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Minimizing the Cycle Time for a Rapid Quantum Efficiency Measurement by Modulating Multiple Channels of LED Solar Simulators

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Abstract. LED-based solar simulators have been shown to provide many advantages compared to Xenon-based flashers in particular regarding the flexibility of the spectrum, flash duration and illumination intensity. Using these extended capabilities, several new inline measurement applications, such as a rapid quantum efficiency (rapid-EQE) or rapid reflectivity measurement have been developed in recent years. In our work, we demonstrate how the rapid-EQE method can be further accelerated by using modulated LED light sources where the data acquisition for the various wavelengths occurs simultaneously during one measurement step. Our results show that the modulated rapid-EQE yields equivalent results compared to the consecutive measurements employed in previous rapid-EQE approaches. Thus, the accelerated approach can be integrated into inline LED solar simulators even for the strongly decreasing cycle times in modern production lines.

Keywords: Quantum Efficiency Measurement, Rapid-EQE, LED, Solar Simulator

1. Introduction and motivation

With decreasing cycle times in solar cell production lines, each process including all characterization steps needs to be optimized regarding its speed. On the other side, more complex cell architectures are finding their way into production. Thus, the inline quality control needs to be extended to provide all necessary information about the cell quality resulting in an increased amount of data that needs to be taken. One promising approach is to integrate new, high-speed measurement applications into existing measurement tools. This has been demonstrated for LED-based solar simulators, which have significantly entered the laboratories and mass production lines during the last few years, in many previous works, e.g. [1-4]. These advanced applications can provide several additional spectral information as for example, a sequential rapid quantum efficiency (rapid-EQE) and reflectivity measurement approach [5]. The proposed rapid-EQE method sequentially measures the cell's current obtained during the illumination with various LED-channels and takes the finite width of the LED spectra into account. It has been shown that measurement times below one second can be achieved by this sequential rapid-EQE method. However, further improvement is needed to leave enough time for other measurements in the I-V-tester characterization step such as the conventional I-V-characterization or additional EL- or IR-imaging.

In this work, a novel modulated rapid-EQE approach is demonstrated where all LED-channels of the solar simulator are switched on at the same time while being modulated with different frequencies. While other approaches to improve the measurement speed associated with I-V-measurements rely on modified data analysis methods, like a hysteresis compensation as described in [6], this new rapid-EQE method requires some hardware changes to implement the modulated light. In particular, a fast time-resolved current measurement is required. We show how the current amplitudes are extracted from the modulated time-dependent signal consistently. This also involves taking the impact of the shunt resistance of the solar cell into account. We apply our method to state-of-the-art solar cells and compare the modulated rapid-EQE results with the EQE obtained by a lab-tool and the previously developed sequential rapid-EQE method [5, 7]. While our novel approach requires some hardware adaptions and a more sophisticated data analysis of the measured current it provides two major advantages. First, the measurement times can be further reduced while keeping the signal-to-noise ratio constant as the switching and ramp-up phases of the individual LED-channels occur simultaneously. Second, the signal is measured at a higher overall illumination intensity which is closer to the real operating conditions of the solar cell. Also, a steady-state bias-light of given wavelength can be implemented for the application of this measurement approach to tandem solar cells. Therefore, we consider the modulated rapid-EQE approach as a significant extension of the previous method.

2. Experimental approach and data analysis

First, a reference quantum efficiency measurement has been performed using the LOANA (pv tools GmbH) cell characterization tool on a set of commercially available PERC solar cells. The same set of solar cells is used to determine the sequential rapid quantum efficiency, see measurement scheme in Figure 1 (left). Then, a measurement recipe has been developed for the SINUS220 LED solar simulator (WAVELABS GmbH), which simultaneously switches several distinct LED-channels on and off, see Figure 2 (left). For a measurement of this modulated rapid-EQE, all channels are operated at the same time but with different frequencies. A representative modulated multi-channel signal can be seen in Figure 1 (left, green line). In our study, we have chosen six channels of which two channels correspond to short wavelengths, two channels to medium wavelengths and two channels to larger wavelengths, respectively. Each of the six channels is modulated with a different frequency. To include at least two periods of the slowest 35 Hz channel, a total measurement time of about 60 msec is required. During the time of modulated illumination, a time resolved measurement of the cell current and voltage very close to short circuit conditions is realized. To improve the accuracy of the measured short circuit current, its value is derived from the current-voltage-measurement close to short circuit current and the value of the cell's shunt resistance.

For the modulation of a single channel, one obtains a cell's current signal as shown in Figure 1 (right). Here, one can clearly observe a transient behavior for the larger intensities due to internal heating and LED settling times which needs to be taken into account for the sequential rapid-EQE method. Based on this data, a device-specific set of basis functions for the individual LED channels can be derived and using these functions, a model representing the irradiance behavior of the solar simulator has been set up representing a simultaneous combination of various LED channels. This model is used to subsequently fit the solar cell's current signal when being measured during the modulated rapid-EQE approach. The acquisition of the single-channel data needs to be done only once for a given solar simulator, because the model only includes the characteristics of the solar simulator but not of the sample.

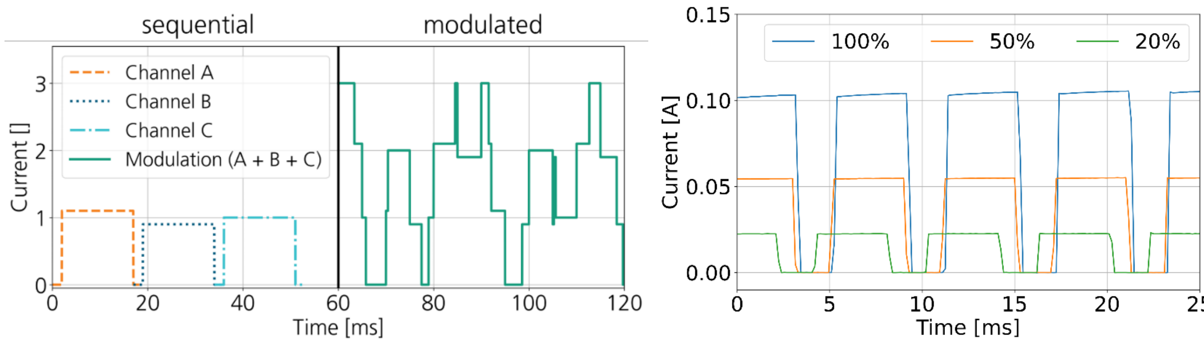

Figure 1. (left) Schematic representation of a sequential measurement of three different LED channels and intensities compared to the time-resolved current data for the multi-channel modulation used as a data basis for the rapid-EQE measurement. (right) Time dependent current signal of a single-channel modulation for different intensities showing non-constant plateaus for larger intensities (blue) due to internal heating and settling times of the LEDs.

Using the device-specific model obtained in the single-channel measurements, the modulated signal can be fit yielding the amplitudes of each individual channel. Due to technical limitations of the measurement electronics, the cell is not necessarily operated precisely at short circuit conditions but still at small voltages very close to short circuit. Thus, in addition to the current measurement, a simultaneous voltage measurement has been performed. This information combined with the shunt resistance value of the solar cell leads to an improved short circuit current value. Hence, based on these measurements, the implemented model returns the short circuit current of the cell for each of the modulated LED-channels.

3. Results

A device specific model has been defined for a SINUS 220 using the measurement data of six channels between 380 nm and 1050 nm wavelength and a modulation frequency from 35 Hz up to 250 Hz. The resulting fit of the measured modulated signal is shown in Figure 2 (orange dashed line). As a result of the fit, one obtains the amplitude and phase shift of each individual LED channel contribution. It can be observed that the overall time-dependent behavior is very well described by the model fit using only these two parameters for each channel. Nevertheless, one can also see some deviations near the signal edges when a certain LED channel is switched on or off. As this is due to some minor phase shifts it does not have any significant impact on the resulting current amplitudes representing the individual short circuit currents for each LED channel.

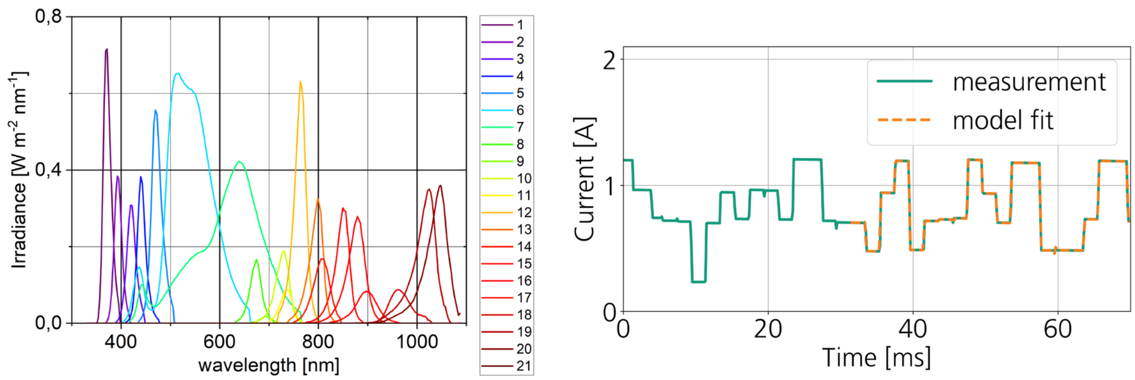

Figure 2. (left) Spectra of 21 single LED-channels available in the SINUS 220 measurement system. (right) Original measurement signal obtained by the short circuit current measurement and model fit used for signal decomposition.

The resulting EQE-values for a monofacial PERC cell are shown in Figure 3. The modulated rapid-EQE values are comparable to the sequential single-channel rapid-EQE values with only minor deviations of less than 5 $\%_{rel}$ and describe major features of the complete EQE. In particular, the relevant rising EQE signal slope for about 400 nm and the falling EQE at around 1000 nm can be observed and quantified using the modulated rapid-EQE values.

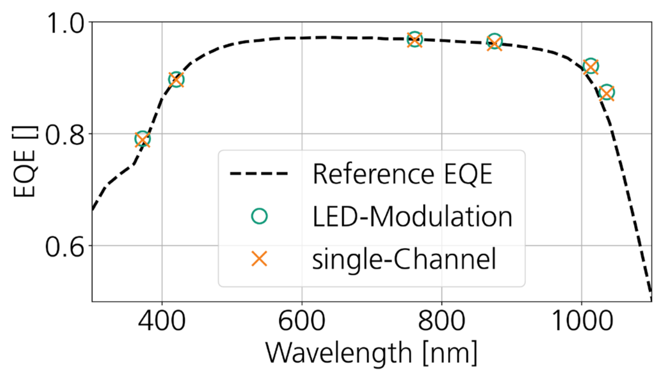

Figure 3. Quantum efficiency of a monofacial PERC cell: reference data obtained with a lab tool (dashed black line), sequential single-channel rapid-EQE data (orange crosses), LED-modulated rapid-EQE data (green circles).

The LED modulation approach reduces measurement pause times thus enabling longer effective acquisition for equal total measurement time. This leads to a higher robustness against measurement errors like noise on the current measurement. In a simulation approach, the current measurement of six LED-channels with a total measurement time of 100 msec is compared for the sequential single-channel method and the LED-modulation approach. To this end, the current signal is modified by numerically adding a normal distributed noise with a standard deviation of 10 mA, for both methods. This inclusion of random noise within the simulation together with a subsequent current determination is repeated 100 times to quantify the spread of the current measurements caused by the random noise. Figure 4 shows the result represented by the standard deviation associated with a current measurement for every LED channel separately. For all channels and corresponding modulation frequencies, an improvement of the signal to noise ratio (SNR) is achieved by the LED-modulation approach when the total acquisition time for this rapid-EQE step is kept equal to the sequential approach.

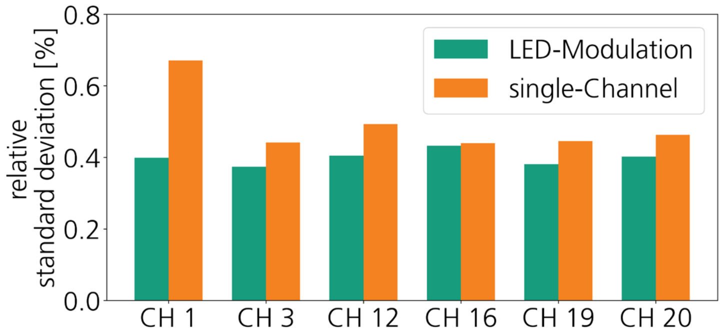

Figure 4. Simulation results for the relative standard deviation of the current measurement for comparable measurement times (100msec) for sequential single-channel rapid-EQE and LED-modulated rapid-EQE.

4. Discussion

In our work, we have shown that the rapid EQE determination by simultaneous LED modulation is a stable and reliable measurement approach. It results in an improvement of either signal-to-noise ratio for fixed data acquisition times or reduced measurement times for fixed signal-to-noise ratios. The comparison with the sequential single channel method shows that the EQE-values of both methods are very close to each other. Obtaining the electrical current value for a single LED-channel by fitting a set of measured basis functions to the modulated data results in a reliable signal fit and confirms the reliability of the LED modulation method.

Using the sequential single channel method, a stabilization time is required for each LED channel during the overall data acquisition procedure. During these stabilization time intervals, no data is acquired. On the other hand, the LED modulation approach enables for continuous data acquisition without any stabilization or pausing times thus allowing for a reduced overall measurement duration. In particular, an acquisition time of two periods of the channel with the lowest modulation frequency is sufficient for reliable EQE determination. By using higher modulation frequencies paired with adequate measurement speed of cell current, the rapid-EQE determination time can be further reduced for inline applications.

The signal-to-noise ratio is directly connected to the data acquisition time as longer measurement times lead to better signal averaging implying reduced errors. An improved signal-to-noise ratio can thus either be used to achieve lower measurement errors or lower measurement times with comparable data quality of the modulated approach compared to the sequential single-channel method.

5. Conclusions

We present a novel rapid-EQE approach using solar simulators with modulated LED channels. This approach relies on a simultaneous LED illumination for different wavelengths rather than sequential, consecutive illumination of the various channels as in previous studies. This simultaneous data acquisition of all channels at the same time is possible as the different LEDs are switched on and off with different frequencies. The data analysis to extract the individual current amplitudes is performed using a model fit relying on a set of experimentally determined basis functions. Our modulated rapid-EQE method leads to a significant reduction of the overall measurement time. We found that a 60 msec measurement cycle yields six relevant EQE values describing the major characteristics of the EQE-signal of various solar cells. Since the switching times of LED are typically in the range of few microseconds, even higher modulation frequencies up to several kHz could be possible which gives a large potential for further measurement time reduction.

Data availability statement

All data related to this work can be provided by the authors upon request.

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Author contributions

Manuel Meusel has been contributing to this work regarding conceptualization, data curation, software, formal analysis, investigation, visualization, and writing. Christian Hagendorf has been contributing to conceptualization, supervision, funding acquisition, validation, and writing. Marko Turek has been contributing to this work regarding conceptualization, formal analysis, supervision, funding acquisition, validation, investigation, methodology, writing, and project administration.

Competing interests

The authors declare that they have no competing interests.

References

1. Kolberg, D., et al., Development of tunable close match LED solar simulator with extended spectral range to UV and IR. Proceedings of the Siliconpv 2011 Conference (1st International Conference on Crystalline Silicon Photovoltaics), 2011. 8: p. 100-105 DOI: https://doi.org/10.1016/j.egypro.2011.06.109.
2. Kohraku, S. and K. Kurokawa, A fundamental experiment for discrete-wavelength LED solar simulator. Solar Energy Materials and Solar Cells, 2006. 90(18-19): p. 3364-3370 DOI: https://doi.org/10.1016/j.solmat.2005.09.024.
3. Bonnet-Eymard, M., et al., Optimized short-circuit current mismatch in multi-junction solar cells. Solar Energy Materials and Solar Cells, 2013. 117: p. 120-125 DOI: https://doi.org/10.1016/j.solmat.2013.05.046.
4. Esen, V., S. Saglam, and B. Oral, Light sources of solar simulators for photovoltaic devices: A review. Renewable & Sustainable Energy Reviews, 2017. 77: p. 1240-1250 DOI: https://doi.org/10.1016/j.rser.2017.03.062.

5. Turek, M., K. Sporleder, and T. Luka, Spectral characterization of solar cells and modules using LED-based solar simulators. Solar Energy Materials and Solar Cells, 2019. 194: p. 142-147 DOI: https://doi.org/10.1016/j.solmat.2019.02.007.
6. Hevisov, D., K. Sporleder, and M. Turek, I-V-curve analysis using evolutionary algorithms: Hysteresis compensation in fast sun simulator measurements of HJT cells. Solar Energy Materials and Solar Cells, 2022. 238 DOI: https://doi.org/10.1016/j.solmat.2022.111628.
7. Paduthol, A., M.K. Juhl, and T. Trupke, Correcting the Effect of LED Spectra on External Quantum Efficiency Measurements of Solar Cells. Ieee Journal of Photovoltaics, 2018. 8(2): p. 559-564 DOI: https://doi.org/10.1109/Jphotov.2017.2787022.