Molecule-based single photon source for quantum radiometry

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In this paper we report on the calibration of the detection efficiency of a Silicon photon avalanche detector via comparison against an analogue, calibrated Silicon photodiode using a single-photon source based on the emission of an organic dye molecule. The single-photon source used had a total photon flux of 1.32 × 10^6 photon per second (corresponding to ≈ 334 fW), an emission linewidth of < 0.2 nm and a single-photon purity given by a $g^{(2)}(t = 0)$ value < 0.1. The obtained standard measurement uncertainty is between 2 % and 6 %, main contribution is the Silicon photodiode detector noise.

INTRODUCTION

Single-photon sources are considered being one of the major building blocks in many quantum optical applications, so e.g. in quantum key distribution, quantum computing and quantum enhanced optical measurements [1]. Besides these applications, also they are considered being ideal sources for radiometry, especially considering the field of quantum radiometry, i.e. where low photon fluxes need to be measured with low uncertainty [2]. Furthermore, single-photon sources in principle offer the possibility to become new standard photon sources [3, 4], complementing the blackbody radiator and the synchrotron radiation source. This is simply due to the fact, that the optical flux is given by $\Phi = fhc/\lambda$, where f is the repetition rate of the excitation laser, h is the Planck constant, c is the speed of light and λ is the wavelength of the emitted radiation. However, current single-photon sources are far from being that ideal, due to non-unity collection and quantum efficiency. In this paper, a single-photon source based on the dibenzoterrylene (DBT) molecule is used as single-photon source for the calibration of a single-photon detector (Si-SPAD) directly against a classical Silicon photodiode, which is traced to the primary standard for optical radiant flux, i.e. the cryogenic radiometer.

THE SINGLE-PHOTON SOURCE

The single-photon source used in the experiments is constituted by an isolated dibenzoterrylene (DBT) molecule embedded into an anthracene (AC) host matrix. Details of the source can be found in [5]. The monochromatic single-photon source has an operating wavelength of (785.6 ± 0.1) nm and generated an adjustable photon flux at the location of the detectors between 144000 photon per second and 1320000 photons per second, corresponding to an optical radiant flux between 36.5 fW and 334 fW. The source showed a high single-photon purity indicated by a second-order autocorrelation function at zero time delay below 0.1 throughout the whole flux range. The single-photon source is operated in continuous wave at a temperature of 3 K.

CALIBRATION OF STANDARD DETECTOR

The standard detector used for the photon flux measurement of the single-photon source was an analogue ultra-low noise Si detector (Femto, FWPR-20-s) . It is a fibre coupled Si-photodiode with an active area of 1.1 mm × 1.1 mm and a transimpedance amplifier with a gain of 1 × 10^{12} V/A. The minimum noise equivalent power (NEP) of the detector is 0.7 fW/$\mathrm{Hz}^{1/2}$. Its spectral responsivity $s_{\mathrm{Si}}(\lambda)$ was determined by calibrating it against a working standard traceable to PTB´s primary standard for optical power, the cryogenic radiometer [6]. The spectral responsivity of the low noise Si detector obtained at 786 nm is:

$$s_{\mathrm{Si}}\,(\lambda=786\ \mathrm{nm}) = (0.5752 \pm 58\times10^{-4})\ \mathrm{A/W} \quad (1)$$

This value was used for the calibration of the Si-SPAD detector in the experiments with the single-photon source.

CALIBRATION OF SI-SPAD

The detection efficiency of a Si-SPAD detector (Perkin Elmer, SPCM-AQRH-13-FC) is determined by comparing the photon flux measurements of the single-photon source carried out with the SPAD detector with those of an analogue reference Si-detector. Both detectors are fibre-coupled, equipped with a FC/PC fibre connector, optimized for a multi-mode fibre. The detection efficiency of the Si-SPAD detector, η_{SPAD}, is determined by

$$\eta_{\mathrm{SPAD}} = \langle N_{\mathrm{SPAD}}\rangle / \langle N_{\mathrm{ref}}\rangle = \langle N_{\mathrm{SPAD}}\rangle / (\langle \Phi_{\mathrm{s}}\rangle E)$$

$$= \langle N_{\mathrm{SPAD}}\rangle / (\langle I_{\mathrm{f}}\rangle / s_{\mathrm{ref}} \mathrm{E}) \qquad (2)$$

where N_{SPAD} is the count rate measured with the Si-SPAD detector, Nref is the photon flux rate derived from the measurement of the optical flux Φs and the photon energy E (with $E = 2.53 \times 10^{-19}$ J for photons at a wavelength of 785.6 nm). Φs is obtained as the ratio between the measured average photocurrent $<I_{\mathrm{f}}>$ and the reference detector responsivity s_{ref}. In the experiments, photon fluxes between 0.144×10^{6} photons per second and 1.32×10^{6} photons per second, which corresponds to an optical power range between 36.5 fW and 334 fW, were applied.

In Figure 1 the detection efficiency of the Si-SPAD detector is shown as a function of the photon rate at the detector. As can be seen, the detection efficiency starts to decrease slightly towards higher photon fluxes, caused by the detector deadtime. This is because the emission rate of the molecule already reaches regimes, where the deadtime of the detector already influences the measured detection efficiency η_{SPAD}, because due to the short emission decay time of the DBT molecule of about 4 ns, there are already multiple emission events within the detector deadtime.

The standard uncertainty of the detection efficiency was also determined. The model equation for the calculation is given by:

$$\eta_{\mathrm{SPAD}} = hc/\lambda \; s_{\mathrm{si}} F_{\mathrm{Amp}} N_{\mathrm{SPAD}} / (V_{\mathrm{f}}(1 - F_{\mathrm{Lin}})) \qquad (3)$$

where h is the Planck constant, c is the speed of the light, λ is the wavelength, F_{Amp} is the amplification factor of the internal amplifier of the reference detector, V_{f} is the photo-voltage measurement of the Si-detector measurement, F_{Lin} is the linearity factor correction of the Si reference detector and N_{SPAD} are the Si-SPAD counts including dark counts correction. The different contributions for a photon rate of $\approx 7.64 \times 10^{-5}$ photons per second, which corresponds to an optical power of ≈ 193 fW, are as follows: $u(h) = 0$ %, $u(\lambda) = 0.01$ %, $u(c) = 0$ %, $u(s_{\mathrm{si}}) = 0.40$ % %, $u(V_{\mathrm{f}}) = 1.87$ %, $u(F_{\mathrm{Amp}}) = 0.10$ %, $u(F_{\mathrm{Lin}}) = 0.03$ %, $u(N_{\mathrm{SPAD}}) = 0.02$ %, giving a combined standard uncertainty $u_{\mathrm{c}} = 1.92$ %. In general, the standard uncertainties are in the range between 2 % and 6 %, depending on the photon rate. The lower the photon rate, the higher the uncertainty, because of the increasing reference detector noise. The final value obtained for the Si-SPAD detection efficiency is $\eta_{\mathrm{SPAD}} = (0.603 \pm 0.012)$.

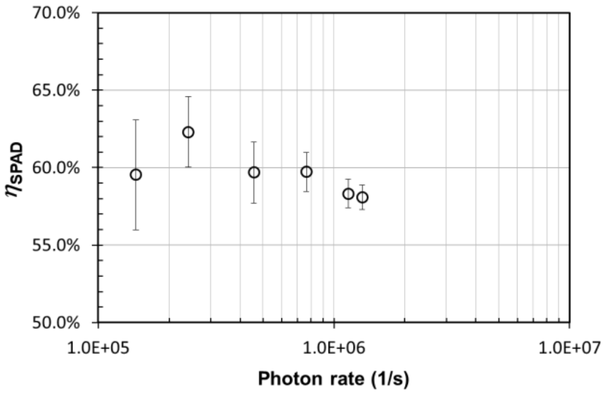

Figure 1. Detection efficiency as a function of the photon rate at the detector. The standard uncertainties are also shown as error bars. (Adapted from [5]).

SUMMARY

The direct calibration of the detection efficiency of a Si-SPAD detector with a calibrated analogue Si-photodiode, traceable to the cryogenic radiometer, using a true, nearly monochromatic single-photon source was presented. The obtained uncertainties were between 2 % and 6 %, mainly caused by the standard detector noise. Next steps will be the implementation of pulsed excitation in order to avoid detector dead time effects on the calibration result.

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