ACCURATE LINEARITY MEASUREMENTS OF THE SHORT-CIRCUIT CURRENT USING A SPECTRAL SHAPING SETUP

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ABSTRACT: An accurate quantification of the linearity of the short-circuit current with respect to the irradiance is an integral part in the electrical characterisation of solar cells. It is especially important for the calibration of irradiance sensors and reference devices. We demonstrate that an in-house developed spectral shaping setup can reproduce the global AM1.5 solar reference spectrum with a high match. The generated irradiance of < 1 W/m² is perfectly adjusted to conduct a dual beam configuration with a differential measurement technique to measure short-circuit currents in the irradiance range from 0 W/m² to over 1000 W/m². We also investigate the short-circuit current spectrally dependent owing to the freely programmable spectral shaping setup with approximately 1088 accessible spectral subsections in the wavelength range from 355 nm to 1200 nm. Deviations from linearity below 0.1 % are detected on a WPVS solar reference cell demonstrating the high sensitivity of the presented setup. A rear side of a PERC solar cell was investigated to demonstrate the measurement of a strong spectrally dependent nonlinearity of 40 %.
Keywords: Characterisation, Calibration, Solar Radiation

1 INTRODUCTION

Reference solar cells are widely used in the photovoltaics community to determine irradiance levels of natural and artificially generated sunlight [1]. In this context, an accurate characterisation of the short-circuit current's linearity with respect to the irradiance is essential. Additionally, deviations from linearity are an important aspect for the prediction of the energy yield of solar cells because the yearly naturally occurring irradiance levels are widely distributed.

This work presents results of using a spectral shaping setup for accurate short-circuit current measurements at various irradiance levels of up to 1000 W/m². The spectral shaping setup can reproduce a variety of spectra with distinct spectral features, including the global AM1.5 solar reference spectrum [2] with a high spectral match in the wavelength range from 355 nm to 1200 nm [3]. The generated irradiance of < 1 W/m² of this spectral shaping setup is perfectly suited to apply a differential, dual beam method [4, 5] at which additionally installed bias lamps irradiate the solar cell with a tunable irradiance to over 1000 W/m². In this White Light Response (WLR) method [5], the first beam, generated by the spectrally shaped radiation, determines the slope of the short-circuit current versus irradiance curve. The purpose of the second beam, generated by the bias lamps, is to determine this slope at different irradiance levels. The linearity determination is thus an integral part of the WLR method.

In comparison to linearity measurements with a sun simulator [6], the N-lamp method [1] or a WLR setup without the spectral shaping ability [5], the WLR setup, presented in this study, benefits from the very well-matching spectrum, as deviations to the reference spectrum can cause errors or time-consuming corrections. Whilst the accuracy of the new WLR setup is seen as comparable to a Differential Spectral Responsivity (DSR) setup in linearity measurements [7], the WLR setup is approximately 100 times faster than the DSR setup by omitting highly spectrally resolved measurements.

However, we can gain an insight into a spectrally dependent nonlinearity by reproducing subsections of the AM1.5 spectrum and investigating the corresponding short-circuit currents.

In this paper, we present a brief introduction to the theory, the experimental setup with the spectral shaping setup and the application of this setup at two test devices. The ability to quickly measure a very high linearity is demonstrated at an exemplarily chosen WPVS solar reference cell which is presented in this work for the first time. Additionally, we demonstrate a new method which provides insights into the spectrally dependent nonlinearity at a nonlinear test solar cell.

2 METHODS

2.1 Theory

In this work, we use the WLR method [5] combined with a new optical spectral shaping setup to determine the short-circuit current of a solar cell at various irradiance levels. The WLR method uses a similar approach as the DSR method [4]. The WLR method utilizes a dual beam configuration at which one beam has a low irradiance but a well-matched spectrum in comparison to the target reference AM1.5 spectrum. This beam has a chopped irradiance with a known frequency generating a small alternating current signal which is precisely detected by a lock-in amplifier. The second beam of the dual beam configuration is generated by additional bias lamps which produce a steady irradiance from 0 W/m² to over 1000 W/m² leading to the measurable steady bias short-circuit currents I_b.

The measured alternating current signal ΔI, which has been previously calibrated with a reference device, is used to determine the AM1.5-weighted differential responsivity $\tilde{s}_\mathrm{AM1.5}$ which describes the slope of the short-circuit current versus irradiance $I(E)$ curve. The $\tilde{s}_\mathrm{AM1.5}$ value is determined at various bias irradiance levels and thus, bias currents I_b:

$$\tilde{s}_\mathrm{AM1.5} = \left.\frac{\Delta I(E)}{\Delta\, E}\right|_{E_\mathrm{b}=E_\mathrm{b,o}(I_\mathrm{b,o})}. \tag{1}$$

A perfect linear solar cell has irradiance-independent $\tilde{s}_\mathrm{AM1.5}$ values.

The short-circuit current $I(E)$ at a specific irradiance E level is determined by integration [4, 8]:

$$E = \int_0^{I(E)} \frac{1}{\tilde{s}_\mathrm{AM1.5}}\, dI_\mathrm{b}. \tag{2}$$

The linearity of the short-circuit currents with respect to the irradiance is quantified with the parameter percentage deviation from linearity NL [8]:

$$NL = \left(\frac{I(E)}{E} \frac{E_{\mathrm{STC}}}{I_{\mathrm{STC}}} - 1 \right) \cdot 100 \tag{3}$$

The parameter NL describes the deviation of the measured short-circuit currents from a linear relation with the same short-circuit current I_{STC} at $E_{\mathrm{STC}} = 1000$ W/m². NL is zero at 1000 W/m² by definition. For a linear device, NL is zero for other irradiance levels as well. For a nonlinear device, NL differs from zero.

The propagation of the uncertainties of the measured AM1.5-weighted differential responsivity $\tilde{s}_{AM1.5}$ values to the uncertainties of the short-circuit currents and the parameter NL is conducted with the Monte Carlo method [9] which allows to consider manifold correlations.

2.2 Experimental setup

The experimental setup involves a dual beam setup at which the chopped light beam is generated by a spectral shaping setup and the other steady light beam is generated by steady bias lamps as illustrated in Fig. 1.

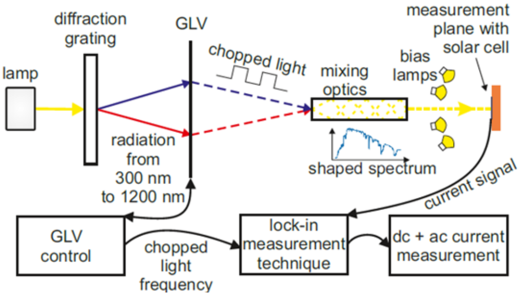

Figure 1: Experimental setup used for linearity measurements of the short-circuit current with respect to the irradiance. Reused from [7].

Cold mirror halogen lamps with less requirements on the spectrum [10] are installed as bias lamps.

The spectral shaping setup consists of a laser-driven lamp with a high radiance, a diffraction grating and a grating light valve (GLV) from Silicon Light Machines [11]. The GLV is a programmable phase diffraction grating and is used as a spectral shaping tool. Details of this setup are given in [3]. The optical setup can reproduce spectra in the wavelength range from 355 nm to 1200 nm with a spectral resolution of 7 nm to 15 nm. The large number of 1088 independently addressable segments of the GLV and the wavelength-dependent irradiation of these segments enables us to reproduce many different spectra with sharp spectral features.

Further details about the measurement conditions, uncertainties and equipment can be found in [7].

2.3 Reproduced spectral irradiance distributions

As seen in Fig. 2, the global AM1.5 solar reference spectrum can be reproduced with a high match in the wavelength range from 355 nm to 1200 nm. The irradiance between 355 nm and 400 nm is slightly boosted so that a typical broadband silicon solar cell would generate the same current under the AM1.5 reference spectrum as under the shaped spectrum in the wavelength range from 300 nm to 400 nm. The spectral mismatch factor [12] of this generated spectrum to the AM1.5 spectrum is equal to unity within its uncertainty of approximately 0.1 % for a wide range of spectral responsivity curves [13]. Thus, a spectral mismatch correction is not necessary.

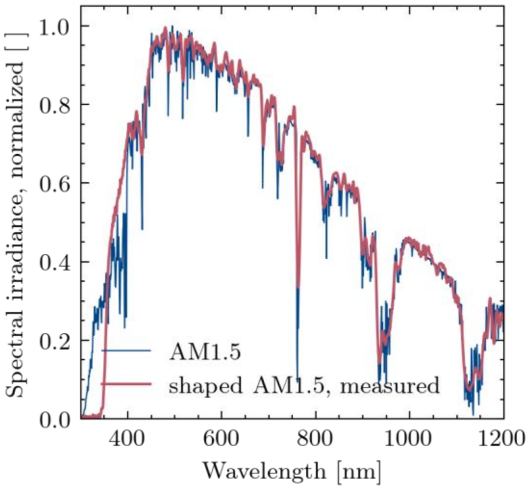

Figure 2: Global AM1.5 solar reference spectrum and the measured, shaped spectrum generated with our optical spectral shaping setup installed at the CalLab PV Cells at Fraunhofer ISE. The high optical resolution of the setup enables a high spectral match.

Additionally, we can use the spectral shaping ability with a high resolution of our setup to generate subsections of the AM1.5 spectrum with abrupt transitions as shown in Fig. 3. The number of subsections and the wavelength boundaries of these subsections can be freely chosen in a wide range.

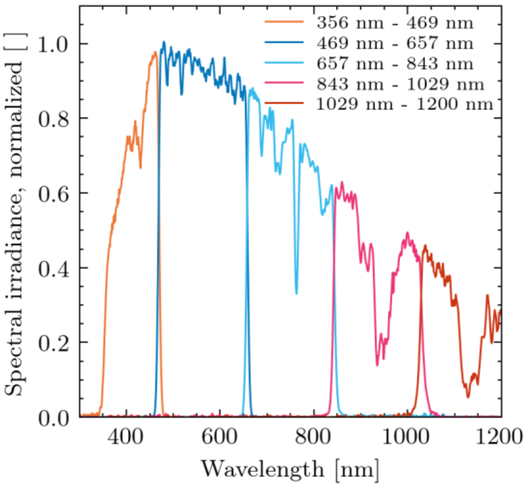

Figure 3: Spectral subsections of the global AM1.5 solar reference spectrum. The subsections can be generated separately and are applied to a solar cell to characterise a possible spectrally dependent nonlinearity.

The presented subsections are generated separately and applied to a test solar cell consecutively. This can be used to detect spectrally dependent nonlinearities in a short time. The measurement time of one data point, generated from the shaped AM1.5 spectrum or of a subsection of the AM1.5 spectrum, was approximately 2 - 10 seconds in this work.

2.4 Test devices

Two different test devices were used in this work. The ability of the presented setup to quantify a high linearity at many adjustable irradiance values from 0 W/m² to over 1000 W/m² in a short time is demonstrated at a WPVS solar reference cell [14]. The ability of the setup to characterise a spectrally dependent nonlinearity is exemplarily shown at a rear side of a piece of a PERC solar cell. In [7, 13], it has been published that this cell is spectrally nonlinear which was characterised by using the Differential Spectral Responsivity (DSR) setup at the Physikalisch-Technische Bundesanstalt (PTB) [10] and at the CalLab PV Cells at Fraunhofer ISE. Additionally, it was reported that the DSR results were consistent with the results of the WLR setup. In this work, we use the generated spectral subsections of the AM1.5 spectrum (Fig. 3) to quantify the spectral nonlinearity.

3 RESULTS & DISCUSSION

3.1 Measuring the high linearity of a WPVS solar reference cell

In Fig. 4, the AM1.5-weighted differential responsivity $\tilde{s}_{\mathrm{AM1.5}}$ values are shown as a function of the bias current. The relative difference of the $\tilde{s}_{\mathrm{AM1.5}}$ values to the s_{STC} value is also shown (right axis). The s_{STC} value is the short-circuit current I_{STC} at 1000 W/m² divided by the irradiance of 1000 W/m². The assigned uncertainty values (coverage factor *k*=2) refer to the left axis with absolute values. The uncertainties of the relative differences would be significantly smaller. The reason is that the uncertainty components which include correlations between the $\tilde{s}_{\mathrm{AM1.5}}$ values cancel out in calculating the relative differences between the $\tilde{s}_{\mathrm{AM1.5}}$ values and the s_{STC} value. The correlated uncertainty components propagate to the s_{STC} value.

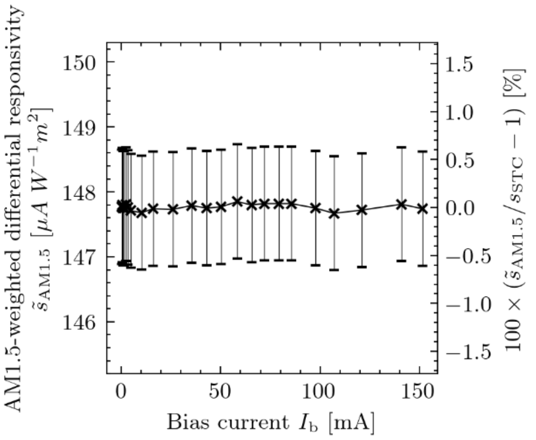

Figure 4: Measured AM1.5-weighted differential responsivities $\tilde{s}_{AM1.5}$ of a WPVS reference solar cell. The relative differences (right axis) of these values to the derived s_{STC} value remain below 0.1 % indicating a very linear solar cell. Uncertainty values refer to the left axis.

The $\tilde{s}_{\mathrm{AM1.5}}$ values remain within a range of approximately 0.1 % around the s_{STC} value. Consequently, it can be stated that this solar cell is highly linear.

The short-circuit current versus irradiance curve is calculated with Eq. (2) using the measured $\tilde{s}_{\mathrm{AM1.5}}$ values and is shown in Fig. 5. Due to the short measurement time of approximately 2 - 10 seconds for each data point, it was possible to determine 29 data points on this short-circuit current versus irradiance curve in a reasonable time.

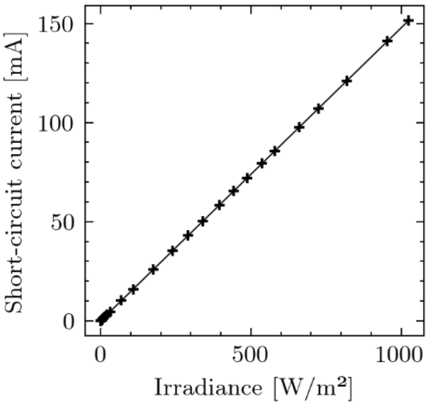

Figure 5: Short-circuit currents as a function of the irradiance. Test device: WPVS reference solar cell. Many measurement points (29) could be determined owing to the fast WLR method.

To take a further look into the linearity of this short-circuit current versus irradiance curve, we calculate the nonlinearity parameter NL with Eq. (3). As seen in Fig. 6, the NL parameter is precisely determined and remains below 0.1 % in the whole irradiance range for the tested WPVS solar reference cell. The assigned uncertainties (*k*=2) decrease with rising irradiance values due to the involved correlations between the $\tilde{s}_{\mathrm{AM1.5}}$ values and the used Eq. (2) and (3) which are considered during the conducted Monte Carlo method. These findings confirm that a high linearity could be measured with a low measurement uncertainty.

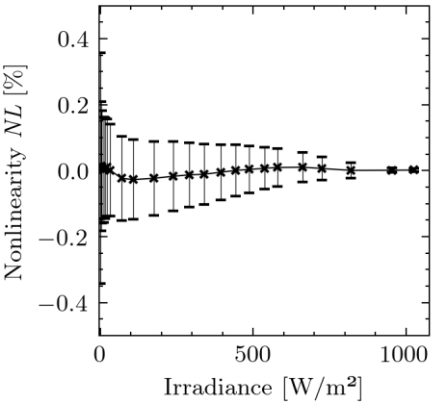

Figure 6: Nonlinearity values for a WPVS reference solar cell which describe the deviations of the short-circuit current versus irradiance curve in Fig. 5 from a straight line. The values are close to zero indicating a very linear solar cell.

3.2 Reproducing subsections of the AM1.5 spectrum to detect spectral nonlinearities

The short-circuit current versus irradiance curve of the rear side of a PERC solar cell is shown in Fig. 7 (black curve). Additionally, the fractions of the short-circuit currents corresponding to the spectral subsections of the AM1.5 spectrum (Fig. 3) are plotted (colored curves). The sum of these colored curves would match with the black curve. The fractions of the short-circuit currents are assigned to equivalent irradiance levels which consider the whole AM1.5 spectrum.

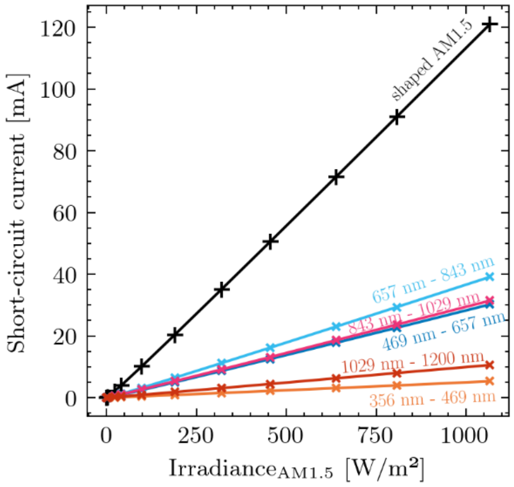

Figure 7: Short-circuit current as a function of the AM1.5 spectrum equivalent irradiance. Test device: Rear side of a PERC solar cell piece. The short-circuit currents generated by the AM1.5 spectrum at different irradiance levels and the fractions of the short-circuit currents corresponding to the generated subsections of the AM1.5 spectrum (Fig. 3) are plotted.

On the first sight, the short-circuit current versus irradiance curve seems to be linear. However, a closer analysis reveals that this solar cell is strongly nonlinear with respect to the irradiance as illustrated in Fig. 8. Deviations from linearity of up to 40 % are observed considering the whole AM1.5 spectrum.

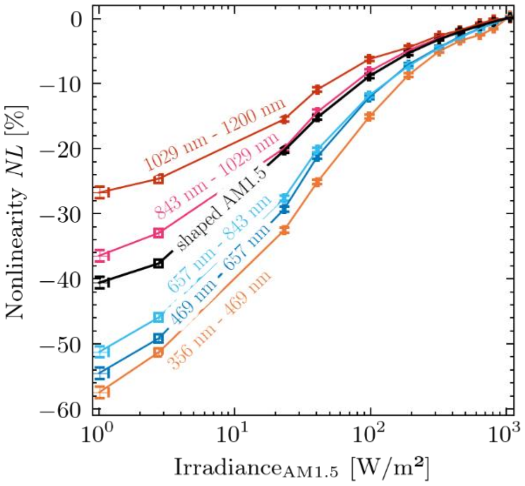

Figure 8: Nonlinearity values produced through the AM1.5 solar reference spectrum (black curve) and spectral subsections of it. Test device: Rear side of a PERC solar cell. The nonlinearity value depends on the irradiance and on the chosen spectral subsection indicating a spectral nonlinearity.

It is evident that the nonlinearity is also dependent on the generated spectral subsection of the AM1.5 spectrum. A stronger nonlinearity is observed towards shorter wavelengths. As a result, we can state that the spectral nonlinearity of this solar cell can be detected and quantified with the presented setup in a short measurement time.

4 CONCLUSIONS

Short-circuit current measurements at different irradiance levels from 0 W/m² to over 1000 W/m² were conducted on two different solar cells. The presented spectral shaping setup can reproduce the global AM1.5 solar reference spectrum with a high spectral match. The generated irradiance of < 1 W/m² for this spectrum is perfectly suited to apply a dual beam approach with a differential measurement technique.

An exemplarily chosen WPVS solar reference cell was characterised to be highly linear. Deviations from linearity were < 0.1 %. The short measurement time for one data point of approximately 2 - 10 seconds enabled us to determine 29 data points on the short-circuit current versus irradiance curve in a reasonable measurement time. The strong nonlinearity of up to 40 % of a rear side of a PERC solar cell was also measured considering the AM1.5 spectrum. By reproducing several subsections of the AM1.5 spectrum and applying these to the solar cell consecutively, we observed that the nonlinearity of the short-circuit current depends on the chosen spectral subsections.

We conclude that the large number of possible data points, owing to the fast measurement technique, allows to have a detailed insight into irradiance-dependent short-circuit current curves. The results of this study demonstrate that our presented setup is highly sensitive in quantifying linearities.

5 REFERENCES

References

[1] H. Müllejans and E. Salis, “Linearity of photovoltaic devices: quantitative assessment with N-lamp method,” *Measurement Science and Technology*, vol. 30, no. 6, p. 65008, 2019.

[2] *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*, IEC 60904-3, IEC 60904-3, Feb. 2019.

[3] M. Mühleis and J. Hohl-Ebinger, “Programmable spectral shaping demonstrated at the solar spectral irradiance distribution,” *Opt. Express*, vol. 29, no. 6, pp. 8223–8234, 2021, doi: 10.1364/OE.417790.

[4] J. Metzdorf, “Calibration of solar cells. 1: The differential spectral responsivity method,” *Applied Optics*, vol. 26, no. 9, pp. 1701–1708, 1987.

[5] J. Hohl-Ebinger, Siefer Gerald, and W. Warta, “Non-linearity of solar cells in spectral response measurements,” in *22nd EU PVSEC*, Milano, 2007, pp. 422–424.

[6] M. Bliss *et al.*, “Interlaboratory comparison of short-circuit current versus irradiance linearity measurements of photovoltaic devices,” *Solar Energy*, vol. 182, pp. 256–263, 2019.

[7] M. Mühleis, I. Kröger, and J. Hohl-Ebinger, “Fast and accurate short-circuit current versus irradiance determination of a spectrally nonlinear solar cell using a spectral shaping setup,” *Solar Energy Materials and Solar Cells*, vol. 230, p. 111208, 2021, doi: 10.1016/j.solmat.2021.111208.

[8] *Photovoltaic devices – Part 10: Methods of linear dependence and linearity measurement*, IEC 60904-10, IEC 60904-10, Sep. 2020.

[9] *Evaluation of measurement data — Supplement 1 to the “Guide to the expression of uncertainty in*

measurement" — Propagation of distributions using a Monte Carlo method, JCGM 101:2008, BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, 2010.

[10] I. Kröger, D. Friedrich, and S. Winter, "Calibration of solar cells beyond STC using the DSR method," in *IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*, 2018, pp. 3492–3497.

[11] D. T. Amm and R. W. Corrigan, "Optical performance of the Grating Light Valve technology," in *Projection Displays V*, 1999, pp. 71–78.

[12] *Photovoltaic devices – {P}art 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*, IEC 60904-7, IEC 60904-7, Aug. 2019.

[13] M. Mühleis, I. Kröger, and J. Hohl-Ebinger, "Highly resolved spectral shaping for fast and accurate solar cell characterization," in *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2021, pp. 48–52.

[14] C. R. Osterwald *et al.*, "The world photovoltaic scale: an international reference cell calibration program," *Progress in Photovoltaics: Research and Applications*, vol. 7, no. 4, pp. 287–297, 1999.