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SPECTRALLY SHAPED SUPERCONTINUUM FOR ADVANCED SOLAR CELL CHARACTERIZATION

Markus Mundus*, Manoj Kumar Dasa, Xudong Wang, Jochen Hohl-Ebinger, Wilhelm Warta
Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, 79110 Freiburg, Germany
*Corresponding Author: Phone: +49 (0) 761 4588 5632 Email: markus.mundus@ise.fhg.de

ABSTRACT: Very recently it has been demonstrated that the special characteristics of supercontinuum lasers allow for a virtually perfect imitation of standard solar spectra. As this eventually makes any spectral mismatch correction redundant, supercontinuum sources are a promising tool for solar cell characterization. This paper contributes to their further establishment in solar cell characterization in two ways: firstly, we will present a differential approach for fast and precise short circuit current measurements by chopped and spectrally shaped supercontinuum radiation. Thereby we overcome the current drawback of limited supercontinuum output power presently impeding their application in large area solar simulators. Secondly, we will assess their potential by comparing spectral mismatch correction factors of shaped supercontinuum radiation to those of state-of-the-art solar simulators for a variety of solar cells. By a Random Walk Monte Carlo method we retrieve the uncertainties of these spectral mismatches and demonstrate that imitating the moving average of a standard spectrum might yield lower measurement uncertainties as its perfect replication. Moreover, the simulations will emphasize that, even in case of a perfect replication of standard spectra, usage of spectrally well matched reference cell remains important for achieving lowest measurement uncertainties. Finally, we will present first experimental short circuit current measurements of Silicon solar cells conducted with the supercontinuum differential approach.

Keywords: Calibration, Characterization, Experimental Methods, Spectral Mismatch, Uncertainty

1 INTRODUCTION

The short circuit current (I_{SC}) is a major parameter for performance evaluation of photovoltaic devices. It does not only reveal important insights into carrier generation and extraction properties of the device under test, but it is also used for solar cell calibrations and, in turn, for solar simulator adjustments.

In indoor measurements, the I_{SC} is generally determined by means of spectral or integral methods. In spectral methods the I_{SC} is mathematically computed from integrating the product of test cell's spectral responsivity (SR) and considered standard solar spectrum. The most widely spread and accepted SR-measurement approach is the differential spectral responsivity (DSR) method [1]. It measures the differential current response of the test device to chopped monochromatic radiation by means of lock-in techniques, thereby achieving lowest measurement uncertainties. In the integral measurement approach broadband solar simulators are applied to directly measure the device's I_{SC}, thus, being significantly faster than the DSR-method. However, as the solar simulator spectra generally deviate from the considered standard solar spectrum, a spectral mismatch correction factor (MM) needs to be applied to the measured I_{SC}. This factor accounts for spectral deviations of test and reference cell responsivities as well as simulator and standard spectrum, by that introducing additional measurement uncertainties [2, 3].

Very recently supercontinuum lasers have attracted interest regarding their application as radiation sources for solar simulators [4]. Owing to their special characteristics, advanced spectral manipulations can be accomplished that virtually eliminate any deviations between simulator and standard solar spectrum, thereby showing the potential of making any spectral mismatch correction redundant. Moreover, programmable spectral shaping tools as e.g. liquid-crystal displays (LCD) or grating light valves (GLV) can be applied allowing for controlled real-time variations of the simulator spectrum [5]. However, the application of supercontinuum lasers in solar simulators for large area industrial solar cells is nowadays limited by the available optical output power of these radiation sources.

In order to overcome this limitation we present an I_{SC} measurement approach that combines advantages of the DSR-method and integral measurements. In analogy to the white-light-response (WLR) method for testing solar cell linearity [6], we illuminate the device under test with chopped supercontinuum radiation in addition to steady bias irradiation. Whereas the chopped supercontinuum radiation closely resembles the considered standard solar spectrum, the required spectral match of bias irradiation and standard spectrum is much less demanding. As the chopped broadband radiation in our approach resembles the considered standard solar spectrum, the differentially measured current response is theoretically identical to the I_{SC} of the device under test and only minor mismatch corrections need to be applied. Owing to the differential measurement approach, supercontinuum output power being orders of magnitude lower than the bias irradiation is sufficient, allowing for short circuit current measurements of large area industrial solar cells. Furthermore, varying the bias irradiation level enables I_{SC} measurement under standard test conditions even for solar cells exhibiting nonlinear behavior.

In this paper, we will firstly present the experimental setup for generating and shaping the supercontinuum radiation. Afterwards, a detailed analysis of the spectral mismatch factor and its uncertainty will be given based on Random Walk Monte Carlo simulations. The performance of the spectrally shaped supercontinuum radiation will be compared to state-of-the-art solar simulators for various reference and test cell combinations, discussing the applicability of the presented experimental setup. Furthermore, the discussion draws important general conclusion on utilizing supercontinuum radiation in solar simulators regarding the lowest possible uncertainties in spectral mismatch correction. Finally, first experimental results of I_{SC} measurements of Silicon (Si) solar cells conducted with the differential supercontinuum approach will be presented.

2 GENERATING AND SHAPING SUPERCONTINUUM RADIATION

The experimental setup applied in this work is schematically shown in Figure 1. Instead of applying a commercially available supercontinuum laser we take advantage of the ultrashort pulse laser system that has been used for the development of a new DSR-measurement-facility at Fraunhofer ISE CalLab [7]. Coupling the ultrashort laser pulses emitted from the laser system into a photonic crystal fiber (PCF) yields a spectral conversion of the quasi-monochromatic radiation into a broadband supercontinuum (dashed blue line in Figure 2) by nonlinear optical effects. For details on supercontinuum generation it is referred to [8].

On the basis of the setup presented by Dennis et al. [5] the coherent supercontinuum radiation emitted by the PCF is collimated (not shown in Figure 1), spectrally dispersed by a prism and focused onto a computer-controlled GLV from Silicon Light Machines. The GLV is a dynamically adjustable grating that allows for controlling the amount of radiation diffracted into higher orders. As the supercontinuum radiation exhibits a certain wavelength-position relation at the GLV, individually adjusting the GLV pixels enables a spectrally resolved amplitude-variation of the back-reflected 0^{th}-diffraction-order. In addition to the GLV, a spatial amplitude mask is implemented close to the GLV front surface to compensate for its limited extinction ratio at wavelengths above 950 nm. The back-reflected, spectrally shaped 0^{th}-order is collected by the same mirror-prism pair and separated from the incident beam by an additional mirror. The spatial separation of input and output radiation is achieved by slightly tilting the GLV. With proper adjustments of the GLV pixels, distinct spectral distributions can be obtained. In Figure 2 a spectrally shaped supercontinuum (solid blue line) imitating the AM1.5G standard solar spectrum (black line, IEC 60904-3 Ed.2 (2008)) is shown. Please note that this shaped supercontinuum needs to be considered as a first shaping attempt. We are currently working on a refined spectral shaping control and expect a shaping capability similar to the one demonstrated by Dennis et al. in [5].

As apparent from Figure 2, the available supercontinuum radiation is limited to the spectral range from approximately 460 nm to larger than 1200 nm. This limitation of the current configuration is given by the properties of the applied PCF and might be compensated for by various approaches: firstly, frequency doubled radiation of one portion of the ultrashort pulses might be added (illustrated by dashed box A in Figure 1); secondly, UV-LEDs might be added (dashed box B); or, thirdly and most conveniently, a new PCF being capable of generating radiation below 460 nm might be applied. In fact, researchers have recently been demonstrating stable and gap-free supercontinuum generation ranging from approximately 200 nm to above 2500 nm by using a new PCF material [9]. As low optical powers are sufficient for the differential measurement approach applied in this work, such new PCFs appear to be very promising for a further development of our setup.

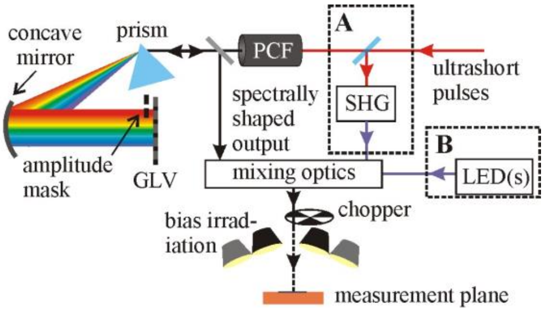

Figure 1: Experimental setup for generation and spectral shaping of supercontinuum radiation. The dashed boxes illustrate the optional addition of second harmonic radiation (SHG) or UV-LEDs being combined with the shaped supercontinuum radiation by mixing optics.

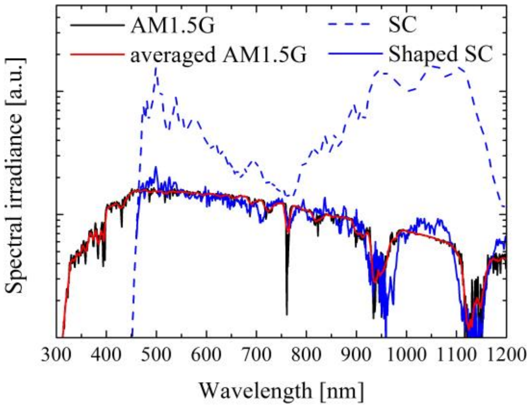

Figure 2: Supercontinuum generated by PCF (dashed blue line), spectrally shaped supercontinuum after GLV (blue line), AM1.5G standard solar spectrum (black line, IEC 60904-3 Ed.2 (2008)) and its moving average with 5 nm bandwidth (red line).

Whereas an improved PCF might simply replace the currently applied PCF, the additional UV sources (SHG and LEDs) are added to the shaped supercontinuum by mixing optics. The radiation emitted by the optical setup is then chopped and directed onto the measurement plane. In addition to the chopped radiation, the device under test is as well illuminated by steady bias irradiation of variable intensity. Using transimpedance and lock-in amplifiers the test cell is kept at short circuit conditions and the differential current gain by the chopped radiation is measured.

In the subsequent section the applicability of supercontinuum radiation sources in solar simulators with a special focus on spectral mismatch and uncertainty in spectral mismatch will be discussed. During that discussion the previously suggested approaches for tackling the missing UV part in the current supercontinuum spectrum will be addressed as well. In section 4 results of first experimental I_{SC} measurements of Silicon solar cells conducted with the new setup will be given.

3 SPECTRAL MISMATCH CORRECTION

3.1 Spectral mismatch factor and its uncertainty

The spectral mismatch correction factor (MM) (IEC60904-7) is a prevalent parameter for correcting I_{SC} measurements. It takes into account differences of the test and reference cell’s relative spectral responsivities (s_{TC}

and s_{RC}) as well as of solar simulator spectrum and tabulated standard spectrum (E_{Sim} and E_{STC}). It is given by

$$\mathrm{MM} = \frac{\int s_{\mathrm{TC}}(\lambda) E_{\mathrm{Sim}}(\lambda)\,\mathrm{d}\lambda \int s_{\mathrm{RC}}(\lambda) E_{\mathrm{STC}}(\lambda)\,\mathrm{d}\lambda}{\int s_{\mathrm{TC}}(\lambda) E_{\mathrm{STC}}(\lambda)\,\mathrm{d}\lambda \int s_{\mathrm{RC}}(\lambda) E_{\mathrm{Sim}}(\lambda)\,\mathrm{d}\lambda}. \quad (1)$$

If test and reference cell are identical or if the solar simulator spectrum perfectly imitates the considered standard solar spectrum, the spectral mismatch factor is unity. Whereas the former case is seldom, it has been recently demonstrated that supercontinuum sources are capable of a virtually perfect replication of standard solar spectra [5]. Although any spectral mismatch correction becomes redundant in that case (as MM approaches unity), the limited accuracy in measuring E_{Sim} causes a non-vanishing mismatch uncertainty u_{MM} that remains important for determination of the overall measurement uncertainty. Thus, a detailed discussion of spectral mismatch uncertainties for spectrally shaped supercontinuum radiation is worthwhile.

For simulating uncertainties of the spectral mismatch factor the Random Walk Monte Carlo method proposed in [3] will be applied. In this approach, spectral responsivities of test and reference cell as well as the spectral distribution of the solar simulator are varied based on Random Walks, thereby taking into account strong correlations of various uncertainty contributions in the respective measurements. The random values are normalized as proposed in [10], ensuring that the standard deviation of the randomized values corresponds to the given measurement uncertainty of spectral responsivity or spectral distribution at each wavelength. The input measurement uncertainties for s_{TC}, s_{RC} and E_{Sim} are chosen equivalently to [3].

Processing 10,000 Random Walks for s_{TC}, s_{RC} and E_{Sim} gives 10,000 spectral mismatch factors that are normally distributed as e.g. shown in Figure 3. The standard deviation of this distribution then corresponds to the standard uncertainty in the spectral mismatch factor u_{MM}.

3.2 Capabilities of Supercontinuum Solar Simulators

As demonstrated above, supercontinuum radiation can be shaped in an unprecedented manner, allowing for a virtually perfect imitation of any standard solar spectrum. To demonstrate the capabilities of a shaped supercontinuum in solar simulator applications, spectral mismatches and their uncertainties are simulated for various combinations of 14 Si solar cells in the preliminary limited spectral range from 460 to 1200 nm. In the next subsection, the discussion is extended to other cell types (and spectrally filtered Si cells) as well as to the spectral range from 300 to 1200 nm exceeding the currently available supercontinuum spectrum.

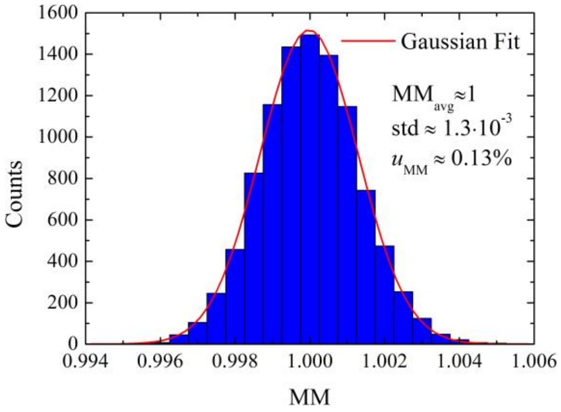

Figure 3: Histogram resulting from Random Walk Monte Carlo simulation for determination of mean MM and uncertainty in MM u_{MM}.

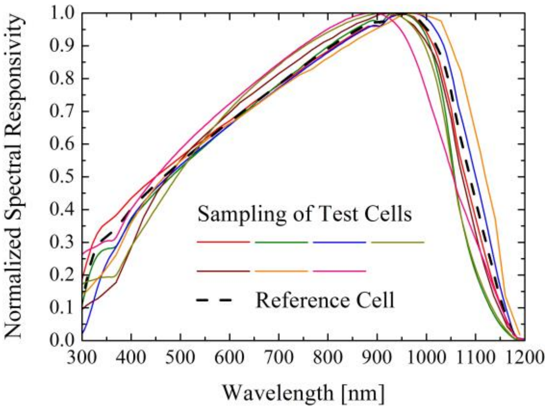

Figure 4: Normalized spectral responsivities of Si solar cells used for statistical analysis of spectral mismatch uncertainty. The reference cell is shown as black dashed line. The sampling of test cells shows seven representative spectral responsivities.

In Figure 4 the normalized spectral responsivities of some of the considered Si test cells are shown, illustrating their typical spectral variations. The dashed black line is chosen to be the reference cell as it exhibits the most unexceptional spectral responsivity.

In order to assess the performance of the shaped supercontinuum, its results are compared to typical spectra from state-of-the-art solar simulators: a Class C and a Class A Xenon simulator (classes refer to the simulator classification given in IEC 60904-9, Ed. 2), a two-source simulator applying a combination of Xe and halogen lamps as well as a LED-simulator made of 18 individual LEDs.

Spectral mismatch factors (top, MM) and standard measurement uncertainties (bottom, u_{MM}) are shown as box plot in Figure 5. The single points mark the mean value over all 14 Si test cells; the straight line marks the median. Bottom and top of the box mark the first and third quantile, the whiskers the minimum and maximum value. The shaped supercontinuum as given in Figure 2 clearly outperforms the other solar simulators. The mismatch factor is generally closer to unity and, more importantly, the standard measurement uncertainty u_{MM} of spectral mismatch is significantly reduced.

The remaining deviation from MM = 1 results from the still imperfect match to the considered standard spectrum AM1.5G. Assuming a simulator spectrum perfectly imitating the AM1.5G (second box from right) yields (per definition) MM = 1 and reduces u_{MM} further. However, u_{MM} does not become zero due to the limited accuracy in measuring the simulator spectrum E_{Sim} and the sharp spectral features of the standard spectrum. As a moving average of the AM1.5G with e.g. 5 nm bandwidth (shown as red line in Figure 2) is much smoother and shows less distinct features, the uncertainty in E_{Sim} and, consequently, u_{MM} is reduced further for a simulator that mimics such a moving average (most right box in Figure 5).

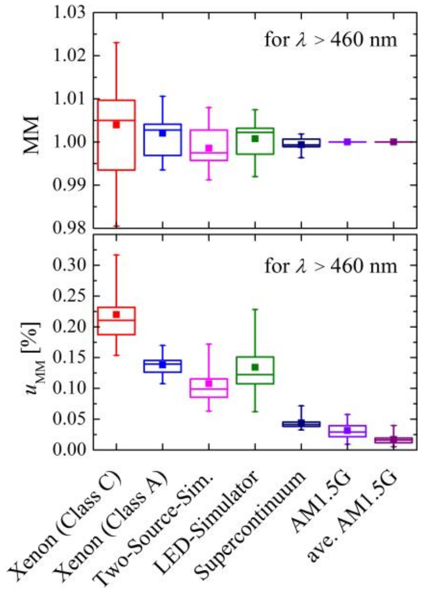

Figure 5: Spectral mismatch (MM, top) and uncertainty u_{MM} (bottom) for the Si solar cells shown in Figure 4 in the spectral range from 460 nm to 1200 nm. In addition to various solar simulator spectra, results for a perfect AM1.5G and a 5 nm bandwidth moving average of the AM1.5G (see also in Figure 2) are shown.

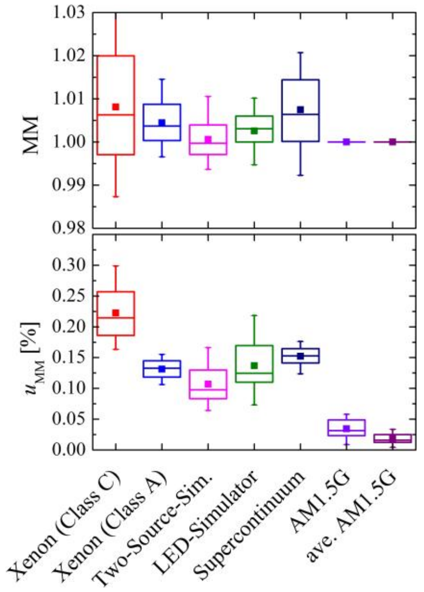

Figure 6: Spectral mismatch (MM, top) and uncertainty u_{MM} (bottom) for the Si solar cells shown in Figure 4 in the spectral range from 300 nm to 1200 nm. The current lack of UV radiation in the supercontinuum spectrum yields an increase in MM and u_{MM}.

This analysis reveals the important conclusion that even if a most perfect spectral imitation becomes feasible with the new supercontinuum solar simulators, it might be more advantageous to create a spectrum that is less rich in detail. Please note, that this conclusion is strongly tied to the individual uncertainties in measuring the simulator's relative spectral irradiance E_{Sim}. In the scope of this work a wavelength accuracy of 0.3 nm is assumed yielding above presented results. For a ten times better wavelength accuracy the standard uncertainty of the perfect AM1.5G imitation approaches that one of the moving average imitation.

3.3 Full Spectrum Analysis

The previous discussion will be extended to the entire relevant spectral range for Si solar cells from 300 to 1200 nm in this subsection. The results of spectral mismatch and its uncertainty for otherwise identical conditions as in the previous section are given in Figure 6.

Due to the lack of UV radiation in the currently available supercontinuum radiation the MM spreads much wider as compared to Figure 5. Likewise, the uncertainty u_{MM} increases significantly. However, u_{MM} is still comparable to other solar simulators and ranges between 0.25% and 0.35% for a 95% level of confidence (k=2). Consequently, the currently available supercontinuum radiation might be readily applied for measurements of Si reference and test cells.

For turning the discussion towards less favorable solar cell combinations, 17 solar cells with spectral responsivities as shown in Figure 7 are added to the simulation. With this, two further measurement situations are considered: firstly, a poor match of reference and test cell and, secondly, the ability of the shaped supercontinuum radiation to measure cells with relatively higher responsivity below 460 nm. The simulation results assuming the same Si reference cell as above are shown in Figure 8. In addition to the boxes, the individual data points for MM and u_{MM} are given.

Due to the poor spectral match of reference cell and some of the test cells, u_{MM} generally increases extensively for all simulator spectra. Likewise, the MM spreads for all simulators, but most distinct for the shaped supercontinuum radiation due to its lack of UV radiation. To compensate for this, adding the frequency doubled radiation of the incident pulses (SHG, dashed box A in Figure 1) or one or more LEDs (dashed box B in Figure 1) to the supercontinuum (SC) spectrum has been proposed in section 2. Applying the spectra achieved in that way (see Figure 9) to the simulation demonstrates that a MM much closer to unity might be achieved. However, due to the additional spectral gradients by SHG and LED radiation, the uncertainty u_{MM} increases as well. This increase is significantly more serious for SHG radiation due to its lower bandwidth as compared to the commercially available LEDs. It might be concluded that, for the time an improved PCF is not yet available (see

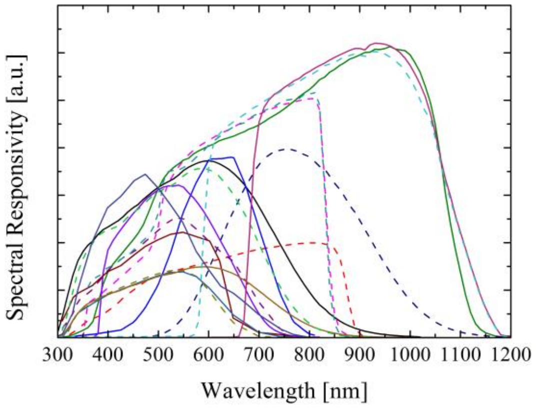

Figure 7: Spectral responsivities of solar cells added for the analysis of supercontinuum performance for poorly matching reference and test cell.

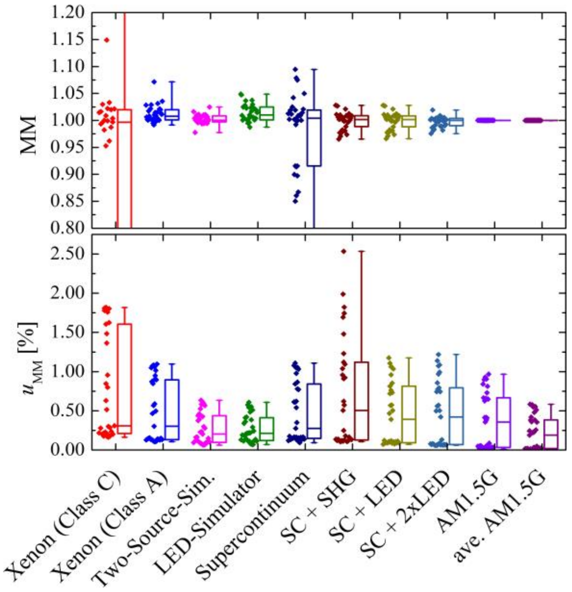

Figure 8: Spectral mismatch (MM, top) and uncertainty u_{MM} (bottom) for the solar cells shown in Figure 4 and Figure 7 (in the spectral range from 300 nm to 1200 nm). In addition to the previous spectra, the combinations supercontinuum plus second harmonic (SC+SHG) as well as supercontinuum plus one or two UV-LEDs (SC+(2x)LED) are considered (see spectra in Figure 9).

discussion in section 2), applying a single UV-LED in addition to the shaped supercontinuum spectrum yields most promising results at reasonable experimental effort.

The presumably most relevant result of the presented simulation is related to the uncertainties retrieved for an assumed simulator imitating the AM1.5G and its moving average perfectly (most right boxes and data points). Naturally, the MM values are (approximately) unity for both cases. However, even for these spectral distributions there is a quite significant expanded mismatch uncertainty of up to 2% (k=2) when considering an unfavorably poor spectral match of reference and test cell (outliers in Figure 8). If reference and test cell spectral responsivities match well, substantially lower expanded uncertainties of well below 0.1% are achieved (see Figure 6 or bottom data points in Figure 8). Thus, although supercontinuum sources are very promising for achieving nearly perfect simulator spectra, making any spectral correction redundant, spectrally well matching reference cells are still required for achieving low measurement uncertainties.

Moreover, and in agreement with above presented results, it might be beneficial to mimic the moving average of the AM1.5G instead of depicting all distinct features of the AM1.5G when shaping an arbitrary spectrum from supercontinuum radiation. It has to be emphasized again, that this conclusion strongly relates to the given accuracy in spectral irradiance measurement.

4 MEASUREMENTS

After the detailed discussion of the capabilities of supercontinuum radiation regarding spectral mismatch and uncertainty in spectral mismatch, some first results conducted with the measurement setup presented in Figure 1 will be given in this section.

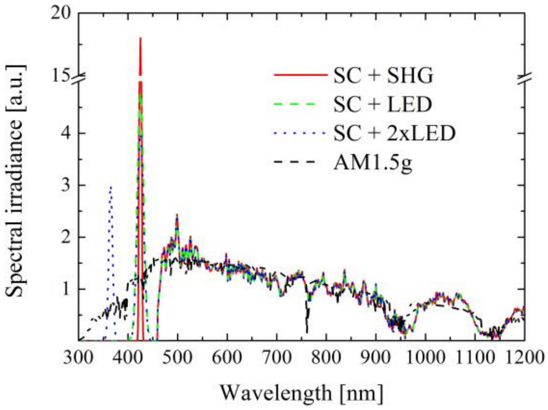

Figure 9: Spectral irradiance for supercontinuum (SC) plus second harmonic (SHG) or UV-LED radiation (LED) at 425 nm as well as SC plus two UV-LEDs at 425 and 365 nm. For comparison the standard solar spectrum AM1.5G is shown as black dashed line.

As concluded in section 3.3 the currently available shaped supercontinuum radiation might be readily applied for short circuit current measurements of Si cells using a Si reference cell. For experimental demonstration of this conclusion short circuit currents of two linear 2x2 cm^2 Si cells have been measured. The results displayed in Table I demonstrate the excellent agreement of the I_{SC} measured with the new approach and the I_{SC} computed from the cell’s SR that deviate by less than 1 ppm. It is noteworthy that the currently applied optics are limiting the setup to cell areas smaller than 4x4 cm^2. In near future, a refined optical setup will allow large area cell measurements of up to 18x18 cm^2.

5 CONCLUSIONS

Supercontinuum radiation sources show the potential for developing solar simulators imitating standard solar spectra at unprecedented spectral match. In this paper, this potential has been assessed in terms of spectral mismatch correction factors and their uncertainties.

Although spectral mismatch factors approach unity using spectrally shaped supercontinuum radiation, thereby making any spectral mismatch corrections redundant, the remaining necessity of applying spectrally well matched reference solar cells for achieving lowest measurement uncertainties has been demonstrated. Likewise the uncertainty analysis has revealed that imitating a standard solar spectrum in a less detail-rich manner (e.g. its moving average) results in lower measurement uncertainties as compared to a perfect replication of the standard spectrum. This, not necessarily intuitive, result might be of practical importance for the further development of supercontinuum based solar simulators as it eases requirements on the resolution of

Cell	MM	u_{MM} [%]	I_{SC} [mA]		Dev. [%]
			SC	DSR	
Si A	1.021	0.16	143.98	144.06	0.05
Si B	1.004	0.12	129.17	129.28	0.08

Table I: Comparison of I_{SC} from differential measurement with supercontinuum radiation to I_{SC} from integrating the spectral responsivity of the test cells.

the spectral shaping setups while simultaneously reducing the measurement uncertainty. However, it has to be emphasized again that for a more accurate spectral irradiance measurement as assumed in the presented simulations, the detail-rich imitation of a standard solar spectrum approaches the uncertainties of replicating its moving average.

Although supercontinuum radiation sources are promising for the development of next generation solar simulators, nowadays major drawback of supercontinuum lasers results from their insufficient optical power being for 1 sun illumination of a large area industrial solar cell. Therefore, a differential short circuit current measurement approach has been presented in this paper. Chopping the spectrally shaped supercontinuum radiation and measuring the induced differential current gain of the device under yields fast and accurate measurements of solar cell short circuit currents. It has been demonstrated that a single differential measurement using this approach yields precise short circuit currents for linear solar cells. Furthermore, the method might be applied to nonlinear cells as well. For this (and in analogy to the WLR-method presented in [6]), the differential current response of the device under test to the chopped supercontinuum is measured at various bias irradiation levels. As the supercontinuum radiation resembles the standard solar spectrum, the device’s current response can be used directly to determine the devices’ short circuit current under standard testing conditions without additional spectral mismatch corrections.

After this successful application of our experimental setup for short circuit current measurements of linear and nonlinear solar cells we are currently working on a refined control of spectral shaping. In addition, we plan to replace the current PCF by an improved one that generates a supercontinuum covering the entire relevant spectral range and is expected to be available in the near future [9]. In the meantime, we will add a single UV-LED to our setup for achieving spectral mismatch factors that are close to unity even for non-Si solar cells and less favorable combinations of reference and test cell.

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