The Application of Spectral Reference Cells to Non-linear Photovoltaic Cells

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Abstract

For evaluation of the characteristics of photovoltaic cells, the solar simulator should be adjusted to 1 kW/m^2 utilizing a reference cell. For adjusting the solar simulator, IEC requires that the spectral responsivity of each reference cell should be the same as the spectral responsivity of the photovoltaic cell under test. This method is very accurate, but it takes time and cost, because this method needs individual physical reference cells. Therefore, we propose a Spectral Reference Cell method that can be used for adjustment of solar simulator intensity for testing photovoltaic cells without using specific physical reference cells. This method adjusts the intensity of solar simulator for various spectral responses within 3% error.

Furthermore, we also expand this method to non-linear photovoltaic cells by using DSR method that can measure using the absolute spectral responsivity at various irradiance levels. Utilizing this method, it was possible to adjust the intensity of solar simulator within 3% error.

This method can dramatically reduce the time and cost of adjusting solar simulator's irradiance for various photovoltaic cells. We think that our "Spectral Reference Cell Method" will be very useful in the development stage of photovoltaic cells, especially for non-linear cells, because this method does not require the developing of specific physical reference cells.

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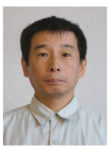
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1 Introduction

For the evaluation of the characteristics of photovoltaic cells, IEC requires the following standard test conditions:

- Cell temperature: 25 degrees Celsius
- Irradiance: 1KW/m^2 = 1 sun
- Spectral irradiance distribution: AM1.5G [1)]

However, the sun's spectral irradiance distribution in real situations is different from AM1.5G, moreover, it is not stable because it is affected by the weather conditions. Because of this, generally solar simulators are used instead of the real sun for this testing.

1. 1 Traditional method (Reference Cell method)

As shown in Fig. 1, the solar simulator's spectral irradiance distribution is different from AM1.5G. As a result, before evaluating the performance of photovoltaic cells, the intensity of the solar simulator light should be adjusted to the 1 sun condition, where the output I_{sc} (short-circuit current) of the reference cell matches its calibration value ($I_{sc\_ref} = I_{sc\_mes}$). After that, the performance of photovoltaic cells can be measured.

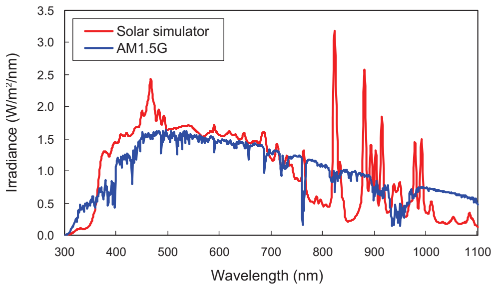

Fig. 1 Spectral irradiance distribution.

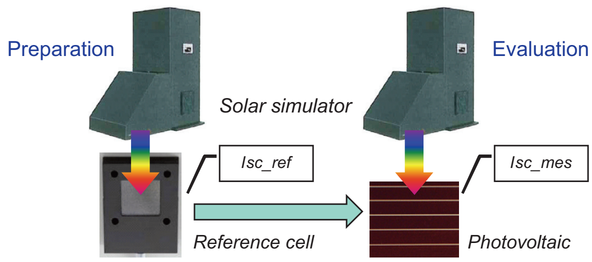

Fig. 2 Adjustment of the solar simulator's irradiance to 1 sun level before measurement.

With this method, precise adjustment is obtained, but there are some demerits in the reference cell method. IEC 60904-2 requires that the spectral responsivity of each reference cell should be the same as the spectral responsivity of each cell under test [2].

For example, in the case of evaluating a DSC (Dye sensitized solar cell) with the solar simulator adjusted using a c-Si type reference cell, the spectral distribution would be as shown in Fig. 3.

A DSC has a spectral responsivity between 300nm and 800nm. For the irradiance of a solar simulator which has been adjusted using a c-Si type reference solar cell, the spectral irradiance distribution in this wavelength range is larger than AM 1.5 G.

As a result, because DSC is measured at an irradiance which is stronger than the standard irradiance, the short-circuit current become larger. In this case, a measurement error of 12.7% occurs. Of course this error is depends on the actual solar simulator spectral distribution, reference cell spectral responsivity, and target cell spectral responsivity.

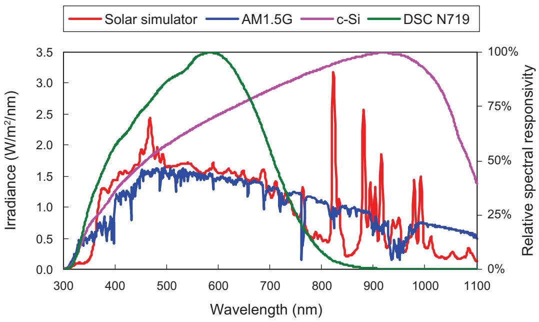

Fig. 3 Irradiance distribution of solar simulator and AM1.5G and relative spectral responsivity of c-Si cell and DSC.

To reduce these errors, it is necessary to make a specific reference cell for each test cell type and calibrate it. However, as shown in Fig 4, that takes time and cost.

To solve these problems, we propose the Spectral Reference Cell method [3) 4) 5)]. This method can be used to adjust the solar simulator's irradiance without making specific reference cells.

Furthermore, in the case of measuring a non-linear cell, it is difficult to adjust the solar simulator to a suitable irradiance level because the spectral responsivity is different at each irradiance level.

For example, as shown in Fig. 5, a DSC's spectral responsivity depends on the irradiance [6]. However generally the calibration value I_{sc_ref} is only defined at 1 sun condition. Therefore we cannot adjust the solar simulator at various irradiance levels.

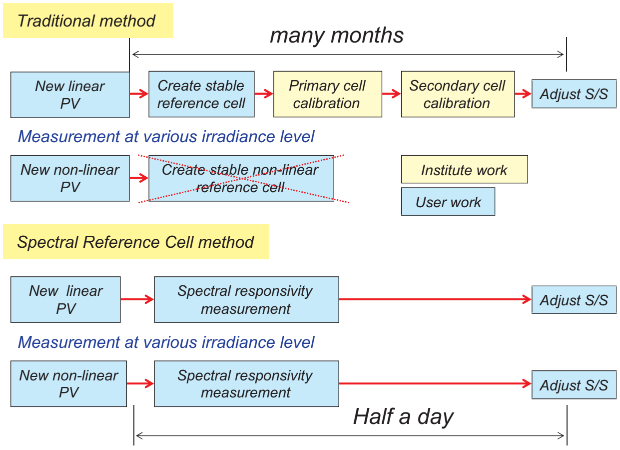

Fig. 4 Solar simulator adjustment process: Traditional method vs. Spectral Reference Cell method.

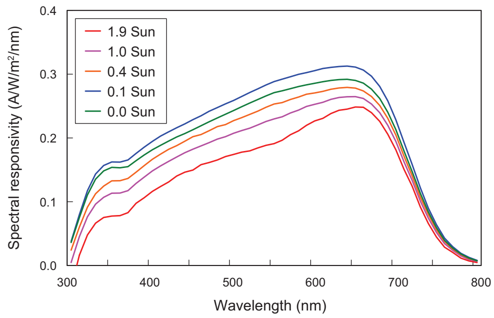

Fig. 5 Non-linearity of spectral responsivity of DSC.

1. 2 New method (Spectral Reference Cell method)

To solve these problems, we propose the Spectral Reference Cell method for linear cells. To solve the problem of non-linear cells, we utilize the DSR (Differential Spectral Responsivity) method [7) 8)]. This method was developed by PTB (Physikalisch-Technische Bundesanstalt), It can take measurements using the absolute spectral responsivity at any irradiance level. So as shown in Fig. 4, the new Spectral Reference Cell method which uses the DSR method can adjust the solar simulator at various irradiance levels.

2 Measuring principles

By integrating the spectral irradiance $E(\lambda)$ and spectral responsivity of solar cell $S(\lambda)$ over the wavelength, I_{sc} is generally calculated as

$$I_{sc} = \int S(\lambda) \cdot E(\lambda) d\lambda \tag{1}$$

The Spectral Reference Cell method uses this principle.

The measuring principle of the Spectral Reference Cell method is as follows.

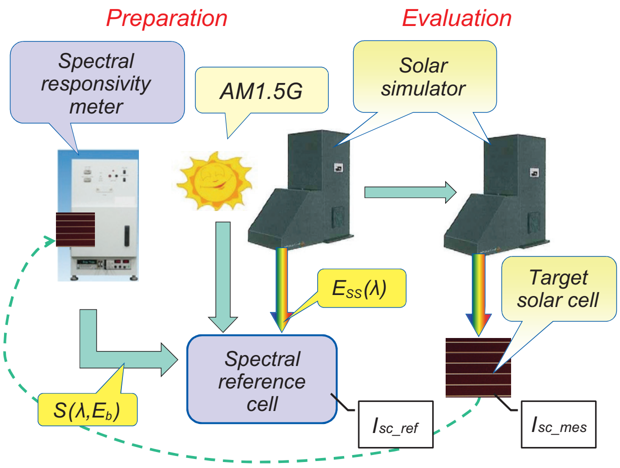

Fig. 6 Measuring principle structure of spectral reference cell.

$$I_{sc\_ref} = \int S(\lambda,\ E_{AM1.5G}) \cdot E_{AM1.5G}(\lambda)d\lambda \qquad (2)$$

$$I_{sc\_mes} = \int S(\lambda,\ E_{SS}) \cdot E_{SS}(\lambda)d\lambda \qquad (3)$$

I_{sc_ref}	Calibrated short circuit current
I_{sc_mes}	Short circuit current under the solar simulator
$S(\lambda,E_b)$	Spectral Responsivity of Photovoltaic cell at Irradiance E_b
$E_{AM1.5G}(\lambda)$	Spectral irradiance distribution of AM1.5G
$E_{SS}(\lambda)$	Spectral irradiance distribution of solar simulator

When adjusting a solar simulator's irradiance:

1st: The Spectral Reference Cell method measures at the specific spectral responsivity and calculates the I_{sc_ref} using Eq. (2).

2nd: The Spectral Reference Cell method measures the spectral irradiance distribution of the solar simulator and calculates the I_{sc_mes} using Eq.(3).

3rd: The Solar simulator's irradiance is adjusted until

$$I_{sc\_mes} = I_{sc\_ref}$$

When adjusting the solar simulator for various types of photovoltaic cells, the traditional reference cell method requires a specific reference cell for each type; however with the Spectral Reference Cell method, there is no need to make a specific physical reference cell. With the Spectral Reference Cell method, all that needs to be done is to change the spectral responsivity data in Eq.(2) and (3). The method thus dramatically reduces time and cost compared to making traditional reference cells and calibrating each one.

For linear photovoltaic cells, $S(\lambda,E_b)$ is equal to $S(\lambda)$, and therefore I_{sc} can be calculated using Eq.(2).

However, for non-linear photovoltaic cells, $S(\lambda,E_b)$ changes according to E_b. It is impossible to measure $S(\lambda,E_b)$ directly. To solve this problem we use the DSR method that calculates I_{sc} without using $S(\lambda,E_b)$.

3 DSR method

The differential spectral responsivity (DSR) method is a spectral calibration method based on the calculation of the DSR as a function of wavelength λ in the presence of steady-state solar-like bias irradiance E_b to set the operating point which is determined by the short-circuit current $I_{sc}(E_b)$:

$$\tilde{s}(\lambda) = \left.\frac{\Delta I_{\rm sc}}{\Delta E(\lambda)}\right|_{I_{\rm sc}(E_{\rm b})} \qquad (4)$$

with modulated quasi-monochromatic irradiance $\Delta E(\lambda)$ and photo-generated AC short-circuit current ΔI_{sc}.

$\tilde{s}$ is the slope of the short-circuit current / irradiance characteristic.

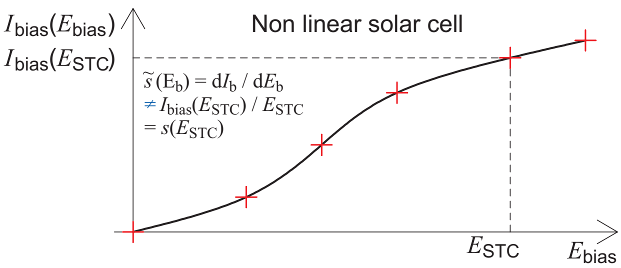

Fig. 7 Short-circuit current of non-linear solar cell with bias irradiation.

The measurement of the spectral responsivity without bias radiation according to Eq. (4) is only acceptable and correct if the solar cell to be calibrated is perfectly linear ($\tilde{s}$ $(\lambda,\ E_b)$ = $S(\lambda)$ independent of $E_b \leq E_{\rm STC}$).

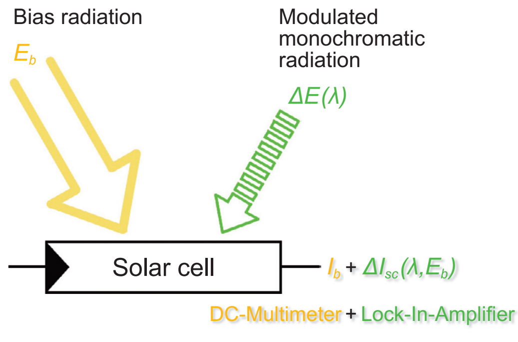

Fig. 8 Dual-beam optical arrangement.

A dual-beam optical arrangement is used to measure relative but equally normalized DSR spectra of a reference cell at a series of discrete operating points that are set with a steady-state bias radiation at levels between 0.001 E_{STC} and 2 E_{STC}. The chopped monochromatic radiation behind a monochromator is measured with a lock-in technique wherein the monitor photodiodes fixed within the spectroradiometer are calibrated against calibrated standard detectors not exposed to the bias radiation while substituting the test cell. To scale the relative DSR, the absolute DSR $\tilde{s}$ (λ_0, E_0) at one (or more) appropriate discrete wavelength(s) is measured at one low (but well-defined) bias level E_0 (about 20 W.m^{-2}). If a cell is linear and the (spectral) responsivity independent of (bias) irradiance, the calibrated responsivity is simply the mean of all the measured responsivities and Eq. (5) is used to calculate I_{STC}. For the case of a non-linear cell, a simple iterative integration procedure is used to obtain I_{STC}.

In the general case of non-linear cells, Eq. (5) is not used but the AM1.5-weighted differential responsivity is calculated from the DSR data

$$\tilde{s}_{\text{AM1.5}}(E_{\text{b}}) \cdot E_{\text{STC}} = \tilde{s}(\lambda_0, E_0) \cdot \int_{s(\lambda)\neq 0} \tilde{s}(\lambda, E_{\text{b}})_{\text{rel}} \cdot E_{\text{STC}}(\lambda)\text{d}\lambda \quad (5)$$

The calibration value I_{STC} of non-linear cells is obtained with the aid of a simple integration of the short-circuit current $I_{sc}(E_b)$ by approximating the unknown upper integration limit I_{STC}.

$$E_{\text{STC}} = \int_0^{I_{\text{STC}}} \tilde{s}_{\text{AM1.5}}^{-1}(I_{\text{sc}})\text{d}I_{\text{sc}} \quad (6)$$

$$\text{with } S_{\text{STC}} = S_{AM1.5}(E_{STC}) = I_{STC} \cdot E_{STC}^{-1}.$$

In this way, I_{sc} can be calculated at any irradiance by utilizing DSR method.

4 Experimental procedure

When measuring a photovoltaic cell under a solar simulator, the calculated theoretical $I_{sc}(I_{sc\_cal})$ can be obtained from Eq. (1) by measuring the spectral irradiance under the solar simulator, and the actual short circuit current of the photovoltaic cell, which we refer to as I_{sc_mes}, can also be measured. In this report, we evaluate the I_{sc} error ΔI_{sc} in Eq. (7) from I_{sc_cal} and I_{sc_mes}.

$$\Delta I_{sc} = (I_{sc\_cal} / I_{sc\_mes}) - 1 \quad (7)$$

In this way, experimental results with respect to the influence of spectral responsivity in linear devices and with respect to bias light intensity in non-linear cells were obtained.

Fig. 9, show the functional block diagram of the Spectral Reference Cell. The main components of the Spectral Reference Cell are a Spectroradiometer that measures the spectral irradiance of the solar simulator and a computer. The computer calculates I_{sc_cal} and I_{sc_mes} by using the absolute spectral responsivity $S(\lambda,E_b)$, measured spectral irradiance $E_s(\lambda)$, and $E_{AM1.5G}(\lambda)$.

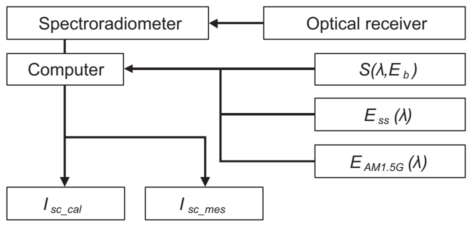

Fig. 9 Spectral Reference Cell.

Fig. 10 shows the functional diagram of the spectral responsivity meter. To measure the spectral responsivity, the bias light provides irradiance E_b on the PV cell and monochrome radiation provides irradiance at various wavelengths on the PV cell. The spectral responsivity meter then calculates the $S(\lambda,E_b)$. The spectral responsivity meter is used in the preparation steps in which the $S(\lambda,E_b)$ of the photovoltaic cell is measured. (Fig. 4)

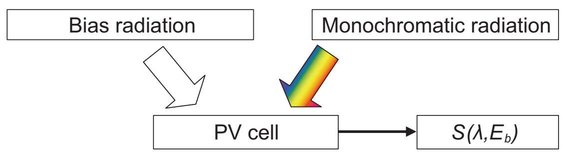

Fig. 10 Spectral responsivity meter.

Linear photovoltaic cells

1) Measure the 9 linear reference cells with different spectral responsivities.
2) Measure the irradiance $E_{SS}(\lambda)$ and I_{sc_mes} under two different solar simulators.
3) Calculate ΔI_{sc}.
4) Calculate the weighted center of the spectral responsivities of the 9 standard photovoltaic cells using Eq. (8).

$$\int (S(\lambda) \cdot \lambda) d\lambda / \int S(\lambda) d\lambda \quad (8)$$

Non-linear multi-crystal photovoltaic cell

1) Measure the spectral response $S(\lambda,E_b)$ of the non-linear cell using the DSR method.
2) Measure the irradiance $E_{SS}(\lambda)$, and I_{sc_mes} under irradiance range of 0.01 sun to 1 sun.
3) Calculate the ΔI_{sc} by using DSR method and non-DSR method.

5 Experimental Results

5. 1 Linear devices

Fig. 11 shows the spectral distribution of solar simulators A (SS-A) and B (SS-B) and AM1.5G. The spectral distribution for each solar simulator is different. Fig. 12 show the 7 traditional reference cells (AK series)[9], and Fig. 13 shows the relative spectral responsivity of the reference cells used in this experiment.

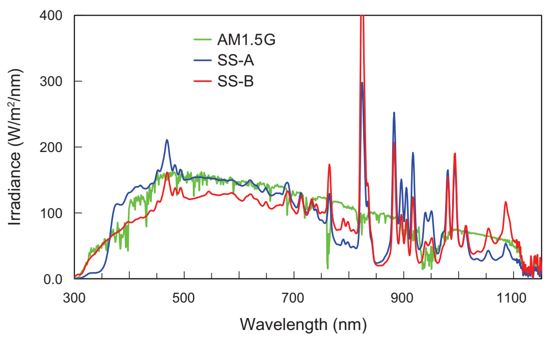

Fig. 11 Irradiance of solar simulator.

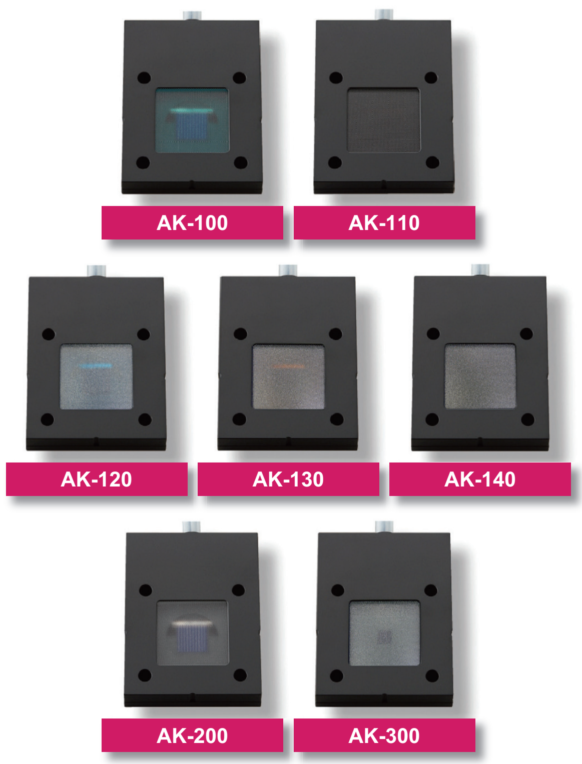

Fig. 12 Reference cells.

Table 1 AK series.

AK series	Description
AK-100	Tandem Top a-Si
AK-110	Tandem Bottom μ-Si
AK-120	Triple Top
AK-130	Triple Middle
AK-140	Triple Bottom
AK-200	c-Si
AK-300	DSC N719

We evaluated the ΔI_{sc}, which is defined in equation (7) by using these cells and these solar simulators.

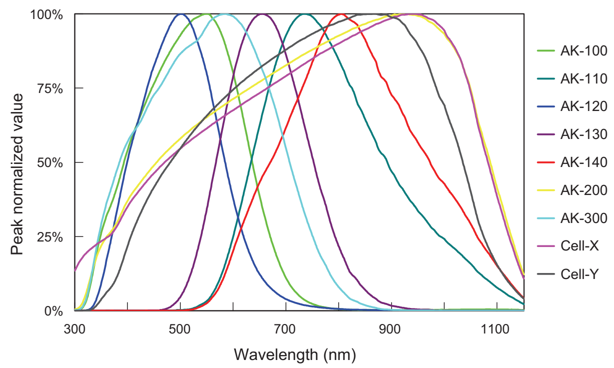

Fig. 13 Spectral responsivity of reference cells.

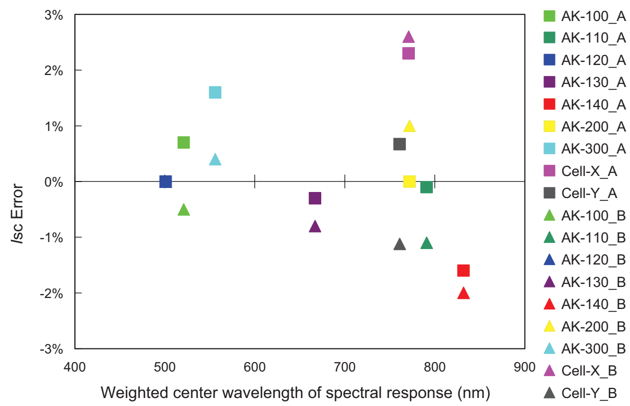

Fig. 14 ΔI_{sc} for various spectral responsivities of linear cells with solar simulators A and B.

The results of ΔI_{sc} are shown in Fig. 14, and are within ±2.6%. These errors are comparable and are not excessively large.

A round robin test which used the traditional reference cells among four nationally authorized organizations with four different calibration methods showed in 1997 that the calibration values of those institutes agree better than ±2% in I_{STC}[10]. As yet, the number of samples used in our tests is limited, but our results are similar to the previous round robin test results. We therefore consider the Spectral Reference Cell method to be comparable to the traditional method.

5. 2 Non-linear device results

We evaluated the effectiveness of the DSR method on the Spectral Reference Cell. For evaluating the effectiveness, we tested 2 non-linear cells at various irradiance levels.

Figs. 15 show the spectral responsivity of the 2 non-linear photovoltaic cells. Cell A's non-linearity is much larger than that of Cell B. The spectral responsivity of Cell A at 1 sun is higher than that at 0.01 sun.

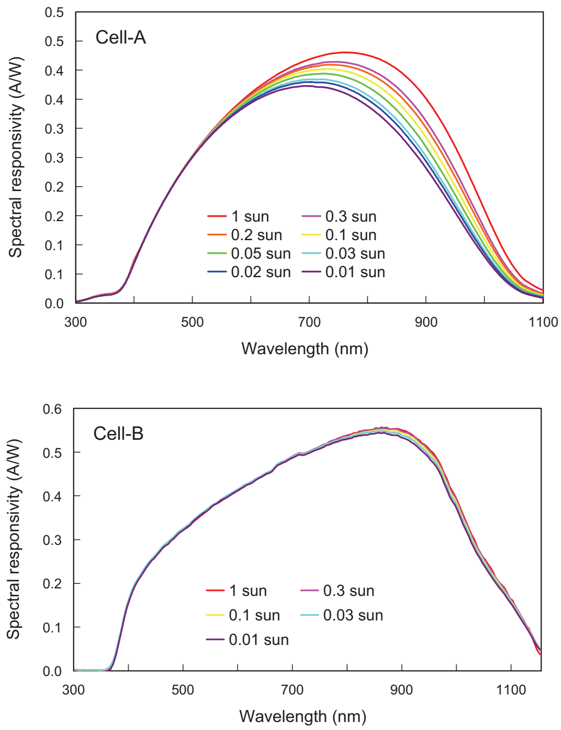

Fig. 15 Spectral responsivity of non-linear device under various irradiances.

As shown in Fig. 16, we varied the solar simulator's irradiance from 0.01 sun to 1 sun while checking the I_{sc} at various irradiance levels.

Fig. 17 and Table 2 show the results of two methods: Non-DSR and DSR.

In the Non-DSR method, the non-linearity of the photovoltaic cells is not considered, since all I_{sc_cal} are calculated using the spectral responsivity at 1 sun irradiance.

In the DSR method, the non-linearity of the photovoltaic cells is taken into consideration as explained in section 3. In other words, the Spectral Reference Cell calculates the I_{Isc_cal} and I_{sc_mes} by using $S(\lambda,Eb)$ instead of $S(\lambda,1\ sun)$

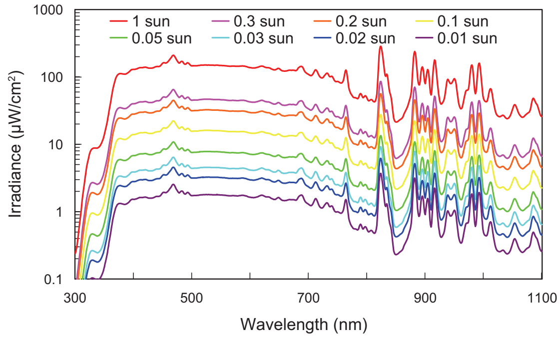

Fig. 16 Spectral irradiance of solar simulator A.

Table 2 Measuring conditions of Fig. 15.

	Responsivity meter	Calculation	Cell type
Non-DSR Cell A	PTB	Non-DSR	Cell A
DSR PTB Cell A	PTB	DSR	Cell A
DSR KM Cell A	KM	DSR	Cell A
Non-DSR Cell B	PTB	Non-DSR	Cell B
DSR KM Cell B	KM	DSR	Cell B

KM: KONICA MINOLTA PTB: Physikalisch-Technische Bundesanstalt

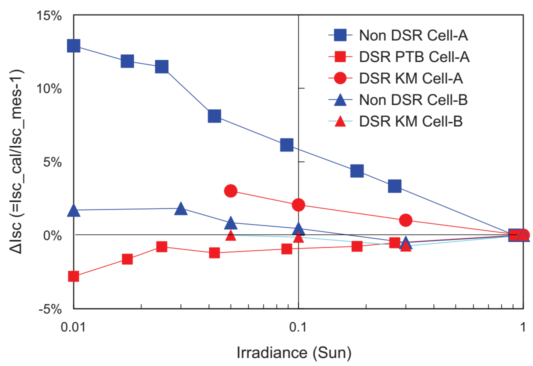

Fig. 17 ΔI_{sc} comparison between DSR and Non-DSR methods

As shown in Fig. 17 with the non-DSR method, ΔI_{sc} increases towards low irradiance and is about +13% at 0.01 sun. On the contrary, using the DSR method, ΔI_{sc} is within ±3% over the range of 0.05 sun to 1 sun.

The results show that the DSR method is effective for adjustment of solar simulators since the ΔI_{sc} is sufficiently low at respective intensities of light even for non-linear photovoltaic cells.

6 Conclusion

For linear cells, the error for the Spectral Reference Cell method is similar to that of the traditional cell method.

For non-linear cells, it was confirmed that the ΔI_{sc} could be significantly reduced by utilizing the Spectral Reference Cell method.

This shows that it is possible to adjust the intensity of solar simulators to ΔI_{sc} within ±3%.

This new Spectral Reference Cell method is suitable for adjusting the irradiance of solar simulators, and has the potential to overcome the following demerits of the traditional reference cell method:

- The need for a specific reference cell for each type of photovoltaic cell.
- The large errors that occur when evaluating non-linear photovoltaic cells.

As yet, the number of test results is limited, and the error of the spectral responsivity meter is larger than that of the PTB one. We therefore intend to further improve the performance of our instruments and to further reduce ΔI_{sc} through evaluation using various photovoltaic cells and various irradiance levels.

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