ADVANCED SPECTRAL RESPONSE MEASUREMENT WITH WIDE RANGE TUNABLE LASER SYSTEM

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ABSTRACT: The measurement uncertainty in a production line depends on the reference cell uncertainty and has a high economic impact. Therefore, there is a steady development in calibration setups and procedures aiming for a further reduction of measurement uncertainty. At the Fraunhofer ISE CalLab PV Cells we develop a new, highly sophisticated spectral response measurement facility based on wide-range tunable ultrashort laser pulses that will improve our calibration chain and supply references with lower measurement uncertainty. In this paper we present our development of this new setup and discuss our approaches to tackle the specific requirements arising from the special characteristics of ultrashort pulses regarding their applicability in spectral response measurements. We demonstrate the functionality of our new Laser-DSR setup by showing first results and comparing them to state-of-the-art calibration setups. Further, we exemplify the advantages of the gap-free wavelength tuning by a temperature coefficient measurement of CdTe. Finally, we discuss the expected improvements in measurement uncertainty and conclude the current status of our setup development.

Keywords: Calibration, Characterization, Spectral Response

1 INTRODUCTION

Solar cells are sold accordingly to their peak power measured at standard test conditions (STC, IEC60904-3). Thus measurement uncertainty has a high economic impact. The main reduction of the measurement uncertainty in a production line can be achieved by the reduction of the reference cell uncertainty. Therefore, highly sophisticated measurement setups and procedures are needed for the transfer from national standards to industrial solar cells.

One of these procedures is the differential spectral response (DSR) measurement that is being applied successfully for calibration of solar cells' short circuit current (I_{SC}) and spectral responses (*SR*) [1]. In DSR-measurements chopped monochromatic radiation induces an I_{SC} gain that is measured by lock-in techniques while simultaneously illuminating the test cell with bias irradiation. Currently, spectrally filtered white light sources are predominantly used for generation of the chopped monochromatic light. These light sources are rather limited in available spectral power which is why a further reduction of measurement uncertainties, mainly arising from spatial inhomogeneity and spectral bandwidth, is unfeasible.

One way to overcome this limitation is to exploit the higher spectral power of laser radiation. Whereas continuous wave lasers are rather limited in spectral tunability, a promising approach to combine the high spectral power of laser radiation with the required wide-range wavelength tunability is achieved in the combination of ultrashort pulse lasers and nonlinear optical effects [2].

Therefore, a new Laser-DSR facility is being developed at the Fraunhofer CalLab PV Cells based on ultrashort laser pulses and nonlinear optical effects. In this paper we will present our realization of the Laser-DSR setup and specify our solution to tackle the special characteristics of ultrashort laser pulses as compared to white light sources that require spatial, spectral and temporal conditioning of the radiation to make it applicable for DSR-measurements. We will show first *SR* measurements and comparisons to *SR*s measured at state-of-the-art calibration facilities and demonstrate the advantages of the new DSR-setup with temperature-dependent measurements. Finally, we will discuss the expected improvements in measurement uncertainties and give an outlook on the remaining development stages of the new facility.

2 NEW LASER-DSR FACILITY

2.1 Ultrashort pulse laser system

The new Laser-DSR facility is schematically shown in Fig. 1. A tunable titanium-sapphire (Ti:Sa) laser (MaiTai/Newport Spectra-Physics) is used as main laser oscillator, emitting ultrashort pulses of approximately 100 fs duration in the spectral range from 690 nm to 1040 nm. Subsequently, the ultrashort pulses of the Ti:Sa are either directed to an optical parametric oscillator (OPO; Inspire/Newport Spectra-Physics) for generation of signal and idler radiation in the spectral ranges between 490 nm to 750 nm and 900 nm to 2500 nm, respectively, or divided at a beam splitter for a partial direct use and a partial generation of the second or third harmonic (SHG: 345 nm to 520 nm; THG: 230 nm to 347 nm; HarmoniXX/APE). Thus, the ultrashort pulse laser system provides gap-free wavelength tuning from 230 nm to 2500 nm.

The average optical output power over wavelength is shown in Fig. 2 and compared to the optical power of the currently used lamp-based DSR-setup. Even if the subsequent power drop by spectral and spatio-temporal

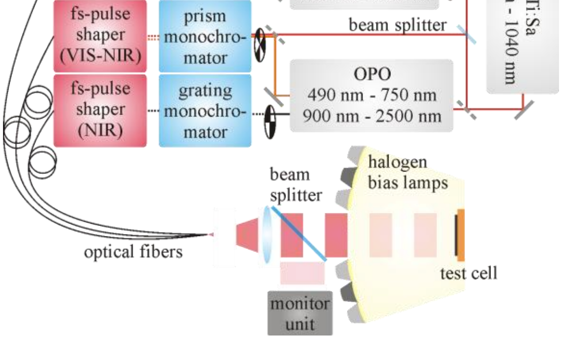

Figure 1: New Laser-DSR setup based on ultrashort pulse laser system

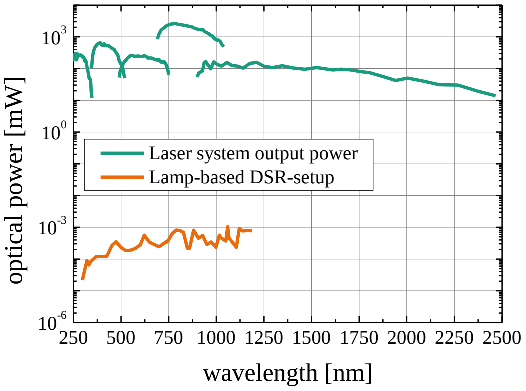

Figure 2: Output power of ultrashort pulse laser system and state-of-the-art lamp-based DSR-setup [3]

laser beam shaping is taken into account, the output power of the new DSR-facility outperforms the lamp-based system by a factor of 1,000 to 10,000. Furthermore, the available spectral range is considerably extended.

Another notably advantage of the new DSR-facility is the availability of two monochromatic wavelengths at the same time: either signal and idler radiation of the OPO *or* Ti:Sa and SHG/THG radiation are available which enables DSR-measurements at two wavelengths simultaneously and, thus, reduces the overall measurement time. In order to make the so-called dual-reference measurements feasible, idler and SHG/THG radiation are chopped at the same frequency, whereas the signal and Ti:Sa radiation are chopped at a different frequency so that the lock-in amplifiers can distinguish between both wavelength-dependent contributions to the I_{SC}. Fully automated beam routing allows for convenient switching to single-reference mode if the potentially undesired second wavelength does have any impact on the measurement result. Since the optical power of the Ti:Sa laser is divided at the beam splitter, implementation of dual-reference configuration incorporates a slight decrease of available optical power. However, an appropriate choice of the beam splitter's division ratio enables assignment of the main power loss to the actually much more intense Ti:Sa radiation. This rather leads to a balancing of optical power over all wavelengths than to a power loss.

2.2 Spectral shaping of ultrashort pulses

The ultrashort temporal duration of the laser pulses enables extremely high pulse peak powers and is, therefore, an intrinsic necessity for efficient generation of the desired wavelengths by nonlinear optical effects. However, the temporal duration is also accompanied by significant spectral bandwidths increasing with the center wavelength of the radiation (~1 nm to >40 nm). Furthermore, leaking radiation from the fundamental or pumping wavelengths is present to some degree. For a reduction of spectral bandwidth and blocking of leakage radiation filters and monochromators are used in the new Laser-DSR facility (see blue boxes in Fig. 1).

Owing to their short wavelengths the spectral bandwidth of SHG/THG radiation is below 5 nm and no further bandwidth reduction is necessary. A combination of bandpass filters is used to efficiently block the leaking Ti:Sa (and SHG) radiation.

The Ti:Sa radiation itself and the signal radiation from the OPO are combined and routed to a purpose-built prism monochromator, whereas the idler radiation is spectrally shaped by a commercial grating monochromator. Thus, the advantages of prism and grating monochromators regarding the specific spectral ranges are exploited ensuring maximum transmission of optical power at high spectral resolutions. The blocking of leakage radiation is readily available in both monochromators owing to the intrinsic monochromatic nature of both desired and leakage radiation.

In day-to-day operation the spectral bandwidth over all wavelengths will be below 5 nm. However, for wavelengths larger 500 nm the spectral shaping components enable a bandwidth reduction to below 2-3 nm if higher spectral resolution is required.

2.3 Spatio-temporal shaping of ultrashort pulses

Besides the necessity of spectral shaping the ultrashort laser pulses need to be conditioned in time and space to make them applicable for DSR-measurements. On the one hand the pulses are linearly polarized and have a spatially Gaussian intensity profile and on the other their pulse durations cause extremely high peak powers of up to 300 kW. Coherence and polarization might cause measurement artefacts by interference and polarization dependent effects, a Gaussian spatial profile, unless strongly widened, is rather inhomogeneous and high peak powers might lead to undesired nonlinear effects in the test cells.

Multimode optical fibers are promising tools to tackle this threefold problem in a single monolithic optical component. Modal dispersion in the fibers leads to propagation delays between different modes and mode coupling ensures a statistical power distribution to all propagating fiber modes. Depending on the fiber characteristics (e.g. material and length) the ultrashort laser pulses will be temporally broadened to a significant degree [4, 5]. Additionally, mode coupling causes randomization of polarization states and spatial intensity distribution.

For the special requirements of our setup a tailored multimode fiber device that completely depolarizes, as well as spatially and temporally averages the ultrashort laser pulses has been successfully designed, built and characterized. However, the final concept is still under development. In the meantime, single multimode optical fibers (see red boxes in Fig. 1) with 100 m length are used to transform the Gaussian input into a top-hat intensity profile at the fiber end facet, depolarize the radiation and broaden the pulses to about 2 ns pulse duration (which accompanies a reduction of pulse peak power by a factor of 10,000 to 20,000).

The three optical fiber devices are merged at their distinct end and their end facets are imaged onto the measurement plane (schematically shown in Fig. 1). The imaging system is surrounded by halogen lamps of two different types used for bias illumination of the devices under test. The two different types are used for spectrally matching the bias illumination to the properties of reference spectra or device characteristics.

A beam splitter is used to direct a portion of the beam to a monitor unit, tracking the current monochromatic irradiation intensity and compensating for possible fluctuations of the laser power.

3 FIRST SPECTRAL RESPONSE MEASUREMENTS WITH LASER-DSR FACILITY

In Fig. 3 the *SR*s of two WPVS reference solar cells are shown. The green curves are the reference measurements from the lamp-based DSR-setup used for calibration of solar cells at Fraunhofer ISE CalLab. The data points are obtained from the new Laser-DSR facility in single-reference and dual-reference configuration, respectively. It is noteworthy that error bars related to the monitor-corrected laser intensity fluctuations are included in this graph. The yet to be finally designed optical configuration induces spatial inhomogeneity in the measurement plane that has been corrected. Combined with comparably low optical intensity at wavelengths below 380 nm, that is caused by the limited transmission of the preliminary UV-VIS multimode fiber at these wavelengths, the limited accuracy of inhomogeneity correction leads to apparent deviations in the spectral response measurements.

However, even at this stage of facility development the reference *SR*s of the Lamp-DSR setup are reproduced very well by the Laser-DSR measurement. In fact, from 400 nm up to 890 nm for the GaAs cell and up to 1150 nm for the Si cell, the relative deviation of the *SR* with respect to the reference data is smaller than 1.5 %. The increasing deviations for longer wavelengths (above 890 nm or 1150 nm, respectively) can be attributed to the much higher spectral resolution of the Laser-DSR setup as compared to the reference data from the Lamp-DSR facility and interpolating errors. The deviations in I_{SC} are below 0.28 % for both Si solar cell measurements and 0.46 % for the GaAs solar cell.

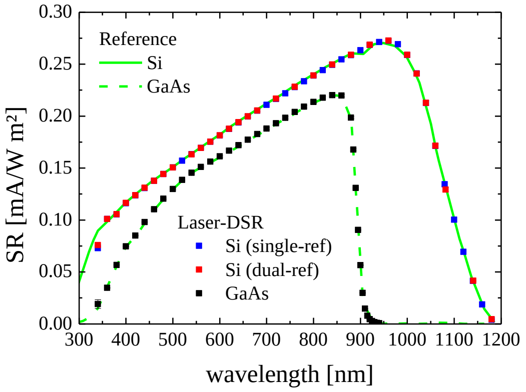

Figure 3: Spectral responses of WPVS reference solar cells measured at lamp-based DSR and Laser-DSR (single- and dual-reference configuration)

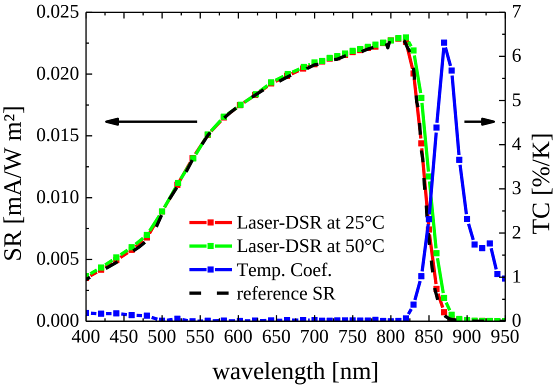

Figure 4: Spectral response of CdTe at 25°C and 50°C as well as temperature coefficient measured with Laser-DSR facility

Furthermore, the *SR* deviations between single-reference and dual-reference configuration are below 0.31 % in the spectral range from 360 nm to 1140 nm providing evidence for the very good accordance of both measurements and reliability of the dual-reference configuration.

Besides the ability of dual-reference measurements, the increased spectral power and reduced spectral bandwidths of the Laser-DSR facility enables measurements at arbitrary wavelengths so that regions of interest can be measured at significantly higher spectral resolutions. In Fig. 4 the temperature-dependent band edge shift of CdTe, its temperature coefficient and the reference *SR* of the respective cell are exemplarily shown.

Again the good agreement of reference *SR* and Laser-DSR measurement (at 25°C) can be observed. The temperature-dependent shift of the band edge is illustrated by comparison of the green and red curve as well as the deduced temperature coefficient of this cell. The high spectral resolution of the new facility allows for very detailed spectral analysis of such cell characteristics.

4 IMPROVEMENT IN MEASUREMENT UNCERTAINTIES

Apart from the presented advantages of the new Laser-DSR facility comprising increased measurement speed as well as spectral range and resolution, the higher spectral power as compared to lamp-based DSR setups can be used for a significant reduction of measurement uncertainties.

The major improvement of measurement uncertainties is related to the spatially homogeneous multimode fiber output that allows for an enormous improvement of field homogeneity in the measurement plane. First measurements suggest that this results in a reduction of the corresponding uncertainty by a factor of more than 4.

Furthermore, the Laser-DSR facility provides spectral bandwidths below 5 nm in day-to-day operation, which is less than half of the bandwidth obtained with the lamp-based DSR-setup and reduces the corresponding measurement uncertainty by a factor of 2. At wavelengths larger than 500 nm, when the prism or grating monochromator are used, even lower spectral bandwidths and corresponding measurement uncertainties are readily available.

Another significant improvement of measurement uncertainties arises from the new optical concept and the fact that the light is chopped before it enters the multimode optical fibers, where it is mixed to become a spatially homogeneous distribution. Owing to the small beam size at the chopper wheels, phase errors become virtually zero. Likewise, blocking uncertainties from remaining wavelengths outside of the desired spectral bandwidth are as well virtually zero, since the laser emits at specific wavelengths and leaking radiation from higher harmonics or pump radiation are eliminated by monochromators (or filters, respectively).

Finally, the divergence of the Laser-DSR facility in its final optical configuration is expected to be less than half of the divergence of the lamp-based DSR-setup, resulting in a reduction of the corresponding measurement uncertainty by more than a factor of 2.

The mentioned reductions of the individual uncertainty contributions will result in a significant reduction of the overall measurement uncertainty. A detailed analysis of the facility's measurement uncertainty will be given in a later publication as soon as the remaining components of the facility (monitor unit, fiber devices for ultrashort pulse shaping and final optical setup for imaging the fiber output to the measurement plane) are implemented.

5 CONCLUSIONS

We presented our new development of a Laser-DSR facility based on ultrashort laser pulses and nonlinear optical effects. The setup enables gap-free *SR* measurements from 230 nm to 2500 nm and outperforms the currently used lamp-based DSR-setup by a factor of 1,000 to 10,000 in terms of available spectral power.

We have discussed our approaches to tackle the specific requirements arising from the special characteristics of ultrashort laser pulses regarding their applicability in *SR* measurements. Further, we have shown first *SR* measurements with the Laser-DSR facility and demonstrated its functionality by comparison of these results with those from state-of-the-art measurement systems for solar cell calibration. We exemplified the advantages of gap-free wavelength tuning by a temperature coefficient measurement of a CdTe device and demonstrated the setup's ability of measuring at two monochromatic wavelengths simultaneously.

The increase in spectral power as compared to previous lamp-based setups is predominantly used for a reduction of measurement uncertainties by improved field homogeneity and reduced spectral bandwidths (overall measurement uncertainty is yet to be determined).

The Laser-DSR facility is subject of ongoing development. We expect completion of the setup and first automated measurements by the end of this year.

ACKNOWLEDGMENT

This work was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Contract Number 0325242, TF-CalLab).

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