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Quality Manual of Solar Cell Measurements

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Symbols, Units and Abbreviations

SR	Spectral Responsivity
DMM	Digital Multimeter
DSR	Differential Spectral Responsivity
QE	Quantum Efficiency
STC	Standard Test Conditions

1.   Definition

This instruction manual describes the equipment and its operation of the measurement setup used to evaluate the differential spectral responsivity of solar cells. The cells can be monofacial or bifacial. Size of the cells can be up to 15 x 15 cm^2 and output current can be up to 10 A. The setup has been published in [1]. The manual will later be extended to cover other measurements of solar cells as well.

1.1.   Object and field of application

The spectral responsivity of a solar cell is an important parameter because it provides useful information needed for solar cell development and cell analysis. This parameter can also be used to test and evaluate the performance of individual cells, or to correct the spectral mismatch between the light sources used in the measurement and the standardized reference spectral irradiance data [2]. Since solar cells can be nonlinear proving a great challenge in SR measurement, the measurement of differential spectral responsivity under biased conditions is generally preferable.

1.2.   Spectral Responsivity of Solar Cell

The spectral responsivity of a solar cell is defined as the ratio between the photocurrent generated by the solar cell and the spectral irradiance incident on the cell. The spectral responsivity s at wavelength λ is calculated as

$$s(\lambda) = \frac{I_{sc}(\lambda)}{E(\lambda) \cdot A} = \frac{I_{sc(\lambda)}}{P(\lambda)}, \tag{1}$$

where $I_{sc}(\lambda)$ is the short-current at wavelength λ; $E(\lambda)$ is the spectral irradiance of the light source; A is the area of the cell-under-measured; and $P(\lambda)$ is the incident spectral radiant power at wavelength λ.

An ideal and a measured SR curve of a solar silicon cell are shown in Figure 1. At long wavelengths, both the ideal and the measured wavelengths are limited due to the inability of the semiconductor to absorb photons when the energy level of a photon is below the band gap. This is like the quantum efficiency curves, which are presented in Figure 2, in the long wavelength region [3, 4]. At intermediate wavelengths, the SR of the measured cell approaches that of an ideal one.

At short wavelengths, the spectral responsivity decreases unlike the square shape of QE curves because the covering glass of the solar module absorbs most of the light. If the energy of a photon is above the band gap, then this energy is not utilized by the cell and this causes the solar cell to heat up [3]. Besides, silicon has an indirect band gap, and for this reason there is not a sharp cut-off at the wavelength corresponding to the band gap [3].
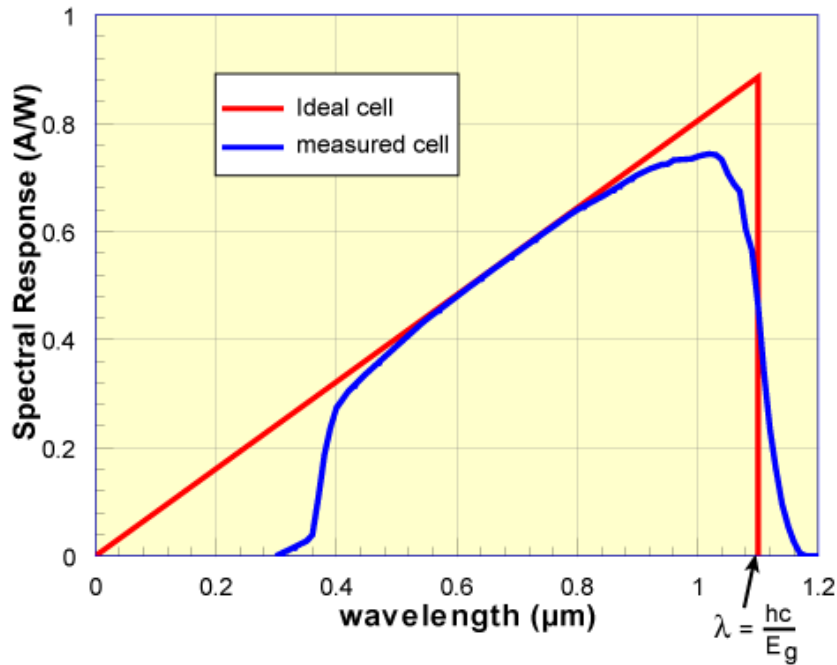
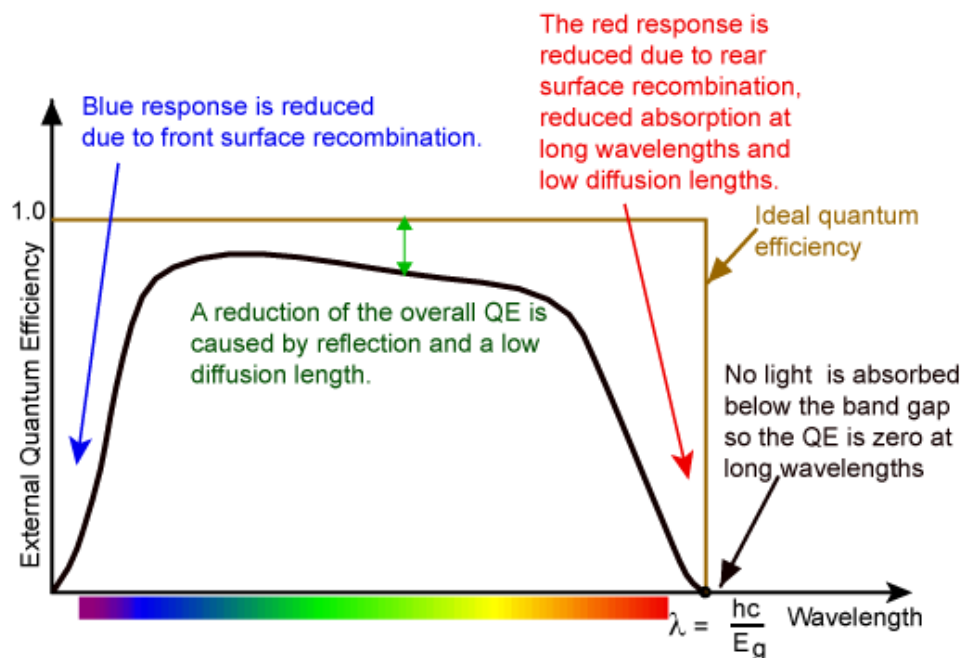Figure 1: Spectral responsivity of an ideal cell and a measured cell under glass. [3]

Figure 2: Quantum efficiency of a silicon solar cell. [4]

Measuring the SR at STC requires the employment of a monochromatic light source capable of providing similar highly intensified monochromatic irradiance as the Sun, which

is not possible for most institutes. To overcome this requirement, a pulsed monochromatic irradiation with white bias light is used to measure differential spectral responsivity instead [2, 5, 6]. Narrow-band quasi-monochromatic light pulses can be generated in several ways such as using LEDs [6], a monochromator [7], or a tuneable laser [5, 8].

The bias lights are used to ensure that the cell is operating at an excitation level equal to daylight exposure. The pulsed current signal must be separated from this continuous bias current, and a lock-in amplifier can be used for this purpose [2]. This process is required to compensate the non-linearity of the response in solar cells and to obtain comparable measurement results.

The measurements will give current produced by the solar cell and reference detector. The dark signal is also measured so that these dark signals can be subtracted from the measured currents. The measurements with solar cell and reference detector give responsivity for each effective wavelength. These effective wavelengths are calculated as

$$\lambda_{eff,i} = \int_\lambda E_i(\lambda)\lambda \ d\lambda \ / \int_\lambda E_i(\lambda) \ d\lambda, \tag{2}$$

where $E_i(\lambda)$ is the spectral irradiance ($\frac{W}{m^2}$); and λ is the wavelength (nm).

For calculating spectral responsivity, the trap current and cell current are also calculated.

Trap currents for each LED are calculated as

$$I_{calc,trap,i} = A_{trap} \int_\lambda E_i(\lambda)R_{trap}(\lambda) \ d\lambda, \tag{3}$$

where: A_{trap} is the area of the trap detector (m^2); and $R_{trap}(\lambda)$ is the reference spectral responsivity $\left(\frac{A}{W}\right)$.

Recursive analysis method is used and therefore, an initial guess $S_{cell}(\lambda) = 1 \frac{A}{W}$ is made for the spectral responsivity of the cell.

Current produced by the cell is calculated as

$$I_{calc,cell,i} = A_{cell} * \int_\lambda E_i(\lambda)S_{cell}(\lambda) \ d\lambda, \tag{4}$$

where A_{cell} is the area of the measured cell (m^2); and $S_{cell}(\lambda)$ is the spectral responsivity $\left(\frac{A}{W}\right)$.

The spectral irradiances of the LEDs are only known relatively so the values are adjusted using information of the reference detector, $I_{trap,i}$ and $I_{calc,trap,i}$.

$$S'_{cell}(\lambda) = \frac{I_{cell,i}*I_{calc,trap,i}}{I_{trap,i}*I_{calc,cell,i}} * S_{cell}(\lambda_{eff,i}), \tag{5}$$

where $I_{cell,i}$ is the measured cell current, $I_{calc,cell,i}$ is the calculated cell current, $I_{trap,i}$ is the measured trap current, and $I_{calc,trap,i}$ is the calculated trap current.

These are only the first values and the results can be improved by interpolating the obtained values $S'_{cell}(\lambda)$ and using these interpolated values as the new values for $S_{cell}(\lambda)$ in the equation (4) and for $S_{cell}(\lambda_{eff,i})$ in equation (5).

2.   Equipment

Equipment used in the measurement of DSR in solar cells consists of white bias light towers, thirty narrow-band LEDs, a LED carousel board where the LEDs are mounted, a temperature controller, a function generator, a lock-in amplifier, voltage-to-current (1 V to 100 mA) and current-to-voltage converter, a digital multimeter, a monitor detector, a source meter, a shunt resistor, an aperture, a beam splitter and two power supplies. A schematic of the measurement setup is illustrated in Figure 3. A detailed description of each equipment and its respective functionalities in the measurement setup is provided below.
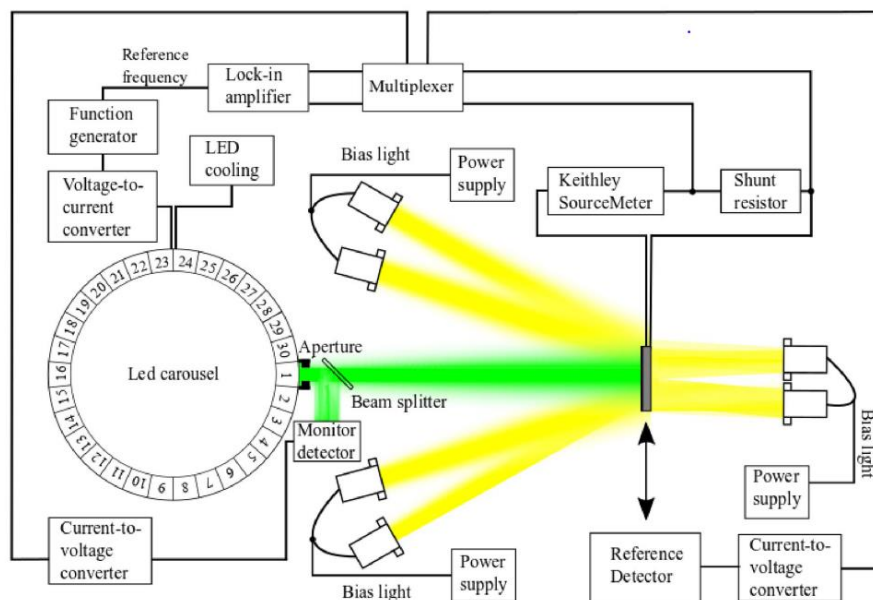
Figure 3: Schematic presentation of the differential spectral responsivity setup. Four lamp towers provide light to the front surface of the cell. Additional two lamp towers light back sides of bifacial cells. [1]

2.1.   Equipment list

Table 1. Equipment needed for DSR measurements.

Description	Quantity	Remarks/Id
LED light source		
LED carousel with 30 LEDs	1	
Temperature controller electronics	1	Wavelength electronics LFI3551
Arbitrary waveform generator	1	Agilent 33120A
Voltage to current converter	1	Self-made

Detection electronics

Shunt resistor	1	2Ω, 5 W
Source meter, I < 3 A	1	Keithley 2420
Source meter, 3 A < I < 10 A	1	Hehkulab Helios
Lock-in amplifier	1	Stanford Research Systems SR830
Multiplexer	1	Self-made

Items to measure

Reference cell 2 x 2 cm^2	1	Fraunhofer ISE, serial nr 119-2016
2-sided cell 15 x 15 cm^2	1	
Holder for the large bifacial cell	1	Self-made
Cooler plate for cells	1	
Cooler unit for the cooler plate	1	Thermo Fischer
Filter radiometer	1	FR-2007

Bias lights

Light towers equipped with 7 x 50 W halogen lamps	1 - 6	Self-made
Power supply	1 - 3	Heinzinger, etc. One power supply for two towers (700 W)

Accessories

XY-translator for scanning spatial uniformities	1	Newmark with 20 x 20 cm^2 scan area
Distance measuring laser	1	Baumer OM70
Thermal camera	1	FLIR E54

Software

Software for manually operating individual LEDs	1	LED Carousel Control.vi Version 10
Software for measuring all 30 LEDs with a cell or a filter radiometer	1	Spectral Response Measurement.vi Version 12
Software for scanning spatial uniformities	1	Single Spatial Uniformity Measurement.vi Version 10
Program to test multiplexer		Multiplexer.vi Version 1

Program for operating distance laser	1	OM70 Laser Distance Sensor Control.vi Version 1
Model for analysing measurement results	1	data_analysis_app.m
Spectral response measurement of cell against a reference cell	1	spectral_response.m

Data acquisition

Measurement computer	1	Under the table
Digital multimeter (DMM, for measuring signals from trap detector)	1	HP34401A
Current to voltage converter (for connecting trap detector to DMM)	1	e.g. MRI CVC

2.2. Description of the equipment

Two different types of light sources are used to illuminate the device under test simultaneously. These light sources are white bias light and monochromatic light sources. White bias light is provided using bias light towers in which each tower is connected in parallel to each other. These towers comprise of seven halogen lamps connected in series. These lamps utilize a special coating on the reflector preventing infrared light from reflecting forward from the lamp which means that only visible wavelengths are reflected towards the solar cell.

The bias light sources are powered using Heinzinger PTN 125-10 and Delta Elektronika SM 120-13 power supplies, each supply providing power for two bias light towers. By adjusting each power supply to provide a current of 7.6 A, the absolute irradiance of the bias lights can be set to approximately 1000 W/m^2 in order to resemble STC conditions. All halogen lamps should be switched on in this case. The bias light towers have integrated fans for cooling which are controlled by a knob in the back of the LED carousel. For monofacial solar cell, only the four light towers located near the LED carousel are used. If the bifacial cell is to be measured, it is recommended to use two additional light towers located in the back.

Thirty channels of high-power, narrow-band LEDs are used to provide the monochromatic irradiance. These LEDs are all mounted to the LED carousel. The working principles of the LED carousel is explained in more detail in [9]. The carousel is attached to a Newmark RT5-M17 rotary stage and controlled using Newmark NSC-1 Series motion controller. The LEDs have their respective temperature stabilized at $300\ K\ (25\ °C)$ by a Wavelength Electronics LFI3551 temperature controller. This is crucial as the spectral properties of LEDs are highly dependent on the junction temperature [10].

The electric current to the LEDs is supplied using Agilent 33120A signal generator and a custom voltage-to-current converter. In this setup 177 Hz square wave is used with 2 V

peak-to-peak voltage and 1 V offset. Using a pulsing frequency of 177 Hz, harmonic components influenced from the grid frequency of 50 Hz are prevented. The offset is used to ensure that no leakage current applies, and the LEDs are completely shut down during each cycle [11]. The LEDs and the carousel are automatically controlled by a custom LabVIEW software.

An adjustable aperture set in front of the LED carousel contains a tube which prevents the scattered light reflecting from the ambient. It can also be used to control the amount of irradiance passing to the sample. A beam splitter, which is a simple piece of glass reflecting about 6% of the light to a monitor detector, passes most of the light to the sample.

A silicon-based trap detector which converts the optical signal to electric current is used as a monitor detector. The monitor detector is placed after the aperture so that the changes of optical power can be monitored during measurements. It sends the signal in the form of electric current and this current signal is amplified and converted to voltage.

The small pulsed current generated by the incident monochromatic irradiance can be detected from the total photocurrent of the solar cell using a Stanford Research Systems SR830 lock-in amplifier. The measured current flows through a shunt resistor whose resistance is accurately measured using four-point measurement. Excess heat is transferred away by a metal housing attached on an aluminium. The voltage over the shunt resistor is measured using four-point measurement which is described in figure 4.
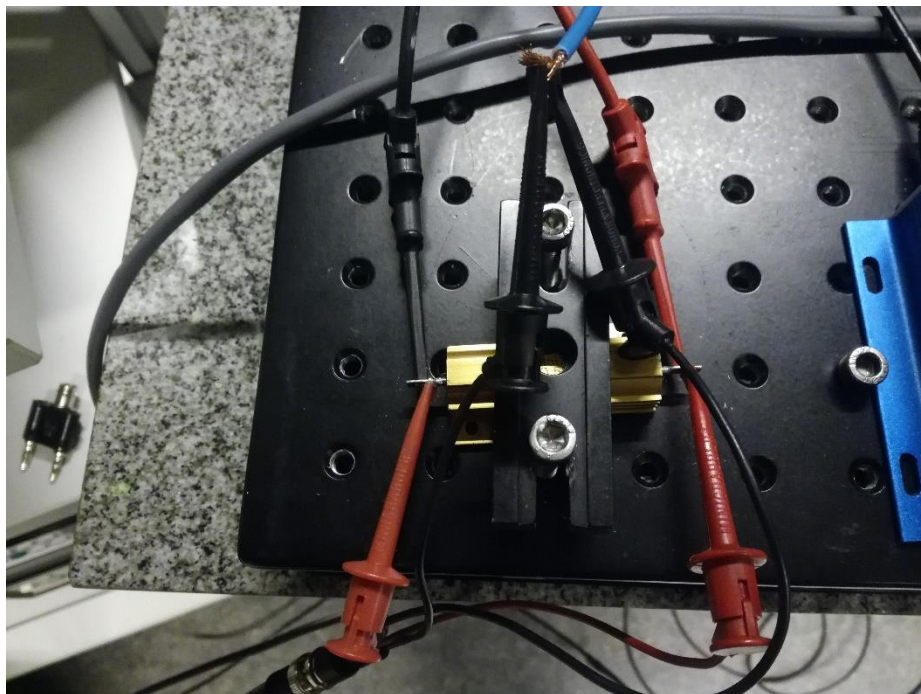

Figure 4: Measuring the voltage over the shunt resistor using four-point measurement.

In order to ensure that the current is equal to short-circuit current, a Keithley 2420 source meter is used. The source meter provides a reverse bias current to ensure that the voltage over the device under test is zero and short-circuit conditions are met. The short-circuit photocurrent flows through a shunt resistor creating a voltage which is measured by the lock-in amplifier.

2.3. Connected devices

This section briefly explains which settings should be applied and how the measurement devices should be connected.

2.3.1. Agilent 33120A Function Generator

The frequency should be set to 177 Hz (Freq, button 6).

The offset is set to 1 V (Offset, button 8) and square wave (button 2) should be selected.

The voltage is set to 2 V (Ampl, button 7).

OUTPUT is connected to the input of voltage-to-current converter (1 V to 100 mA) and SYNC is connected to the lock-in amplifier input REF IN.

Output termination has two settings, 50 Ω and high impedance. The default is 50 Ω and this setting is stored in volatile memory. It resets when power has been off or after a remote interface reset. Check that high impedance setting is selected before measurement.

How to change output termination:

1. Shift + enter
2. Choose "D: SYS MENU" with < and > buttons and press down arrow to select.
3. Change "1: OUT TERM" setting by pressing down arrow
4. Choose HIGH Z setting with < and > buttons
5. Press ENTER

2.3.2. HP 34401A multimeter

Output of voltage-to-current converter (1 V to 100 mA) is connected to input of HP 34401A multimeter. The multimeter should display approximately 0.1 AAC. The output of voltage-to-current converter also goes to the LED carousel.

2.3.3. Current-to-voltage converter

Connect monitor/trap detector to the input of current-to-voltage converter. Select pre-amp setting.

2.3.4. Multiplexer

Multiplexer has five ports (A-E). Devices can be connected to any ports and these ports are configured in the measurement software so that the correct ports are used during the measurement.

2.3.5. Lock-in amplifier SR830

The gain can be automatically selected by selecting AUTO -> Gain. The solar cell should be measured using differential measurement so setting A-B should be selected. Monitor and trap detector use setting A in the measurements. This setting can be changed in the measurement software.

The SR830 measures the single Fourier (sine) component of the signal at reference frequency. The input signal is square wave, which is composed of many sine waves at multiples of the frequency. For example, a 2 V peak to peak square wave can be expressed as

$S(t) = 1.273 \sin(\omega t) + 0.4244 \sin(3\omega t) + 0.2546 \sin(5\omega t) \ldots$

The Lock-in amplifier detects the first sine component, $1.273 \sin(\omega t)$. The measured and displayed magnitude of the signal is then $\frac{4*\sqrt{2}}{\pi*2}$ or approximately 0.9 V [12, 3-3].

2.3.6. FISE Reference Cell

2.3.6.1. Lemo connector

Lemo connector used with the reference cell is marked with reference cell label. Connector that is used with the reference cell can be also seen from figures 5 and 6.

2.3.7. Source meter Keithley 2420

First, 4-wire sense mode is selected:

1. Press CONFIG button
2. Press V button from measurement side
3. Select SENSE-MODE and press enter
4. Select 4-WIRE and press ENTER

From connection side, the source meter should be connected as depicted in figures 4 and 5. The left side (4-wire sense side) is connected to measure the voltage from solar cell. The right side (Input/Output side) is connected in series with shunt resistor. Source meter does not work properly without background lights so lights should be turned on when measuring with source meter.

In the source side, V should be selected.

In the measure side, I should be selected.

If the measurements are done with reference cell the source meter configuration is shown in figure 6. If the measurements are done with reference cell and without the source meter, the source meter should be connected to short circuit as depicted in figure 7.
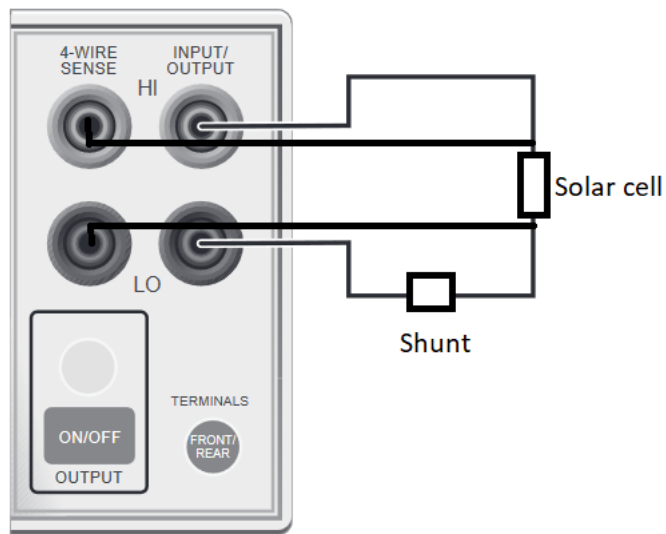
Figure 4: Source meter configuration.
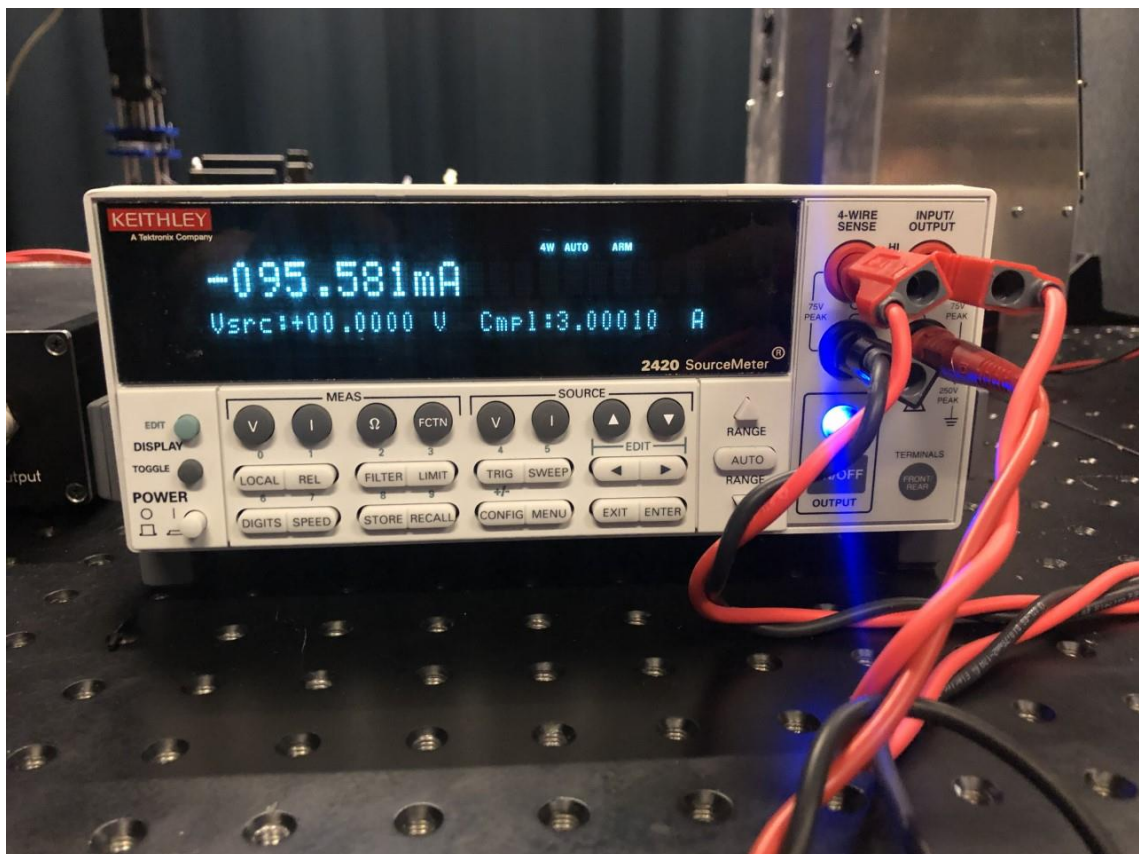
Figure 5: Source meter configuration when using source meter.
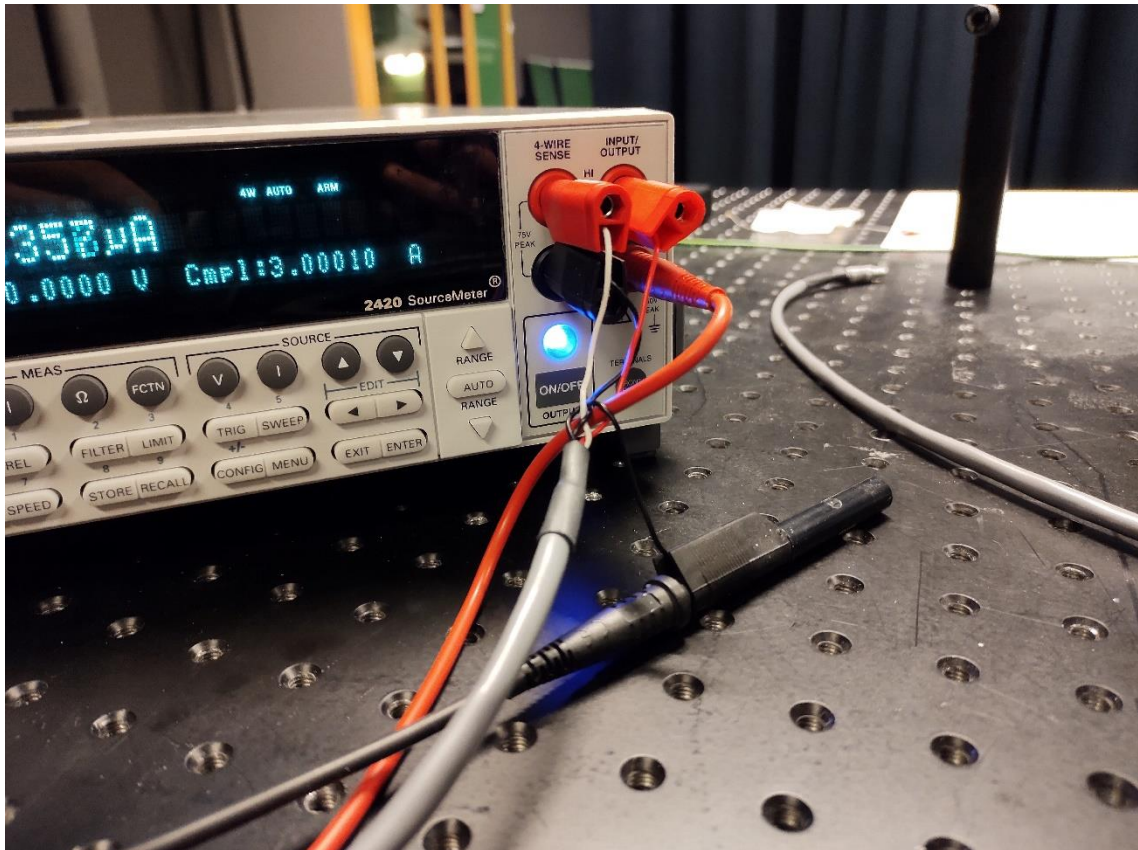
Figure 6: Source meter configuration when reference cell is used.
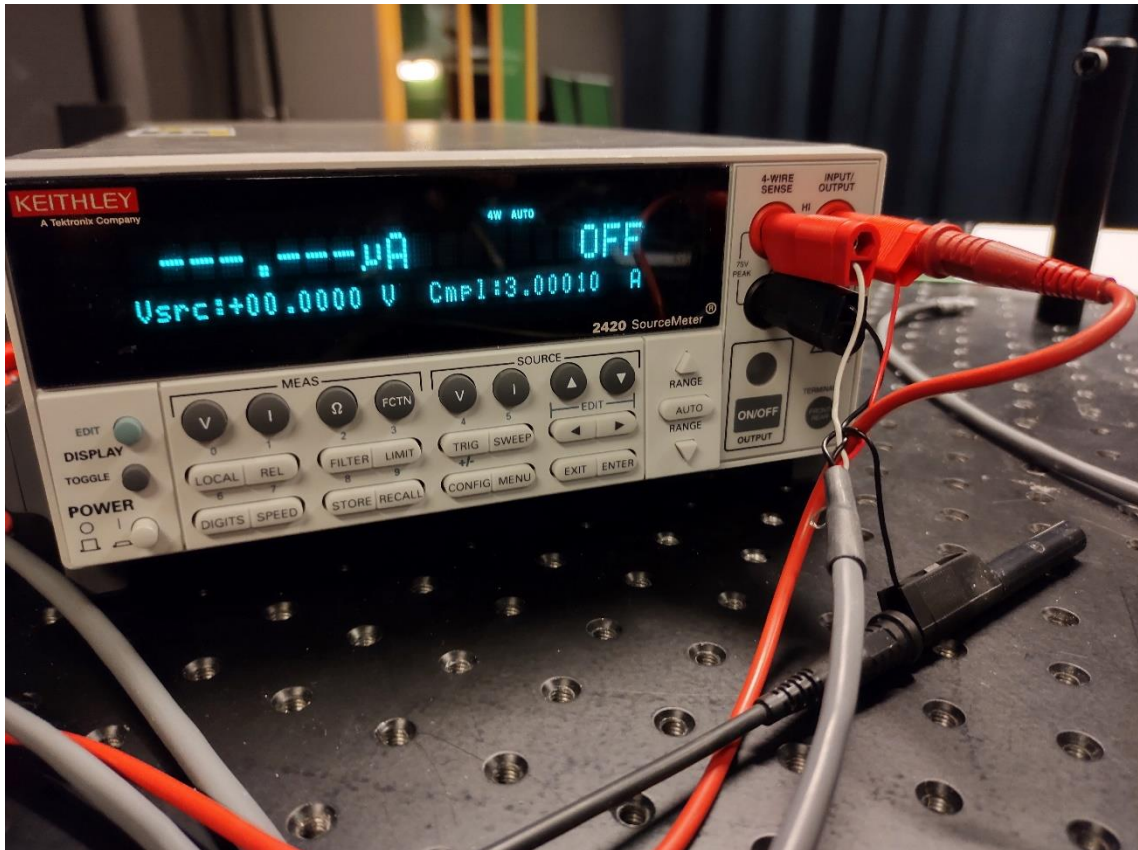
Figure 7: Source meter configuration in the case of reference cell and when source meter is not used.

2.3.8. Hehkulab Helios

Hehkulab Helios is connected as shown in Figure 8. Source terminal is connected in series with the shunt and the sense terminals are connected to measure voltage over the cell. (Connection is basically same as in Figure 5). Helios can be used either grounded of floating.

Figure 8: Hehkulab Helios connected to control the cell.

2.3.8.1. Operation in grounded mode

Helios back panel has grounding connections to the internal signal ground and the device chassis. Helios is typically grounded by connecting the chassis and GND terminals to the ground of the electricity network. This can be accomplished with a SCHUKO adapter as shown in Figure 9. Grounding should be done especially when operating in high noise environment.
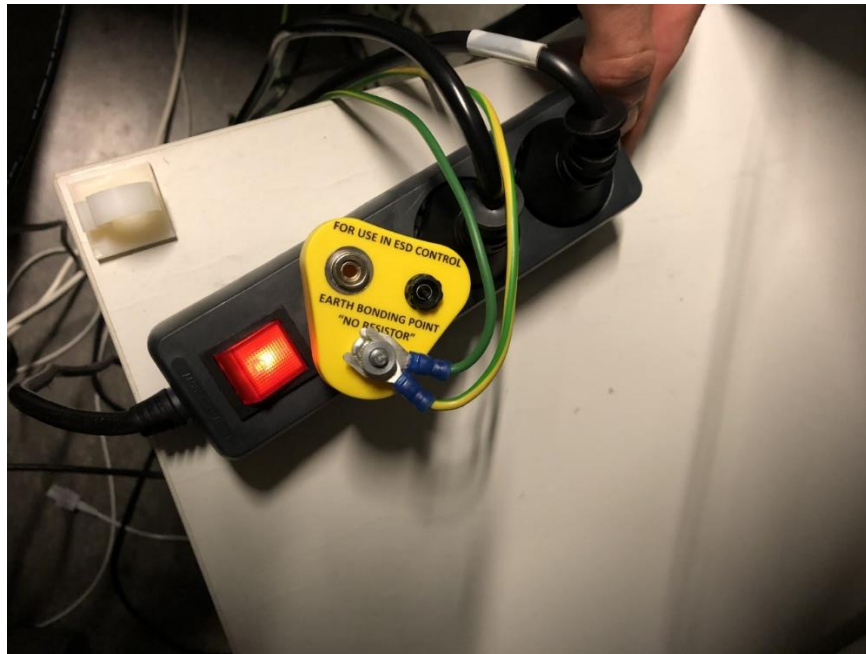
Figure 9: SCHUKO adapter

2.3.8.2. Floating

In the floating connection, chassis and GND terminals are not connected to ground. If the Helios shunt, DC output, or AC output are used with a nonfloating device, it is the best practise to not use additional signal grounding (GND terminal) in order to avoid ground loops. Chassis can be connected to common ground point.

2.3.9. OM70 distance measurement laser

The distance measurement laser is used to measure the distance between the cell and the LEDs. The distance measurement sensor can be powered with batteries (two 9V) or with a laptop charger. Manuals can be found in the following folder: \\work.org.aalto.fi\T405\MIKES-Aalto\Resources\Equipment\Baumer OM70 laser distance sensor

The driver for USB-RS485 is in the following folder: \\work.org.aalto.fi\T405\MIKES-Aalto\Resources\Software_and_drivers\USB-RS485 FTDI

2.3.10. Thermal control of the cell

To control the temperature of the cell, it is attached to the thermal control unit, a large aluminium plate with water circulation. Water connectors are connected to a Thermo Fisher water cooler unit. The temperature is set to the required temperature, typically 25 deg C as defined in standards. The temperature can be additionally or alternately monitored with the FLIR E54 thermal camera.

2.3.11. FLIR E54 thermal camera

The FLIR thermal camera is used to monitor the temperature of the solar cell. Manuals can be found in the following folder: \\work.org.aalto.fi\T405\MIKES-Aalto\Resources\Software_and_drivers\FLIR Exx E54 Thermal Camera

2.3.12. Wavelength electronics LFI3551 LED temperature controller

LED temperature is stabilized using Wavelength electronics LFI3551 temperature controller. Controller is switched on by pressing AC power switch. After that one can change temperature limits etc. When your settings are ready press Output Enable Button. More information can be found from the data sheet. Manual can be found from \\work.org.aalto.fi\T405\MIKES-Aalto\Resources\Equipment\Temperature Controllers

2.4. Drivers and settings for software

LabVIEW drivers are installed to the Labview\instr.lib directory. For example, the location of Agilent 34401 driver files and their relative directory structure is shown below:

\C:\Program Files (x86)\National Instruments\LabVIEW 2019\instr.lib\Agilent 34401\

- Examples
- Private
- Public
- Agilent 34401 Readme.html
- Agilent 34401.lvlib
- Agilent 34401.lvproj

Required drivers should be installed to this *instr.lib* folder.

2.4.1. Installing drivers using LabVIEW

Some drivers can be installed using LabVIEW which detects connected devices automatically. For example, SR830 Lock-In Amplifier drivers can be installed using LabVIEW:

1. Launch LabVIEW
2. Go to **Tools** tab >> **Instrumentation** >> **Find Instrument Drivers**
3. **Find connected** >> **sr830** >> **search and install driver sr830 Instrument Driver**
4. After installing the drivers can be found in Labview\instr.lib\SR830 directory as described in the previous section

2.4.2. Installing drivers using directory

Some of the drivers are in the following directory which can also be used to install required drivers. For example, folders which contain Agilent 3458 and Agilent 34401 drivers can be found in this directory.

\\work.org.aalto.fi\T405\Mikes-Aalto\Resources\Software_and_drivers

For example, USB driver is required to operate the Newmark NSC-1 and it is in the following directory:

\\work.org.aalto.fi\T405\MIKES-Aalto\Resources\Software_and_drivers\Delock\USB to serial(DB9)\PL2303 Drive\Vista_Win7

NI MAX (Measurement & Automation Explorer) can be used to determine connected devices and which ports they are connected to. Devices can also be renamed in NI MAX for easier recognition.

List of drivers:

- Agilent 34401
- NI-4882
- Stanford Research 830
- Agilent 33XXX Series
- Delock

2.4.3. VI file locations

The LabVIEW software requires some VI files to operate. These files are located mainly in the following directories. If LabVIEW requires the location of some VI files, these directories should be searched for the files.

\\work\T405\MIKES-Aalto\Quality\Solar_Cell_Measurement\Measurement_software (LabView)\Libraries

and

\\work\T405\MIKES-Aalto\Quality\Solar_Cell_Measurement\Measurement_software (LabView)\Subroutines

3.   Measurement

The SR measurement is conducted using custom LabVIEW software. A description of this software and things that should be considered before starting the measurement procedure is provided below.

3.1.   Software

Login information of the laboratory computer:

  Username: t405.kitchen3

  Password: 8ZPUvbREbfLUzX

The measurement and data acquisition are automated by LabVIEW software. All the required files are in the following directory:

[\\work\T405\MIKES-Aalto\Quality\Solar Cell Measurement\Measurement software (LabView)](#)

In this folder, the file *LED Carousel Control.vi* contains the program used to manually control the LED carousel. It is recommended the run this program before moving to any actual measurement to evaluate whether the LEDs and the carousel operate properly.

The software *Spectral Response Measurement.vi* contains the program used to execute the measurement of spectral response of the solar cell.

Spectral response.vi is a newer software for measuring the spectral response of the solar cell.

The software *Single Spatial Uniformity Measurement.vi* contains the program used to measure spatial uniformity.

The software *OM70 Laser Distance Sensor Control.vi* contains the program used to control the laser distance sensor.

Data should be stored in the following directory:

[\\work\T405\MIKES-Aalto\Quality\Solar Cell Measurement\Measurements](#)

It is recommended to store the acquired data based on its respective measurement for easy navigation. For example, if the acquired data is from the spectral response measurement, it should be stored in the subfolder *Spectral measurements*.

3.2.   Before measurement

The following things should be done before starting the measurement:

- The measured detector should be aligned using a laser pointer. The target at the wall and middle of the LED can be used as reference points.

- Oscilloscope should be used to check that there is no leakage voltage that could damage lock-in amplifier
- Lock-in amplifier displays correct frequency of 177 Hz
- Measurement device is connected using IEEE 488 GPIB to the GPIB USB HS so that the measurements can be read by the measurement software
- Correct settings are used in waveform generator (High Z should be selected)
- Bias light cooling is on (if bias lights are used)
- Run *LED Carousel Control.vi* to test that the LED carousel works
- Run *Spectral Response Measurement.vi* to start the measurement
- The measurement software contains instructions for measurement, but the instructions are also located below.
  - 1. Choose measurement method.
  - 2. Choose "Multiplexer" if it is used in measurements. Select multiplexer ports at the right side to determine which ports should be connected at specific parts of the measurement.
    For example, if outputs from solar cell are connected to ports C and D, and inputs to the lock-in amplifier are connected to ports A and B, input "AC" for the reference detector, and "BD" for the differential measurement. Trap detector can be connected using the "Reference detector" - selection.
  - 3. Select if monitor detector is used in the measurement.

3.3. Manually operating LEDs one by one

The software *LED Carousel Control.vi* contains the program used to manually control the LED carousel. It is recommended the run this program before moving to any actual measurement to evaluate whether the LEDs and the carousel operate properly. The software is used in the following way: first you start the software by clicking arrow in the upper right corner. After that you specify the next led you want to light up and press *GO!* button. When you want to quit measurements you should press stop button.

3.4. Measuring multiple LEDs automatically

The software *Spectral Response Measurement.vi* contains the program used to execute the measurement of spectral response of the solar cell. The software is used in the following way:

- Define *Stabilization Time (s), number of samples and Time between each sample (ms).* Default values are 30 s, 10, 1000 ms, respectively.
- Select either *Single-ended* or D*ifferential* SR830 input depending on your measurement connection.
- User defines file path from left up corner. Data is stored in txt format.

The setup has suffer a problem of instability of the measurement values. This problem associated with measurement oscillation was repaired by changing and adjusting SR830 dynamic reserve parameter. The traditional definition of dynamic reserve is the ratio of

the largest tolerable noise signal to the full scale signal. High Reserve parameter was changed to Auto Reserve. This change seemed to solve most of the problem, from the level of 10% to <1% for reference cells. For an organic cell, interference can still exceed 1%.

3.5. Measuring spectra of the LEDs

3.6. Measuring spatial uniformities of the radiation fields

3.7. Measuring UI curve of solar cell

The software measure.vi contains the program used to execute the measurement of UI curve of the solar cell. The software is used in the following way:

- Select *Visa resource name*
- Select *Number of Points*
- Insert *Minimum* and *Maximum voltage Amplitude*
- From *How to measure* select *Sweep*
- User selects if the measurements are saved to file by clicking *Save to file* button and defines file path where the measurements are stored. Save the measurement to data subfolder. The measurement file contains two UI curve measurements since sweep is performed in forward and reverse directions.
- After that you can start the measurements

The software is located in \\work.org.aalto.fi\t405\MIKES-Aalto\Quality\Solar Cell Measurement\Measurement software (LabView)\UI curve measurements

4. Data analysis

4.1. Maesurement of cell against a trap detector

For analysing the measurements, the Matlab App app.mlapp located at:

\\work\T405\MIKES-Aalto\Quality\Solar_Cell_Measurement\Data_Analysis_(Matlab_Excel)

can be used. This data analysis software can also be ran using the data_analysis_app.m file which is located at the same directory. The app can be modified by typing "appdesigner" in the Matlab command window and selecting the app in the opening window. This chapter describes how the software calculates the spectral responsivity and how this software is used.

4.1.1. Explanation of the Matlab code

The Matlab model interpolates the spectral responsivity using iterative process as described in chapter 1.2. The analysis uses a cubic smoothing spline for interpolation. It uses a smoothing parameter which can be changed between 0 and 1. If the value is 0, the model fits a line to the data. If the value is 1, the interpolation follows the points more closely and in the case of 30 data points, overfits the data. This value can be changed to get a smoother result that does not follow the points too closely.

The code first reads reference information, for example spectral irradiance, areas and resistor information from reference_data.xlsx Excel file. These values can be changed in this Excel file, but the location of the values should not be changed so that the model can find the correct values.

Next, the currents produced by the cell are calculated by dividing the measured cell voltages with the resistance. The trap currents are determined using the gain, so the trap currents are read from the measurements without any modifications. If monitor detector is used, these values are also read from the measurement data. If monitor detector is not used, monitor detector values are handled as a vector of ones. Note that the model has not been tested with monitor detector so it might require testing to get the monitor detector measurements implemented in the right way.

The code calculates the total irradiance for each LED and calculates the effective wavelengths. Also, the effective wavelength indices are determined, so that later these indices can be used to search values based on the effective wavelength.

Next, the trap currents are calculated. This calculation is done using a for-loop in which the area is multiplied by the product some of spectral irradiances and reference trap responsivity.

The cell currents are calculated in the function calculate_current(S_cell). The variable S_cell consists of values one because the initial guess for spectral responsivity was 1 A/W. The cell current is calculated quite similarly as the trap current.

The first values for spectral responsivity are calculated outside of for-loop. These first values are passed to a for-loop which takes care of the interpolation. Initially the values for spectral responsivity are one. Using this initial guess, the first values for spectral responsivity are calculated in function called calculate_responsivity which uses equation (5) for the calculation. Spectral responsivity values are now updated, and they are stored in a variable called S_cell.

Now the values outside the effective wavelengths are interpolated using interpolate_responsivity -function which uses cubic smoothing spline (csaps) for interpolation:

```
interpolation=csaps(eff_wavelength,S_cell_eff,parame-
ter,wavelengths);
```

The first two inputs are the datapoints that have been calculated. Parameter is the parameter specified by the user and final parameter includes the values of x, in this case every wavelength, for which the interpolation is done.

Now, the first values for spectral responsivity are calculated and these are passed to a function called iteration which repeats this process multiple times. In this loop, new values are calculated for current and responsivity. After calculating these new values, they are used in interpolation. Finally, the results are plotted and in addition, stored into an Excel file which is specified by the user.

4.1.2. The data analysis instructions

1. Select date and add description of the measurement.
2. The measurement data should be placed in an Excel file called measurement_data.xlsx. Figure 7 depicts how this Excel file should be formulated so that the software can analyse the results. Any Excel file which is formulated in this way can be used to run the program.
3. The second column (B) is titled "Cell voltage (V)". The measured voltages from the measurement software should be manually placed here. The unmodified measurement data should be placed here because the Matlab code considers corrections for the data, for example the correction for the lock-in amplifier.
4. The third column (C) is titled Trap Current (A). The measured trap currents should be placed here. The Matlab code does not consider the gain used in the measurements, so multiply the measured voltages with the correct gain value before passing the measurements into this column. Lock-in amplifier does not consider the correction for the lock-in amplifier automatically.
5. If monitor detector is used in the measurements, the monitor detector values should be placed into columns four (D) "Cell monitor (V)" and five (E) "Trap monitor (V)". Gain should also be included before inputting the values here.
6. In the app, the Excel file that contains the measurements in this format should be placed into "Data file".
7. Select smoothing parameter between 0 and 1. Value 0 corresponds to straight line and value of 1 tries to follow the points closely.
8. Select if monitor detector is used in the measurements.

9. The results are saved to the location which is specified by the selection "Save results to Excel". The results can be stored anywhere but it is recommended to store them to the following location:

   \\work\T405\MIKES-Aalto\Quality\Solar Cell Measurement\Data Analysis (Matlab_Excel)\Results

   This way the Excel files which are required for the Matlab software to work, won't get mixed up with the result files.

10. After running the analysis, Matlab plots a figure of the results.

11. The results are also stored into an Excel file. It includes original measurement data on sheet called "Measurement data" and the calculated results for every effective wavelength on the sheet called "Results". The third sheet "Interpolated and FISE" includes the interpolated and reference spectral responsivity so that they can be plotted in Excel. The final sheet includes description of the measurement.

Table 2: Measurement data should be given to the software in this format.

	A	B	C	D	E
1	LED	Cell voltage (V)	Trap current (A)	Cell (monitor)	Trap (monitor)
2	1	8.94E-06	1.94598E-07	1	1
3	2	1.63E-05	3.47716E-07	1	1
4	3	1.97E-05	4.22206E-07	1	1
5	4	2.15E-05	4.5604E-07	1	1
6	5	8.81E-06	1.95939E-07	1	1
7	6	2.67E-05	5.74535E-07	1	1
8	7	1.03E-05	1.75776E-07	1	1
9	8	1.25E-05	2.78857E-07	1	1

4.2. Measurement of cell against a reference cell

4.2.1. Principle of analysis

In short, principle of this method is to use calibrated spectral response measurement to obtain spectral response of unknown cell. First, spectral irradiance is obtained using calibration measurement data and own measured reference cell data. After that we can obtain spectral response of unknown cell.

4.2.2. Software used and location

Matlab software (Spectral_response.m) is used in this case. It can be found from: \\work.org.aalto.fi\t405\MIKES-Aalto\Quality\Solar Cell Measurement\Data Analysis (Matlab_Excel)\Measurement of cell against a reference cell.

4.2.3. Data needed to use software

The following should be considered before running software:

1. All data should locate in: \\work.org.aalto.fi\t405\MIKES-Aalto\Quality\Solar Cell Measurement\Data Analysis (Matlab_Excel)\Measurement of cell against a reference cell\Data.
2. FISE or PTB spectral responsivity calibration data should be in data folder (PTB already there). This Excel data file is called Kalib-Data.xlsx.
3. User should measure reference cell (See Section 3.4). Save the measurement results in txt format with name "ref_cell_data.txt".
4. User should measure unknown cell (See Section 3.4). Save the measurement results in txt format with name "spectral_response_unknown_cell.txt".
5. Txt files should be exactly in same format as LabVIEW measurement software gives them (See Section 3.4).

4.2.4. How to use the software

When you have saved files as described in section 4.2.3 you only have to press run when using spectral_response.m. As a result, you get table that contains spectral response of unknown cell. Data is stored in a txt file called data.txt and it is saved to \\work.org.aalto.fi\t405\MIKES-Aalto\Quality\Solar Cell Measurement\Data Analysis (Matlab_Excel)\Measurement of cell against a reference cell\Data.

5. Measurement traceability

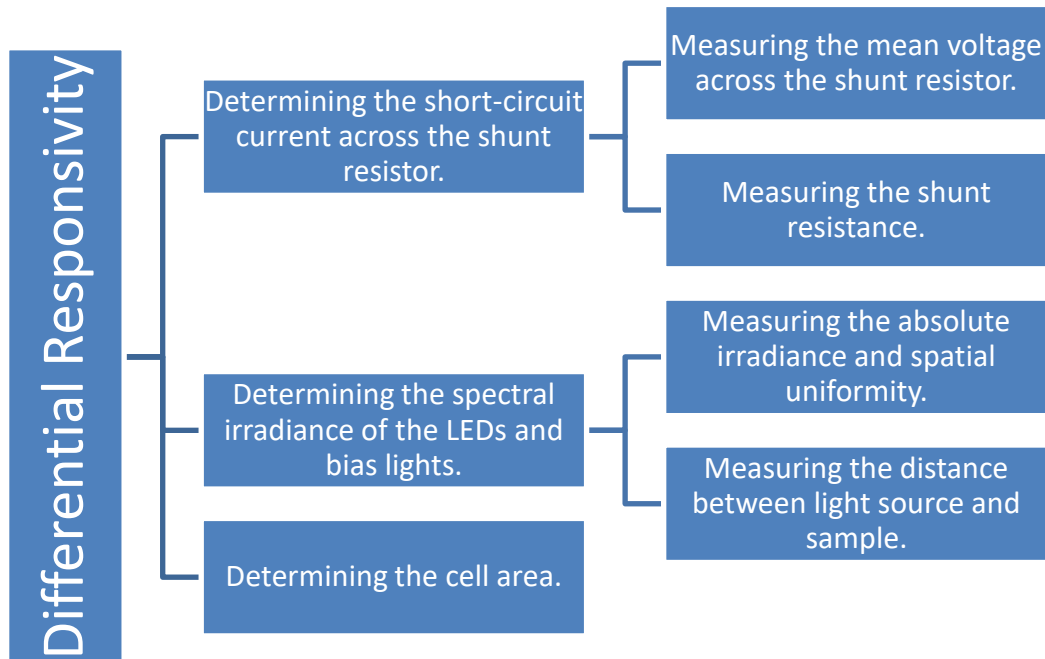The accuracy of the DSR can be described by employing the following measurement procedure diagram.

Figure 10: DR measurement procedure.

The DSR of a solar cell for a wavelength can be described as a ratio between the generated short-circuit current from the cell and the product of both the corresponding spectral irradiance of that wavelength and the cell area.

$$DSR(\lambda) = \frac{I_{sc}(\lambda)}{E(\lambda) \cdot A_{cell}}$$

The short-circuit current is obtained by using Ohm's Law: the mean voltage over the shunt resistor divided by the shunt resistance results the short-circuit current. The mean voltage is traceable from the differential voltage measurement obtained by the lock-in amplifier. Meanwhile, the resistance of the shunt resistor is traceable from the measurement obtained by the digital multimeter (DMM), which is calibrated from the working standard.

The spectral irradiance used for the determination of DSR is traceable from the quasi-monochromatic characterization of individual LEDs. It is traceable from the absolute irradiance and spatial uniformity measurements conducted by employing a spectroradiometer and a calibrated trap and photometer detectors. As the irradiance of a light source is inversely proportional to the square of distance, it is important to note that the spectral irradiance measurement can also be traceable from the distance measurement. For the cell area, it is traceable from its own measurement by a calibrated device.

For the measurement of DSR, there are several factors contributing to its uncertainty.

The temperature of a solar cell in some cases has been noted to significantly affect the measured spectral responsivity. This effect is notable for cells having a large temperature coefficient of the I_{SC}. Therefore, it is ideal to keep the temperature cell within the room temperature range ($20°C$ to $25°C$) for accurate approximation of the DSR.

Spatial and spectral variation in both bias and monochromatic light should be considered as well [13].

Optical and electrical errors cannot be neglected from the total uncertainty. Optical errors contain for example multiple reflections and misalignment of the device under measurement and detectors whereas electrical errors relate to measurement devices and the tolerances of the electronic components including but not limited to the locked-in amplifier, the DMM, the spectroradiometer, the light trap and photodetectors, and the shunt resistor. In addition, the distance from the illumination source to the device and the cell area should be known as accurately as possible since they affect the irradiance and the DR respectively [5].

During the DSR measurement of the reference sample, it is noted that by introducing waveforms used for turning on and off the LED sources with different amplitudes, which is done by setting various values for peak-to-peak voltage and offset voltage, the resulting DSR plots are significantly different from one to another. Therefore, it is important to consider the voltage fluctuation presented in the waveform generator, the voltage-to-current and current-to-voltage converters.

6.   Uncertainty analysis

The uncertainty budget for a reference cell, as calculated for the intercomparison in [1],

Table 3. Uncertainty budget when measuring absolute differential spectral responsivity of a 2 x 2 cm^2 reference cell. All values are in [%]

LED #	12	20	25	19	17	14	16	13	3	18	2	6	8	1	24	4	7	9	27	30	10	26	21	23	22	5	15	11	28	29
Effective wavelength / nm	290	301	346	371	401	413	425	434	447	472	503	522	527	543	588	622	632	635	663	722	727	731	804	844	866	936	1005	1032	1187	1288
Trap responsivity	0.64	0.64	0.50	0.30	0.20	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.50	0.50	0.60	2.00	5.00	8.00	10.00	15.00
Aperture area	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Relative spectral irradiance	4.00	4.00	4.00	2.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	2.00	4.00	8.00	8.00
Spatial correction	0.43	0.39	0.22	0.27	0.30	0.07	0.26	0.02	0.03	0.25	0.04	0.08	0.05	0.02	0.27	0.05	0.06	0.02	0.31	0.51	0.62	0.11	0.45	0.13	0.42	0.06	0.07	0.12	0.14	0.13
Alignment	0.43	0.39	0.22	0.27	0.30	0.07	0.26	0.02	0.03	0.25	0.04	0.08	0.05	0.02	0.27	0.05	0.06	0.02	0.31	0.51	0.62	0.11	0.45	0.13	0.42	0.06	0.07	0.12	0.14	0.13
Distance (1 mm)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Lock-in amplifier gain	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Current resolution (1 nA)	1.39	0.52	0.12	0.03	0.03	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.02	0.06	0.01	0.02	0.01	0.06	0.03	0.00	0.00	0.02	0.00	0.02	0.02	0.01	0.02	30.99	1.36
LED stability	0.26	0.10	0.03	0.14	0.13	0.12	0.11	0.03	0.04	0.06	0.10	0.09	0.04	0.11	0.06	0.07	0.34	0.09	0.06	0.90	0.22	0.10	0.06	0.05	0.49	0.02	0.02	0.08	0.84	0.84
Combined standard uncertainty	4.37	4.16	4.08	2.14	1.24	0.77	0.85	0.76	0.76	0.84	0.77	0.77	0.76	0.77	0.85	0.76	0.84	0.76	0.88	1.38	1.17	0.78	1.10	0.92	1.23	2.31	5.42	8.96	33.54	17.09
Expanded uncertainty	8.74	8.32	8.17	4.27	2.49	1.55	1.70	1.52	1.52	1.67	1.53	1.54	1.52	1.53	1.71	1.53	1.67	1.53	1.76	2.76	2.35	1.56	2.21	1.84	2.46	4.61	10.83	17.93	67.09	34.17
Aalto high	9	8	8	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	2	5	11	18	67	34
Aalto low	-9	-8	-8	-4	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-3	-2	-2	-2	-2	-2	-5	-11	-18	-67	-34
FISE uncertainty	26	29	10	9	9	6	3	2.5	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	5	10	206	
Combined high	27	30	13	10	9	6	3.4	2.9	2.5	2.6	2.5	2.5	2.5	2.5	2.6	2.5	2.6	2.5	2.7	4.1	3.8	3.4	3.7	3.5	3.9	5.5	12	21	217	34
Combined low	-27	-30	-13	-10	-9	-6	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-4	-4	-3	-4	-4	-4	-6	-12	-21	-217	-34

7.   Intercomparisons

7.1.   Own primary calibration against FISE

The setup can be used to absolutely calibrate reference cells. Comparison of these measurements against measurements of Fraunhofer Institute of Solar Energy (FISE) has been presented in [1]. The final result is shown in Figure 11.
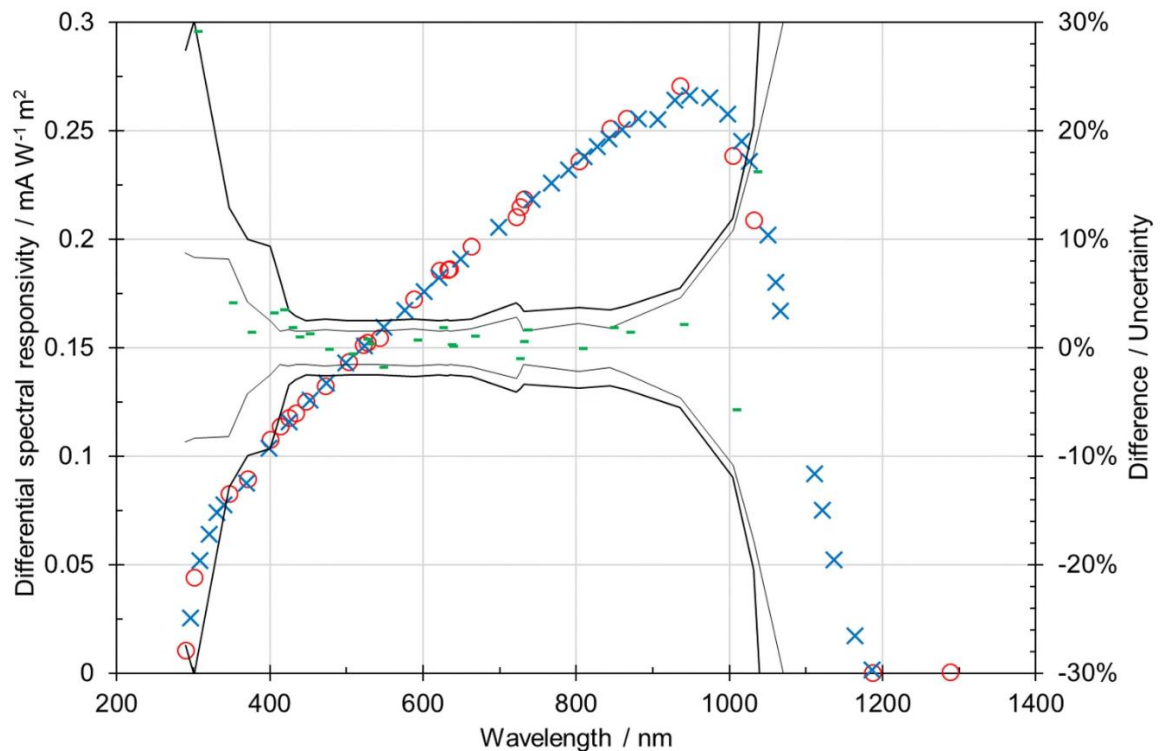

Figure 11: Comparison of Aalto measurements on the FISE reference cell to the measurements of FISE.

Alternately, unknown cells can be calibrated against reference cell. The primary reference cell of Fraunhofer ISE has been calibrated.

7.2.   FISE calibration of reference cell against PTB

The Fraunhofer ISE reference cell (Fraunhofer ISE, serial nr 119-2016) has been calibrated by both FISE (3001081ISE, 22.03.2017) and PTB (No certificate produced, measured 10. - 12.05.2022). Figure 12. Shows the spectral irradiance responsivities measured and the associated difference in the measurements. The measurements are in agreement at the level of 0.2697% (k = 1) in the wavelength range 400 – 1000 nm.

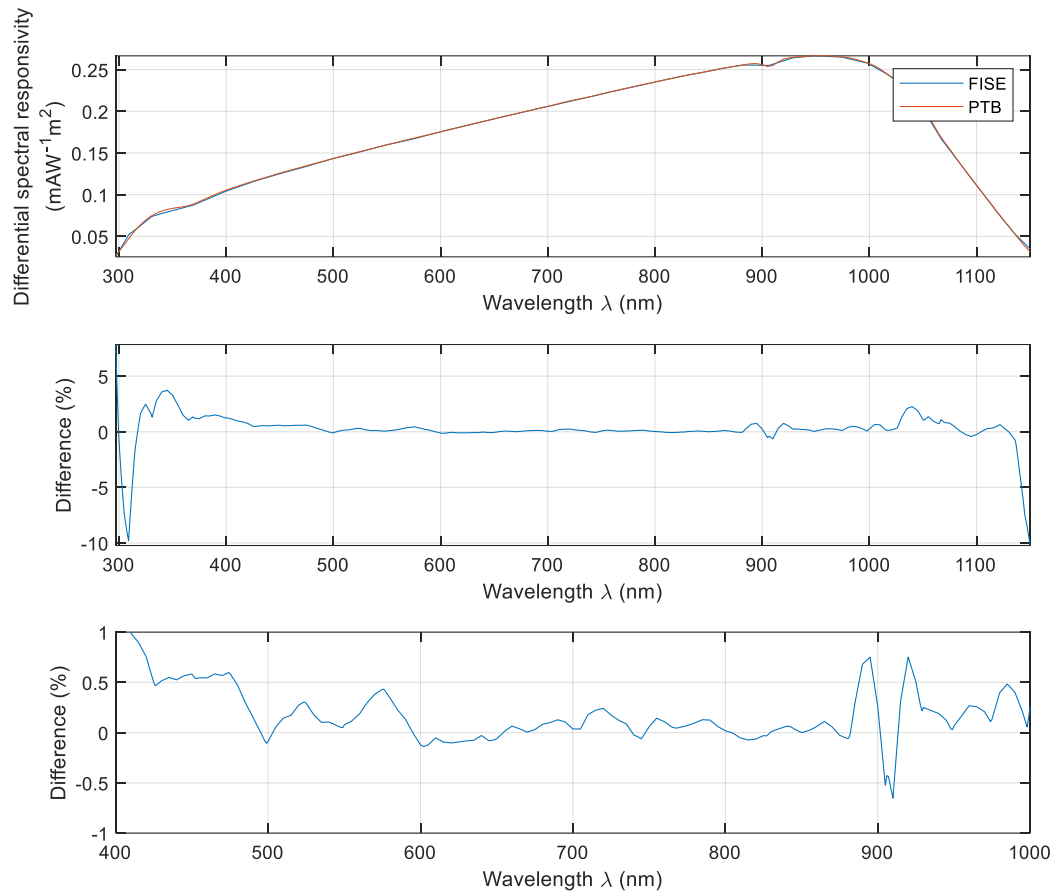Figure 12. Comparison of Fraunhofer ISE and PTB calibrations.

Calibration data location is: \\work.org.aalto.fi\t405\MIKES-Aalto\Quality\Solar Cell Measurement\FISE Reference Cell

8. Old archives

Older files related to the differential spectral responsivity measurement project can be found in the following folders:

\\work.org.aalto.fi\T405\MIKES-Aalto\Projects\PVEnerate

\\work.org.aalto.fi\T405\MIKES-Aalto\Projects\PVClass

 \\work.org.aalto.fi\T405\MIKES-Aalto\Users\Sami Talvitie

\\work.org.aalto.fi\T405\MIKES-Aalto\Users\Z Old personnel

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