It is noted that simply applying V_{oc1} multiplied by $(n–1)/n$ to the module results in the voltage of the target cell to be slightly forward biased. This condition is also acceptable if the spectral responsivity of the device is not dependent on the bias voltage.

9.3.5 Measure the currents of the device under test and the light monitor (if appropriate) as a function of the wavelength.

9.4 Calculation of spectral responsivity

Determine the spectral responsivity according to Clause 7.

10 Report

Following completion of the procedure, a certified report of the spectral responsivity measurements shall be prepared by the test agency in accordance with the procedures of ISO/IEC 17025. Each certificate or test report shall include at least the following information:

a) a title;

b) name and address of the test laboratory and location where the calibration or tests were carried out;

c) unique identification of the certification or report and of each page;

d) name and address of client, where appropriate;

e) description and identification of the item calibrated or tested;

f) characterization and condition of the calibration or test item;

g) date of receipt of test item and date(s) of calibration or test, where appropriate;

h) identification of calibration or test method used;

i) identification of reference devices used in the calibration;

j) reference to sampling procedure, where relevant;

k) any deviations from, additions to or exclusions from the calibration or test method, and any other information relevant to a specific calibration or test, such as environmental conditions;

l) type of monochromatic light source and its bandwidth (FWHM);

m) level of bias light, and test device voltage;

n) test device temperature and its deviation;

o) reference device temperature and its deviation from the calibration temperature;

p) monochromatic light levels or the current generated in the device under test by the monochromatic light;

q) area of the device under test, where relevant;

r) chopping frequency of the monochromatic light (where applicable);

s) measurements, examinations and derived results of the spectral responsivity as function of wavelength;

t) a statement of the estimated uncertainty of the calibration or test result (where relevant);

u) a signature and title, or equivalent identification of the person(s) accepting responsibility for the content of the certificate or report, and the date of issue;

v) where relevant, a statement to the effect that the results relate only to the items calibrated or tested;

w) a statement that the certificate or report shall not be reproduced except in full, without the written approval of the laboratory.

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