HIGH ACCURACY FILTER TRANSMISSION MEASUREMENT FOR DETERMINATION OF THE DETECTION EFFICIENCY CALIBRATION OF Si-SPAD DETECTORS

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Abstract: A high accuracy filter transmission measurement for the determination of the detection efficiency of a Si-SPAD detector has been carried out using an integrating sphere with attached detector. The measurement method and the improvement of total measurement uncertainty of the Si-SPAD detection efficiency calibration are described in this paper.

Key words: Si-SPAD detector, integrating sphere, filter transmission measurement, detection efficiency.

1. INTRODUCTION

Over the last decade, silicon single-photon avalanche diodes (Si-SPADs) have become increasingly important in different application fields such as quantum operations, vision systems, astrophysics telecommunications, biology and medicine. Such a variety of usage fields of Si-SPADs is based on their high detection efficiency at few photon levels in a wide spectral range; from the visible to the near infrared. The detection efficiency is typically measured by sending few photons onto the detector at a known repetition rate and recording the number of detection events [1]. Typically a strong attenuated laser or incandescent lamp is used as a light source. Thus, in order to achieve reliable measurements for the detection efficiency calibration, the Physikalisch-Technische Bundesanstalt (PTB), the national metrology institute of Germany, established recently a compact setup for Si-SPAD calibration that uses traceable transfer standards and a measurement procedure based on filter transmission technique, see Fig. 1 and ref. [2, 3]. However, the previous calibration results of the Si-SPAD detection efficiency have shown that one of the major uncertainty contributions in the measurement uncertainty budget comes from the neutral density filter transmission measurement [3]. For this reason, a high accuracy filter transmission measurement is required to improve the measurement uncertainty of the Si-SPAD detection efficiency. The novelty of this research work is that instead of using a single silicon detector (Si-Diode), an integrating sphere is employed for the filter transmission measurement. The integrating sphere is a device used for collecting and spatially integrated radiant flux [4]. The systematic errors that may be introduced due to specular reflections between the Si-Diode and the objective used during the filter transmission measurement are practically eliminated by using the integrating sphere.

![Fig. 1. Schematic view of the calibration setup for Si-SPADs](image-url)
2. MEASUREMENT METHOD AND SETUP

For the determination of the Si-SPAD detection efficiency applying this technique, the transmission of the filters is required to calculate the optical power impinging on the Si-SPAD detector. However, since a very low filter transmission is needed, which is not possible to be measured directly with an analogue detector, a two step measurement procedure for the filter transmission determination is required. This is carried out as follows: in a first step, the filter transmission is measured individually for each filter ($T_{F2}$, $T_{F3}$) by using high accuracy translation position stages and the integrating sphere with attached detector as a light sensor. In a second step, the filter transmission of the two filters is measured as a filter package ($T_{Combined}$); i.e. both filters are simultaneously placed in the beam path. From these three measurements a deviation between individual filters and total filter combination can be calculated, that is,

$$Dev = 1 - \frac{T_{F2} \cdot T_{F3}}{T_{Combined}}.$$  (1)

This deviation can be taken as an overall uncertainty contribution of the filter transmission measurement for the determination of the detection efficiency of Si-SPAD detectors, as described in [3].

The measurement setup for the filter transmission measurement and the determination of the quantum detection of Si-SPAD detector is shown in Fig. 2. A tunable laser source with a wavelength range from 766 nm to 781 nm is used. The laser beam is focused through a microscope objective APO M-PLAN 20x with a numerical aperture of 0.42 and a working distance of 20 mm. We have used neutral density filter NG9 D 2.6 for Filter 2 and neutral density filter NG9 D 3.0 for testing the measurement procedure.

An Agilent VEE program has been developed for the realization of automated measurements. At each wavelength, in the range from 766 nm to 781 nm with steps of 2 nm, were realized 100 measurements. In the measurement procedure, Filter 2 and Filter 3 are moved in x-direction of the translation stage. The position repetition of the translation stages is $\leq 5 \mu$m, which avoid errors due to the spatial non-homogeneity of the filter transmission. The translation range of the stages is 80 mm. The measurement program is composed of 4 modules. In module 1 the optical power of the laser is measured with the integrating sphere without any filter. The mean value of the measurement obtained with module 1 is used as a reference value.
for calculation of the filter transmission in relation to the results obtained in the next measurement modules. Afterwards, the measurement module 2 only Filter 2 is moved in the beam path (x = 37 mm). Module 3 continues with the measurement of the individual filter transmission by moving Filter 2 to position x = 0 mm and Filter 3 to position x = 37 mm. Finally, module 4 completes the measurement procedure by measuring the total transmission of the filter combination, i.e. Filter 2 and Filter 3 are positioned in the beam path (position x = 37 mm) simultaneously.

3. MEASUREMENT RESULTS

The summary of the filter transmission measurement results with their deviations for different wavelengths are shown in Table 1 and dispersions of the deviations are depicted in Fig. 3. The deviation between the transmission measurement of the single and combined filters is ≤ 0.05 % for the whole measured wavelength range.

<table>
<thead>
<tr>
<th>Nr</th>
<th>λ (nm)</th>
<th>Filter 2</th>
<th>Filter 3</th>
<th>Combined Filters</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>766</td>
<td>0.0186882</td>
<td>0.0086968</td>
<td>0.0001262</td>
<td>0.020</td>
</tr>
<tr>
<td>2</td>
<td>768</td>
<td>0.0188345</td>
<td>0.0087792</td>
<td>0.0001654</td>
<td>0.012</td>
</tr>
<tr>
<td>3</td>
<td>770</td>
<td>0.0189695</td>
<td>0.0088636</td>
<td>0.0001681</td>
<td>-0.023</td>
</tr>
<tr>
<td>4</td>
<td>772</td>
<td>0.0190674</td>
<td>0.0089108</td>
<td>0.0001699</td>
<td>0.016</td>
</tr>
<tr>
<td>5</td>
<td>774</td>
<td>0.0191584</td>
<td>0.0089864</td>
<td>0.0001724</td>
<td>-0.044</td>
</tr>
<tr>
<td>6</td>
<td>776</td>
<td>0.0193084</td>
<td>0.0090481</td>
<td>0.0001748</td>
<td>0.030</td>
</tr>
<tr>
<td>7</td>
<td>778</td>
<td>0.0194161</td>
<td>0.0091363</td>
<td>0.0001769</td>
<td>-0.012</td>
</tr>
<tr>
<td>8</td>
<td>780</td>
<td>0.0195284</td>
<td>0.0091665</td>
<td>0.0001791</td>
<td>0.035</td>
</tr>
<tr>
<td>9</td>
<td>781</td>
<td>0.0195746</td>
<td>0.0091978</td>
<td>0.0001800</td>
<td>-0.011</td>
</tr>
</tbody>
</table>

Table 1: Summary of the filter transmission measurement results and deviations calculated by equation (1).

4. DETECTION EFFICIENCY UNCERTAINTY

The mathematical model for determination of the detection efficiency of the Si-SPAD accompanied with all possible contribution factors for evaluation of the measurement uncertainty is given by \[ \eta = \frac{h \lambda}{4 \frac{A_1}{A_3} Q_1 Q_3} s_{\eta F_{filt}}, \] (2)
where $\eta$ is the detection efficiency of the SPAD; i.e. the measurand value, $h$ is the Planck constant, $c$ is the speed of light, $\lambda$ is the wavelength, $A_1$, $A_2$, $A_3$ are the signal amplification factors, $Q_1$, $Q_2$, $Q_3$ are the ratios of the signal of the Si-diode attached to the integrating sphere and the monitor detector signal, $Q_4$ is the ratio of the counter and the monitor detector signal, $s_{Si}$ is the spectral responsivity of the integrating sphere with the attached Si-diode, and $F_{filt}$ is the factor taking into account the use of two filters.

The estimation of uncertainty of the detection efficiency measurement is carried out following the guide to the expression of uncertainty in measurement (GUM) [5]. Based on the propagation law of uncertainty and uncertainty of input quantities, we can evaluate the combined uncertainty as [1]:

$$u^2(\eta) = c_1^2 \cdot u^2_h + c_2^2 \cdot u^2_e + c_3^2 \cdot u^2_\lambda +$$
$$+ c_4^2 \cdot u^2_{A_1} + c_5^2 \cdot u^2_{A_2} + c_6^2 \cdot u^2_{A_3} + c_7^2 \cdot u^2_{Q_1} +$$
$$+ c_8^2 \cdot u^2_{Q_2} + c_9^2 \cdot u^2_{Q_3} + c_{10}^2 \cdot u^2_{Q_4} +$$
$$+ c_{11}^2 \cdot u^2_{s_{Si,Filt}} + c_{12}^2 \cdot u^2_{F_{filt}},$$

(3)

where the $u(i)$ are the standard uncertainties of the input quantities and $c_i$ are the sensitivity coefficients which are calculated from the partial derivatives of all input quantities.

In continuity on the improvement of the total measurement uncertainty we will not focus to the estimation of all possible contributor factors but only at the factor of the use of two filters as one of the major contribution. The deviation between combined and individual filters measurements will influence in the correction factor. The expression of the deviation between two measurements is estimated from equation (1) and correction factor by equation (4):

$$F_{Filt} = \frac{T_{combined}}{T_{individual}} = \frac{T_{combined}}{T_{F_2} \cdot T_{F_3}},$$

(4)

where $T_{F_2}$, $T_{F_3}$ are the filters transmission of each individual filter and $T_{combined}$ is the filter transmission of combined filter.

These results have shown that the largest deviation $\sim 0.05 \%$ comes from the transmission measurements carried out at $\lambda=774$ nm. This deviation is used, for simplicity, for the estimation of the uncertainty of the correction factor $F_{Filt}$ for each wavelength. Thus, the standard uncertainty of the correction factor that uses two filters is estimated:

$$u_{F_{filt}} = \frac{T_{individual} - T_{combined}}{T_{combined} \cdot \sqrt{3}} = 3.3 \cdot 10^{-4}. \quad (5)$$

The uncertainty contribution of the factor which uses two filters is obtained:

$$u_e(F_{Filt}) = \sqrt{c_{12}^2 \cdot u^2_{F_{filt}} = 2.2 \cdot 10^{-4}}, \quad (6)$$

where sensitivity coefficient is $c_{12} = 0.64$.

The final result has shown that uncertainty contribution is 8.1 %. Referring to the previous estimated results we have improved one of the major uncertainty contributions by significantly reducing measurement uncertainty from 54.8 % [3] to 8.1 %. The new contribution value of the factor using two filters is included into the uncertainty budget and is used to estimate the combined uncertainty $u_e(\eta)$. Finally, the obtained detection efficiency of the Si-SPAD detector is:

$$\eta_{SPAD} = 0.6359 \pm 0.0014,$$

$$\eta_{SPAD} = 0.6359 \pm 0.22 \%.$$

5. CONCLUSIONS

In this paper, the accurate filter transmission measurement method and the improvement of its measurement uncertainty have been developed for the calibration of the detection efficiency of Si-SPAD detector. The use of an integrating sphere instead of a single Si-Diode for the filter transmission measurement has significantly reduced the measurement uncertainty contribution of the filter factor from 54.8 % to 8.1 %. The relative standard uncertainty of the detection efficiency of the Si-SPAD was improved from $< 0.5 \%$ to $< 0.25 \%$.

Future work will be focused on reducing the uncertainty contribution of the absolute spectral responsivity on the integrating
sphere as the last larger contribution factor for the determination of detection efficiency of Si-SPAD detectors.

6. REFERENCES


7. ADDITIONAL DATA ABOUT AUTHORS

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