About significance of absolute photocurrent values
determination during the solar cell external quantum
efficiency measurements

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Abstract. In the work, the link of registered relative and absolute current signals of different
amplitude and shape in recording spectral characteristics of the sunlight PV converter external
quantum efficiency is investigated, and the need to use absolute current in spectral response
studies of multijunction solar cells with clearly pronounced luminescent coupling is
established.

1. Introduction
In experimental practice, in studying spectral dependencies of the solar cell (SC) external quantum
efficiency (EQE), the comparative approach is used, which is based on direct comparing photocurrent
signals from a reference calibrated photo-receiver and from a tested SC. Mainly, conditions for
measuring the SC EQE are determined by low levels of monochromatic radiation illumination, what
leads to weak values of photocurrent generated by a SC. To register small current signals, specialized
devices ensuring enhancement of such signals, their frequency filtration and accentuation are applied.
Such devices and instrumentation systems, due to using in them band-pass filters and converting-
amplifying signal electronic cascades, can influence the registered values decreasing them compared
to the absolute output value. It is obvious that, in using the matching method for comparing two
electrical values (in our case, photocurrents of a reference photo-receiver \( J_{ref} \) and tested SC one \( J_{SC} \)
with applying the formula \( EQE_{SC} = \frac{J_{SC}}{J_{ref}E_{EQE_{ref}}} \), where \( EQE_{ref} \) and \( EQE_{SC} \) - quantum efficiency
values for the reference photo-receiver and tested SC, respectively), any substantial effect of electronic
devices on the result of estimation of the \( EQE_{SC} \) should not be expected. The situation changes in
investigating complicated cells such as multijunction (MJ) SCs with pronounced optical (luminescent)
coupling phenomenon. Such a coupling is known to affect significantly the spectral characteristics and
the \( EQE_{SC} \) values being determined underestimating the measurement results. To eliminate such a
negative effect, a multistage procedure was proposed, which is based only on using the absolute values
of photocurrents in determining the EQE values [1]. For this reason, to spread the comparative method
advantages for solving the task of determining MJ SC spectral dependences and using it satisfactorily
in determining the \( QE_{SC} \) values, an unambiguous association between relative signals from a
measurement equipment and absolute photocurrents generated by MJ SCs at corresponding conditions
of irradiating by monochromatic light should be established.
2. Experimental details
In a standard experimental procedure, in determining the MJ SC EQE values, the principle of optical frequency modulation of monochromatic radiation with following amplification-conversion of a current signal from a SC and synchronous detection for weak useful signal isolation is used [2]. A low-noise current preamplifier (Stanford SR570) converts a current signal into voltage with 3-9 orders of magnitude amplification. Together with a useful signal, noise is also amplified. Isolation of a useful carrier-frequency signal is ensured by a Stanford SR830 lock-in amplifier [2]. It, according to the Fourier transformation, presents any input signal in a form of a sum of sinusoidal waves, what leads to some proportional variation of an output value being measured. To determine the proportionality coefficient, the following calibration procedure is applied in the work (the measurement circuit is presented in Fig.1).

![Figure 1. Schematic representation electronic layout and detected signals of the experiment: line 1 – reference signal ($f^{abs}$); line 2 – amplified signal without application of filters (is equivalent to the reference one); lines 3, 4 – distorted signal with application of filters ($f^{rel}_1$); line 5 – useful signal obtained at a definite frequency ($f^{rel}_2$) after lock-in conversion.](image)

In a SC light biasing condition, the absolute current signal $f^{abs}$ being reference one in an experiment is registered. Then the monochromatic radiation flux is modulated by an optical chopper with a preset chopping frequency (in the present work, a frequency of 90Hz was used), and an alternating current signal passes through a low-noise current preamplifier (all filters are switched off) to a registering device (oscilloscope or lock-in amplifier). At inactive frequency filters the current preamplifier does not change the current signal amplitude. Therefore, it does not affect directly the absolute signal value: the output signal oscillation amplitude equal to that of the reference signal is recorded. Application of built-in band-pass filters (30-100Hz) of the preamplifier SR570 ensures more correct signal accentuation on the operating frequency of 90Hz at simultaneous distortion of a signal waveform and amplitude (see the oscillograms in Fig.1). The following relation is valid for the signal being obtained:

$$f^{rel}_1 = k_1 \cdot f^{abs},$$  \hspace{1cm} (1)

where $f^{rel}_1$ – amplitude of the output signal measured in arbitrary units; $k_1$ – coefficient depending on the input signal waveform and on the filter frequency range, $f^{abs}$ - absolute input current signal.
The synchronous detector presents, according to the Fourier theorem, any input signal in a form of a sum of sinusoidal waves, what leads to variation of output values being registered. Thus, the output values under consideration become not proportional to the input photocurrents and last ones are different by the value from the absolute ones. Hence, having amplitude values of the reference (Fig.1, line 1) and modified (Fig.1, lines 3, 4) signals, one can find the coefficient of the reverse conversion from relative to absolute units with obtaining the sought-for photocurrent value for a SC. According to the special feature of action of the algorithm for treating the signal of the synchronous detector, the following is valid:

$$J_{2}^{rel} = k_{2} \cdot J_{1}^{rel};$$  \hspace{1cm} (2)

where $k_{2}$ – coefficient depending on a waveform of the signal from the preamplifier.

As a result, in allowing for (1) and (2), the following is valid:

$$J_{2}^{rel} = k_{1} \cdot k_{2} \cdot J_{1}^{abs};$$ \hspace{1cm} (3)

To determine the conversion coefficient $n_{1} = k_{1} \cdot k_{2}$ of a signal of an arbitrary amplitude $J_{1}^{abs}$ and waveform, it is enough to know at least one reference signal with a known coefficient $n_{2}$ and with a corresponding amplitude $J_{2}^{abs}$:

$$n_{1} = \frac{n_{2} \cdot J_{2}^{rel}}{J_{1}^{rel}};$$. \hspace{1cm} (4)

This relation has been verified experimentally in studying signals of different configurations, for which the parameter $n_{1}$ is known in advance:

$$\text{meander} \rightarrow J_{1}^{abs} = \frac{\pi \cdot \sqrt{2}}{2} \cdot J_{1}^{rel}$$ \hspace{1cm} (5.1)

$$\text{triangular signal} \rightarrow J_{2}^{abs} = \frac{\pi \cdot \sqrt{2}}{4} \cdot J_{2}^{rel}$$ \hspace{1cm} (5.2)

$$\text{sine} \rightarrow J_{3}^{abs} = \frac{6 \pi \cdot \sqrt{2}}{3 + 2 \pi} \cdot J_{3}^{rel}$$ \hspace{1cm} (5.3)

The results of comparison of a signal before and after passing through a synchronous detector with rated data (5.1-5.3) are presented in Fig.2:

![Figure 2](image_url)

**Figure 2.** The dependencies (both measured and rated) of relative values of current amplitudes on absolute ones for different input signal waveforms: meander, triangle and sine.
Also, the dependence of the conversion coefficient $n$ on the alternating signal frequency for different levels of current generation (from $10^{-2}$ to $10^2 \mu A$) corresponding to different SC illuminations was studied. The investigation has shown that, even for similar amplitudes of the input signal, the conversion coefficient depends strongly on frequency (Fig.3), what, in the whole, introduces the additional uncertainty in searching for its value. It should be noted that, at optimum measurement conditions (optical chopper rotation frequency is 90Hz, frequency range of low-noise preamplifier filters is 30-100Hz, signal range is from several $\mu A$ to mA), the coefficient of conversion from relative units to absolute values of a tested signal tends to $\frac{n\sqrt{2}}{2}$.

![Figure 3. Dependence of the coefficient (n) of converting a relative value into absolute one at active filters on an optical chopper rotation frequency.](image)

### 3. Conclusions

In the work, the degree of the effect of filtering and detecting elements on the absolute SC photocurrent values has been studied in realizing the procedure for determining the EQE spectral dependence. An association between relative (being registered) signals and absolute (being searched-for) photocurrents, which is determined by the coefficient $n$ depending on the input signal waveform, has been established. The investigation results have shown that, in dependence on the modulated signal waveform, the absolute values, in using a synchronous detector, should be determined according to the expressions (3, 4) and (5.1-5.3) at corresponding selection of a pair of parameters – filters-frequency.

The results obtained in performance of the work are applied in realizing the multistage procedure for determining real values of the quantum efficiency values of MJ SCs with a strong luminescent coupling between p-n junctions [3, 4].

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### References

[1] Kozhukhovskaia S A, Filimonov E D, Mintairov M A and Shvarts M Z 2015 Elimination of light coupling negative effect on the accuracy of external quantum yield determination in a MJ SC Journal of Physics: Conference Series 643, p 012064

[2] Armen G B 2008 Phase sensitive detection: the lock-in amplifier (Knoxville: The University of Tennessee)
[3] Shvarts M Z, Emelyanov V M, Evstropov V V, Mintairov M A, Filimonov E D, Kozhukhovskaia S A Overcoming the Luminescent Coupling Effect in Experimental Search for the Actual Quantum Efficiency Values in Multi-Junction Solar Cells AIP Conf. Proceedings, v.1766, 2016, pp. 06005, ISSN: 0094-243X, E-ISSN: 1551-7616.

[4] Kozhukhovskaia S A, Filimonov E D and Shvarts M Z Optical leakage versus luminescent coupling in a multijunction solar cell: how to recognize a source of additional photocurrent in subcells Journal of Physics: Conference Series 816, (2017) 012040