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Development and Evaluation of the Angular Response Measurement Setup for Solar Cells

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Abstract: The paper presents the development and practical evaluation of a basic setup for measuring the angular dependence of solar cells. The main goal of this study is to verify whether it is possible to use off-the-shelf components to build a simple but reliable measurement setup which performs fast and efficient characterization of angular dependence and therefore enables quick evaluation of various design ideas, especially when it comes to evaluating reference solar cells. The proposed setup consists of a rotary stage, a source measure unit for measuring the short circuit current of a cell under test, a digital multimeter for measuring the irradiance power drift via a photodiode, a solar simulator and a computer which controls all of the instruments. The paper focuses on the mechanical construction of the setup and on the problems affecting the measurement precision, to which appropriate solutions are proposed.

Keywords: solar cells, angular response, measurement setup development, mechanical construction, measurement precision issues

Razvoj in ovrednotenje sistema za merjenje kotne odvisnosti sončnih celic

Izvleček: Sledeči članek predstavlja razvoj in praktično ovrednotenje osnovnega sistema za merjenje kotne odvisnosti sončnih celic. Poglavitni namen študije je preveriti, ali je mogoče s pomočjo splošno dostopnih komponent izdelati enostaven vendar zanesljiv merilni sistem, ki nudi hitro in učinkovito karakterizacijo kotne odvisnosti ter tako omogoča nezamudno ovrednotenje različnih načrtovalskih idej, še posebej v primeru ovrednotenja referenčnih sončnih celic. Predlagani merilni sistem sestoji iz rotacijske enote, napajalno-merilne enote za merjenje kratkostičnega toka merjene sončne celice, digitalnega multimetra za merjenje lezenja jakosti osvetlitve s pomočjo fotodiode, simulatorja sončnega obsevanja in računalnika, ki nadzoruje vse inštrumente. Članek se osredotoča na izvedbo mehanske konstrukcije merilnega sistema ter na težave povezane z merilno točnostjo in natančnostjo, za katere predlagamo ustrezne rešitve.

Ključne besede: sončne celice, kotna odvisnost, razvoj merilnega sistema, mehanska konstrukcija, merilna točnost in natančnost

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1 Introduction

Angular response of a photovoltaic module plays an important role since it is related to angle-dependent energy losses [1], which can become a crucial part of yearly performance losses due to nonstandard operating conditions [2] or due to poor orientations and tilt angles [1]. An accurate knowledge of the angular dependence is also important in predicting the performance of a PV system [2] and crucial to the precision of photovoltaic sensors [3]. All of the above makes the angular response measurement setup an essential part of the PV characterization equipment. Although many studies and experiments have been published concerning the behavior of the angular response of solar cells (e.g. [2], [1], [3]), there is usually little specific detail on constructing the actual angular response measurement setup and on the problems related with performing accurate measurements.

In this paper we present the development and practical evaluation of a basic setup for measuring the angular dependence of solar cells. The focus is put on the mechanical construction of the setup and on the problems that arise during measurements and affect the measurement precision.

2 Setup construction

2.1 Setup description

The setup is basically comprised of a Keithley 238 SMU source measure unit which is used to provide 4-wire measurements of the short circuit current of the device under test (DUT); an Agilent A34401A digital multimeter used for measuring the irradiance power drift via a reference photodiode; a Newport Oriel Class A solar simulator 93194A; a precision rotary stage OWIS DMT65 used to set the DUT's angle of incidence and a computer which controls all of the instruments via a Labview routine through GPIB (General Purpose Interface Bus) and USB interfaces. At this point of development we are interested in using such a setup only to precisely measure the shape of the angular response and to be able to make relative comparisons of responses from different solar cells, which is why the measured responses presented in the paper are typically normalized and represented by the abbreviation NR (i.e. normalized response).

2.2 Mechanical construction

The supporting construction for the DMT65 rotary stage (Figure 1 and Figure 2) was built from a medium-density fiberboard (MDF) because this material is consistent in strength and size, has stable dimensions (in normal environmental conditions it does not expand or twist like wood, especially if painted) and is easy to shape. The rotary stage was mounted so that the axis of rotation becomes horizontal. The stage was placed on a spacer which allows a 20 cm long rail (Edmund optics) to be fixed onto it. The rail allows the distance between the DUT and the line of the rotation axis to be set. Two dovetail slide carriers were then attached onto the rail. These slide carriers hold the right angle metal bracket, onto which the optical filter holder (Edmund optics) is then fixed. The filter holder is used to hold the DUT in place during the rotation. Typically, devices under test were attached to a special Plexiglas adapter which was then inserted into the filter holder. The mounting of the rotary stage onto the supporting construction was reinforced in order to minimize the bending when the DUT is inserted into the holder. The rigidity and mechanical stability of the whole setup is crucial for good repeatability and comparison of the measurements. Almost every construction part was spray painted with black matte paint in order to minimize light reflections. The rotary stage was mounted onto a tabletop that was placed on two supporting columns of modular spacers, which allow the distance between the DUT and the solar simulator lens to be varied (Figure 1).

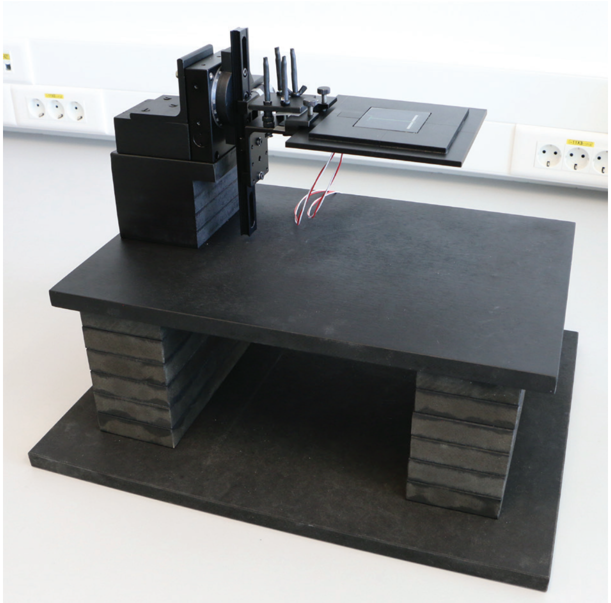

Figure 1: The rotary stage mounted onto the supporting construction. A DUT is mounted into a Plexiglas adapter which is then attached to the rotary stage through the two-screw optical filter holder.

3 Measurement precision issues

In the following, four groups of problems which, in our opinion, have important effect on measurement precision are discussed.

3.1 Mechanical and geometrical problems

3.1.1 Mounting the DUT into the setup

Firstly, it must be assured that the distance between the DUT's photosensitive area and the imaginary line of the rotation axis is as small as possible. Secondly, this imaginary line must also run so that it splits the photosensitive area into two symmetrical parts. When these two conditions are met, the average distance between the photosensitive area and the source of (imperfectly) collimated light (i.e. the solar simulator collimating lens) does not change during the rotation. If it would, this would be a source of a systematic measurement error because at some point the photosensitive area would be in average closer to the source of light than at some other point.

While the second problem of aligning the line of symmetry of the photosensitive area with the line of the rotation axis is simply a matter of proper positioning of the DUT when inserting it into the holder, the first problem of minimizing the distance between the photosensitive area and the line of the rotation axis requires additional calibration. A simple solution is possible using a laser-cut Plexiglas calibration tool (Figure 2). The calibration procedure is as follows. First, additional slide carrier is attached onto the rail so that its top face lies exactly at the axis of rotation (Figure 3). This is how we get a zero-height reference point on the rail. Then an optional spacer is put on top of this carrier, which compensates for the material that covers the photosensitive area (in our example this is glass and ethylene-vinyl acetate (EVA) laminate). At the top of this spacer comes the bottom of the calibration tool. At the same time the vertical side of the calibration tool is pressed parallel to the rail. Now the two slide carriers that attach the DUT to the rail are made loose which allows the DUT to be slid upwards to meet the horizontal side of the calibration tool (Figure 2). Since the horizontal side of the calibration tool is perpendicular to the vertical side, the height relative to the rotation axis at the bottom of the tool is now the same as at the horizontal side that is touching the top of the DUT (i.e. the glass in our case – see Figure 2). In other words, the calibration tool simply helps translate the level at its bottom over the mechanical parts that hold the DUT to the location where the DUT actually lies.

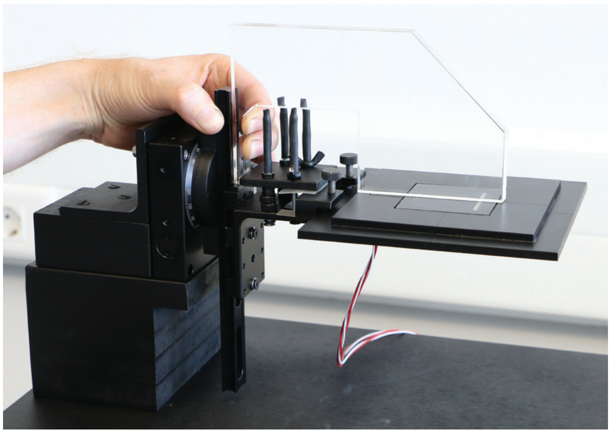

Figure 2: Calibrating the distance between the photosensitive area of the DUT and the imaginary line of the rotation axis. At the same time the tilt of the DUT relative to the holder can be minimized.

The height of the DUT on the rail is now set so that the photosensitive area that lies beneath the glass and EVA laminate is at the same height as the imaginary line of the rotation axis. The optional spacer assures that the DUT is moved slightly higher, compensating for the thickness of glass and EVA. As a matter of interest, some setups do not perform this compensation (e.g. [1]).

Typically, it is desired that the plane of the photosensitive area is parallel to the line of the rotation axis. The calibration tool can also be used to minimize the tilt of the DUT. A narrow strip of elastic material is placed between a Plexiglas DUT adapter and the filter holder. If this strip is placed at the right location, then we can control the tilt of the DUT by increasing or decreasing the force provided by the two fastening screws in the filter holder. The elastic strip contracts under the pressure which causes the DUT adapter to tilt upwards or downwards, depending on the location of the strip relative to the screws. The tilt of the DUT is minimized when the face of the DUT is parallel to the horizontal side of the calibration tool (Figure 2). But in some situations it is useful to provide a small amount of tilt as we will demonstrate later.

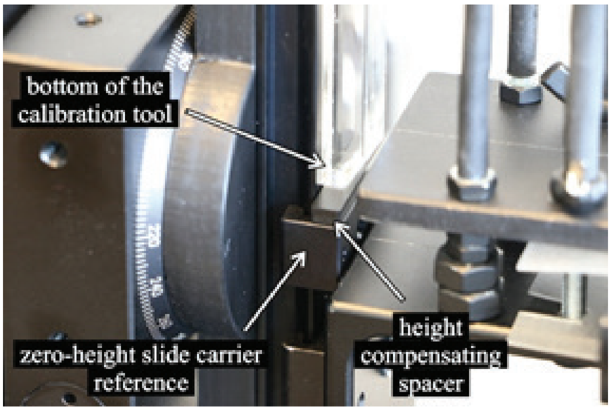

Figure 3: Calibrating the distance between the photosensitive area of the DUT and the imaginary line of the rotation axis – a detail.

3.1.2 Initial position problem

When the DUT is fixed into the setup, the measurements can begin. But in order to provide measurements with high repeatability which can be used in quality comparison analyses, the *same* initial position for all measurements must be defined. In order to demonstrate the importance in the precision and repeatability of the initial point, let us study the plot in Figure 4. The plot shows a comparison of a short circuit current response for two similar reference cells: one with white back sheet and the other with black back sheet. From the short circuit current ratio (solid line) one would conclude that the first cell has better response at high angles of incidence α than the second cell. Now, if the initial point of the measurement for the second DUT is offset by 1° relative to the original initial point (dashed line), a completely different conclusion is derived. The angular response measurements are very sensitive to errors in mechanical positioning, especially at high angles [4] due to the increased slope of the response.

The initial position problem is not as simple as it seems at first sight. For instance, if we decide to use a fixed absolute position of our rotary stage as the initial point, then as soon as the setup (or DUT) is moved from its current location, the actual orientation of the setup (and DUT) relative to the beam of light emanating from the solar simulator may change. This means that the irradiance at the initial point becomes sensitive to the orientation and position of the setup (and DUT), which is a nuisance if precise measurements with high repeatability are required. Besides, the precision and repeatability of the absolute home reference point of the rotary stage may also be problematic, as it proved in our case.

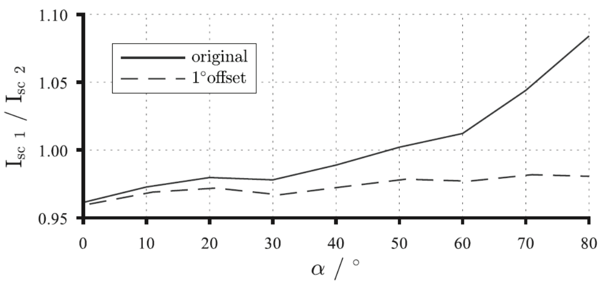

Figure 4: The effect of the precision of the initial point of a measurement. A relatively small offset in the initial point position can cause a completely different measurement conclusion when comparing short circuit responses of two different solar cells.

From the thought experiment above one can already sense the solution to this problem. The initial point must be defined relative to the beam of light provided by the solar simulator. If before each measurement the rotary stage is positioned so that the light hits the DUT at zero angle of incidence, i.e. $\alpha = 0° \equiv \alpha_0$, then the repeatability of the measurement results is very much improved and does not depend on the exactness of the position and orientation of the setup and DUT.

The process of finding the position of the rotary stage where the zero angle of incidence occurs at DUT can be automated in our measurement setup. We developed two algorithms to calibrate the α_0 point. The first algorithm is based on a fact that at the zero angle of incidence a DUT provides the maximal response. The algorithm is therefore designed to iteratively search for the maximal response in a given range of rotational positions by sampling the DUT response with a specified resolution. At each next iteration, the range is narrowed and the resolution increased. The algorithm stops at the prescribed minimal resolution and the point of maximal response is declared the zero incidence angle α_0 In order to decrease the effect of the measurement noise, the measurement samples can be smoothed by filtering and the algorithm then works with the smoothed samples. The problem with this approach is that the typical response of a DUT has the shape of a cosine function [1], which means that the maximum is very unpronounced, i.e. the small region around the peak is very flat, which makes the detection of the peak location difficult and at the same time the effect of measurement noise is increased. Nevertheless, the algorithm has still proved useful in most cases, especially if averaging of the measurement samples is increased.

The second algorithm we devised takes into account the problem of the unpronounced maximum and searches for the α_0 point indirectly. The algorithm is based on a fact that in most cases the angular response of a solar cell is very much symmetrical [1] in a region near the α_0 point. Therefore, the α_0 point is determined on a criterion that for symmetrical angles $\pm\alpha$ around the a_0 point the measurement samples have the maximal symmetry. The idea is demonstrated in Figure 5. Three measurement sets are made with samples 15° apart. Each next measurement set is offset by $\Delta\alpha$ from the previous set. The central measurement samples of each set lie around the actual zero angle of incidence point $\alpha = 0 = \alpha_0$. Now for each of the sets the symmetry around the central sample is checked. For the first set we can observe that samples left of the central point (negative α) have smaller measured values than their symmetrical counterparts on the right side of the central point (positive α).

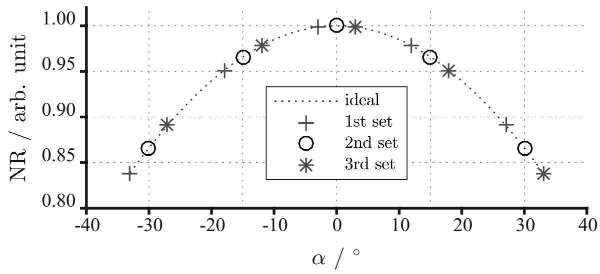

Figure 5: Calibrating the zero angle of incidence point α_0 by maximizing the symmetry of the samples around the α_0 point.

Obviously, there is an asymmetry to this set and we can conclude that the central point of the set does not lie in the zero angle of incidence point. Similar is true for the third measurement set, where the situation is turned around. In case of the second measurement set, at symmetrical angles around the central point we get symmetrical measurement samples, which indicates that the central point of the second set lies in the α_0 point. The zero incidence angle is thus determined indirectly via the symmetry criterion. The algorithm proved to be much more sensitive with a much more pronounced maximum of the criterion function, which results in a high repeatability of the calibration results. The resolution of this search algorithm is determined by the offset between the sequential measurement sets $\Delta\alpha$. In our experience, the $\Delta\alpha = 0{,}2°$ proved to be a practical value for the offset.

We performed a repeatability test for the second algorithm in the following way: a reference solar cell was mounted into the setup and then the calibration algorithm was run 15 times. The absolute position of the rotary stage (i.e. the absolute offset of the stage) where the α_0 point was detected was then recorded and used to plot a histogram in Figure 6. Obviously, the repeatability of the zero angle of incidence point is quite high, especially if the averaging of the measurement samples is increased.

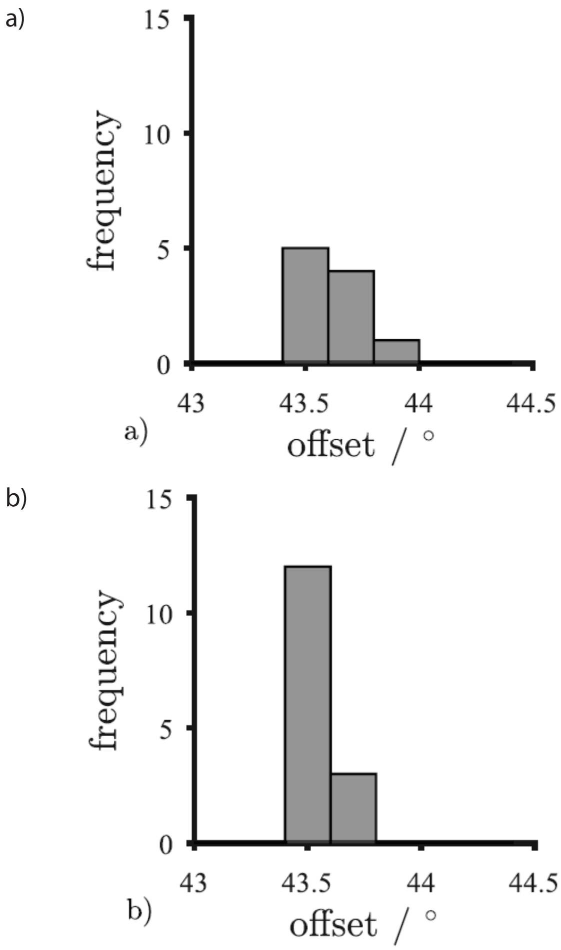

Figure 6: A repeatability test for the calibration of the zero angle of incidence point α_0. In case of b), the averaging of the measurement samples was increased. The resolution of the calibration was $\Delta\alpha = 0{,}2°$.

The obvious drawback of the second algorithm is that it can be used only in cases where the expected response is fairly symmetrical. Luckily, this practically holds true in many cases. In cases of asymmetrical responses, the first algorithm can be used instead or both algorithms combined, using the second algorithm only on a smaller region that still displays fair symmetry.

3.2 Optical problems

The first problem that can be considered as an optical one is the problem of stray light. By stray light we mean the light that emanates from the solar simulator and reaches the DUT indirectly due to reflections from the surrounding objects. Minimizing stray light is important since it can cause large relative measurement errors at higher angles of incidence. Namely, at very high angles there is expected that less and less direct excitation light reaches the photosensitive area (at 90° no light should hit the area), so the DUT response should approach zero value. But if the stray light is present and hits the DUT, this is not the case since the stray light cannot be distinguished from the direct excitation light and its effect compensated from the measurements. In order to minimize this effect, we developed a cascade system of masks that are placed in between the solar simulator lens and a DUT with intention to shape the light beam only to the DUT and the nearby surrounding area (Figure 7). Also, the objects surrounding the setup were either moved far away or covered with a low reflectance mask (i.e. black painted plywood).

The second problem also deals with indirect light hitting the photosensitive area, but in this case the light is not reflected from the surrounding objects but from the solar simulator optics itself. These reflections are named multiple- or also double-reflections and have been studied to some degree [5, 6].

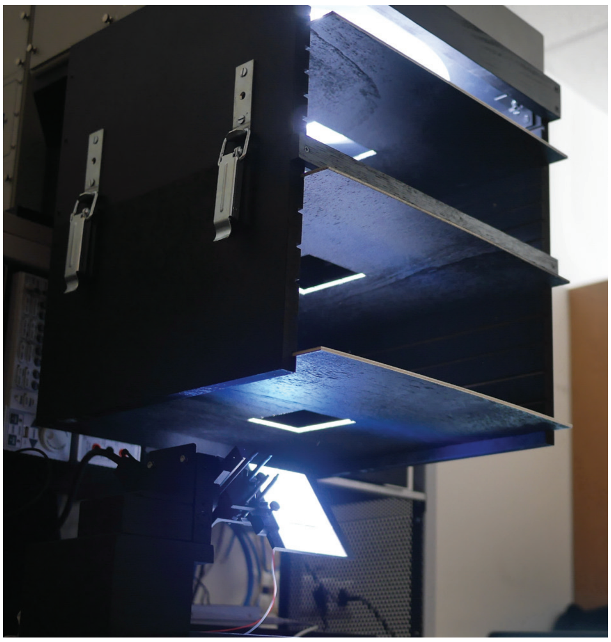

Figure 7: A cascade system of masks that limit the light beam in order to minimize the stray light errors.

Most references claim that the light is reflected back to the DUT from the collimating lens, but we have discovered that this is not a complete understanding of the problem. Namely, not just a lens, but every optical component that lies behind the lens inside the solar simulator also plays an important role in these double-reflections. These reflections cause a strong increase in DUT response near zero angle of incidence where a DUT reflects the incidence light directly back to the solar simulator. Figure 8 shows an example of this phenomenon in case of a WPVS reference cell from Fraunhofer ISE (see Figure 11a). The loss function is determined as a difference between the ideal normalized cosine response and the normalized measured value at a given angle α.

To mitigate this problem, two different approaches were used. The first solution tilts the DUT in order to direct the light reflected from the DUT away from the central axis of the collimating lens (Figure 10a) thus redirecting these reflections away from the simulator optics. A tilt of e.g. $\beta = 5°$ causes a decrease in response at zero angle of incidence α_0 for a factor of cos(5°) = 0,9962, which is about 5 per mills. This factor can be simply neglected if only normalized measurement response is required. Figure 9 shows the mitigating effect of such a solution in case of the same WPVS reference cell.

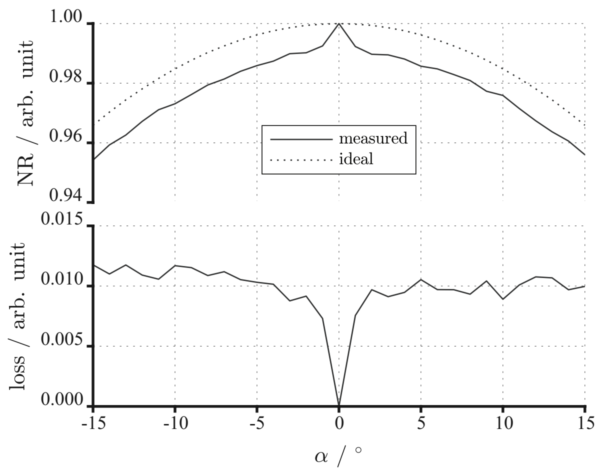

Figure 8: The effect of double-reflections in a measurement response of a WPVS reference cell. A relatively large spike occurs at zero angle of incidence.

The second solution (Figure 10b) moves the DUT away from the central line of the lens where double-reflections are most prominent and also increases the distance from the lens, which decreases the solid angle taken by the area of DUT as seen from the center of lens and therefore decreases the power density of double-reflected light. Besides, increasing the distance is also beneficial because it mitigates the effects of light beam uniformity [1]. The second solution is as effective as the first one and the solutions can, of course, be combined if needed.

To complete the picture about light hitting the DUT during measurements, we must explain how to deal with the effect of room ambient light. The procedure also applies to the case where a bias light is used to decrease the effect of non-linearity of a DUT at low illumination (as in e.g. [2]). Effect of this light can be easily compensated for in the following manner: at each angular position α the response of the DUT is first measured *before* the DUT is exposed to the solar simulator light. In this way we get the information about the ambient light intensity. Then the electronic-controlled shutter is opened and another measurement is taken, combining the response to both ambient and solar simulator light. The final measurement result is simply the difference between the second and the first measurement, since it can be assumed that the DUT provides a linear response [1]. In this case it is important that the instrument that is measuring the response has the resolution that is high enough, since we are subtracting two measurements that can be close to each other. This compensation is actually a simple variant of a lock-in measurement technique.

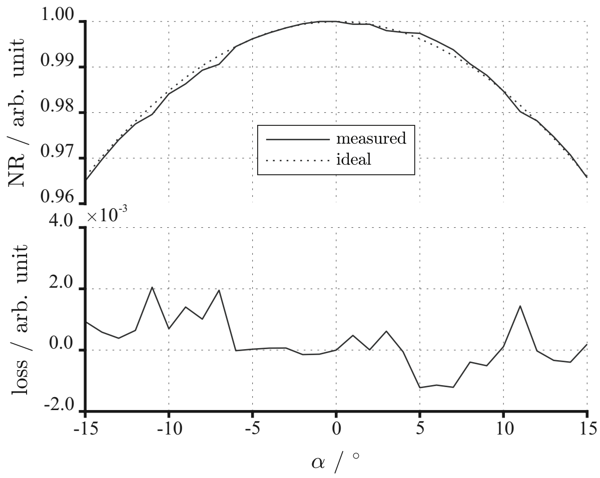

Figure 9: The effect of double-reflections in the case of a WPVS reference cell is mitigated by tilting the DUT.

The last problem concerning the optical circumstances is the problem of the solar simulator irradiance drift. This effect is compensated in the following way. At the same time when the DUT response is measured, the response of a reference PIN photodiode which measures the solar simulator irradiance intensity is also recorded. These reference irradiance measurements are then used to correct the DUT response measurements by scaling them all to the same irradiance intensity, relying on the proportionality of both DUT and PIN diode responses.

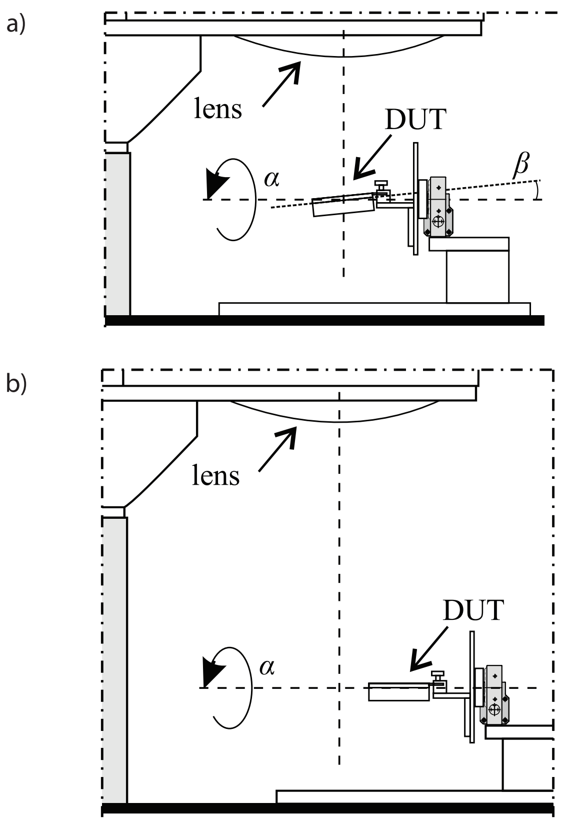

Figure 10: Two practical solutions to the double-reflections problem.

3.3 Temperature dependence

The main problem here is the rise of the DUT temperature due to the irradiation caused by the solar simulator, which affects the response of the DUT. Since our setup does not provide any kind of cooling mechanism as in [2] and since there are cases where the additional DUT temperature measurement for the temperature effect compensation is not available, the temperature problem can be addressed only by minimizing the temperature rise during the measurement. The *average* power absorbed by the DUT through irradiance $\overline{P}$ is

$$\overline{P} = \frac{t_{ON}}{t_{ON} + t_{OFF}} P, \quad (1)$$

where P is the power being absorbed by the DUT when exposed to solar simulator light and the t_{ON} and t_{OFF} are the durations of the solar simulator shutter being opened and closed, respectively. Obviously, there are two ways in decreasing the average absorbed power $\overline{P}$ during measurement and thus decreasing the temperature rise: the power of the solar simulator can be decreased, which decreases the P term, or the duty cycle of the shutter can be decreased by increasing the t_{OFF} term. The first solution can be easily achieved by decreasing the power of the solar simulator lamp or increasing the distance between the DUT and the collimating lens, which at the same time helps mitigate the problem of double-reflections (see chapter 3.2). The second solution means that the time required to perform the whole measurement gets increased, which is not that problematic.

3.4 Electrical measurements

To increase the precision of the short circuit current measurements, a 4-wire measuring technique is used. As with any other precise electronic measurement, the important source of error is the measurement noise. Since in our case we are measuring a DC signal (i.e. a constant value response), the noise can be reduced by applying the averaging technique where greater number of measurement samples is taken and then averaged. But this means that the time when the DUT is exposed to the solar simulator light t_{ON} is also increased, which causes the DUT to heat up. In order to prevent this, the duty cycle of the shutter must not be changed. Instead the number of measurement samples for a given angle α is increased using the same duty cycle. In other words, instead of making one long measurement with large t_{ON}, we make several short measurements with small t_{ON} and unchanged shutter duty cycle, which means that the average absorbed power by the DUT is not increased. As an additional benefit of such an averaging several measurements for each angle α are recorded, which means that the measurement uncertainty can be evaluated for each angle.

4 A measurement example

Angular responses of a reference cell that we developed were measured at three different stages of production: before lamination (i.e. bare), after lamination (glass and EVA on top) and when in enclosure (Figure 11 b), c) and d), respectively). The results are shown in Figure 12.

It can be clearly observed that the lamination reduces the losses at lower angles of incidence α, while the losses at higher α are increased, most probably due to the increased light reflection from the glass and due to different surface texturing [1]. The loss function of the laminated cell agrees well with the ones measured in [1]. The effect of the enclosure can also be observed, where at angles higher than about 50° the loss is increased due to the shading effect of the enclosure.

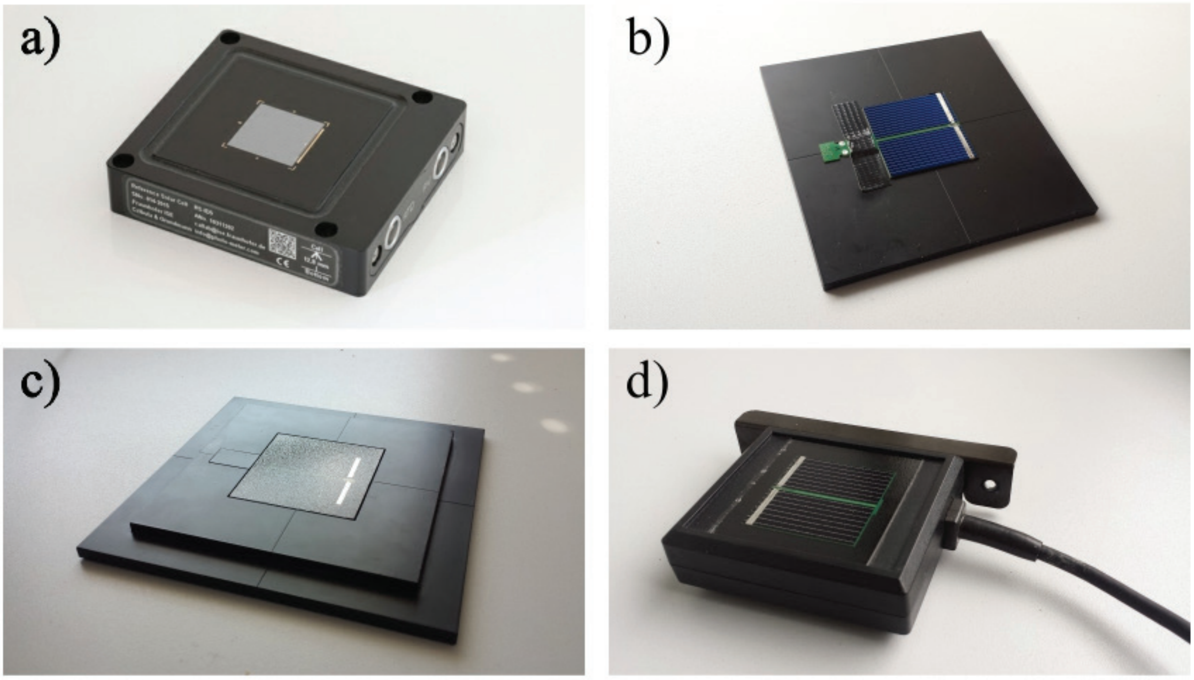

Figure 11: Devices under test: a) WPVS reference cell from Fraunhofer ISE and in-house developed mono-Si reference cells: b) non-laminated (bare), c) laminated (glass +EVA on top) and d) in-enclosure.

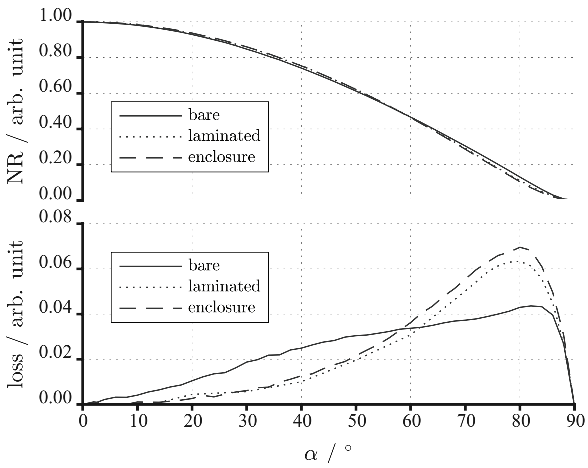

Figure 12: Normalized angular response of a mono-Si reference cell in three different stages of production.

5 Conclusion

A development of a basic setup for measuring the angular dependence of solar cells was presented. We believe that the concept of the proposed measurement setup proved successful as well as the solutions to the key problems that affect the measurement precision. The setup was used to perform a series of other measurement experiments which cannot be presented here and, to our belief, the setup proved precise with high level of repeatability being able to provide insightful results, despite its somewhat simplistic approach. In future we are planning to validate the precision of our setup by comparing our results to the results of a certified measurement laboratory.

6 Acknowledgement

We would like to thank Mizarstvo Jankovec for kindly providing the wooden building blocks required for the setup construction.

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