Pilot study on the detection efficiency measurement of InGaAs/InP single-photon detectors

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We present the results of a pilot study on the detection efficiency calibration of a free-running fibre-coupled InGaAs/InP single-photon avalanche detector carried out by four European national metrology institutes (NMIs). The calibration is performed using different experimental setups and reference standards with independent traceability chains at the wavelength of 1550 nm. The detection efficiency of the single-photon detector under test was determined for a mean photon number from 0.07 to 1.8, which correspond to approx. from 16250 photons/s to 203 000 photons/s, respectively.

INTRODUCTION

InGaAs/InP single-photon avalanche detectors (SPADs) are today the most frequently used detectors in ultra-high sensitivity applications such as quantum communication and quantum information processing, specifically fibre-based Quantum Key Distribution (QKD) [1-2] usually operated at the wavelength of 1550 nm. The traceable calibration of such detector is of great importance to fully guarantee the reliability of a quantum detection systems. Therefore, several national metrological institutes (NMIs) are currently putting great efforts into developing novel measurement methods and calibration facilities, enabling the performance of traceable calibration of such detectors by using reference standards.

In this paper we present the results of the pilot study on the detection efficiency measurements carried out by four European metrology institutes: CMI, INRIM, NPL and PTB, whose main purpose is to provide a snapshot of their measurement capabilities in the field of photon counting detection at telecom wavelengths.

DEVICE UNDER TEST

The device under test (DUT) used in this study was a fibre-coupled free-running InGaAs/InP single-photon avalanche detector from ID Quantique, model: ID-220, see Figure 1(a). Previous to the calibration, the detection probability level and the dead time of the DUT were configured to 10 % and 10 µs, respectively. Furthermore, to achieve high reproducibility of the measurements, the DUT was operated with a single-mode FC/PC fibre patch cable connected to its input optical port, where the measurement setups of all participating laboratories were connected by means of an FC/PC mating sleeve. Thus, the detection efficiency measured by all participating laboratories is referenced to this optical connection.

MEASUREMENT PRINCIPLE

The measurement principle used by all participating laboratories for determining the detection efficiency of the DUT η_{DUT} is based on the substitution method

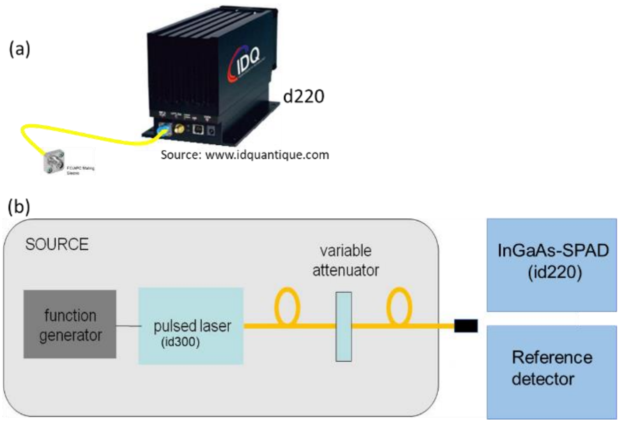

Figure 1. (a) InGaAs/InP free-running single-photon avalanche detector (ID Quantique ID-220). (b) Simplified scheme of the measurement principle (substitution method) used for determining the detection efficiency of the SPAD detector.

(see the simplified setup in Figure 1(b)). This method consists in comparing the optical power, corresponding to the effective number of photons per second, registered by the SPAD detector with the incident mean optical power per laser pulse determined by using a reference analogue detector. That is, $\eta_{\mathrm{DUT}} = P_C/\alpha \cdot P_0$, where P_0 is the optical power measured with the variable attenuator set to 0 dB, α is the attenuation factor of the variable attenuator and P_C is the average optical power corresponding to the effective photon rate measured by the DUT. P_C is calculated from the photon rate ρ absorbed by the DUT, corrected for dead time and dark counts, and the energy of the photon $h{\cdot}c/\lambda$, that is, $P_C = \rho \cdot h \cdot c/\lambda$.

The light source used for the detector calibration was a short-pulse laser source (ID Quantique, id300) externally triggered to produce sub-nanosecond pulses of approximately 300 ps duration at a repetition rate f_{lase}=110 kHz. Thus, the value of the photon rate absorbed by the DUT is calculated by $\rho = -f_{\mathrm{laser}} \cdot (1-q)$,where q is the probability of having a "*click*" per laser pulse during the detection process. However, since the dead time D of the DUT is larger than $\tau=1/f_{\mathrm{laser}}$; i.e. $\tau < D < 2\tau$, a correction to obtain the real value of q is required. The model developed in this work for q corrects the influence of the dark counts and the dead time D of the detector during the detection process. That is,

$$q = \frac{\rho_{\mathrm{click}}}{f_{\mathrm{laser}}-\rho_{click}} + \frac{f_{\mathrm{laser}}\cdot\left(\rho_{click}-\rho_{click}^{2} D+f_{\mathrm{laser}}\cdot\left(\rho_{click} D+\rho_{click}^{2}\cdot D^{2}-1\right)\right)}{D\cdot(f_{\mathrm{laser}}-\rho_{click})^{2}(f_{\mathrm{laser}}-\rho_{click}+\rho_{click}\cdot f_{\mathrm{laser}} D)} \cdot \rho_{\mathrm{dark}} \cdot D \quad (1)$$

where ρ_{click} is the photon rate counted by the DUT and ρ_{dark} is the dark counts. In addition, since the detector dead time D also affects the detector dark counts, we corrected it by $\rho_{dark} = \rho'_{click,dark}/(1-\rho'_{click,dark} \cdot D)$, where $\rho'_{click,dark}$ is the dark counts measured in absence of light.

RESULTS

Figure 2 shows the detection efficiency of the DUT determined by all participants for a mean photon number per pulse between 0.07 and 1.8, which corresponds to a photon rate of approx. 16250 photons/s and 203 000 photons/s, respectively. The detection efficiency without dead time corrections, obtained from the measurements performed by CMI, is also included, which clearly shows the typical detection efficiency saturation of the detector. Moreover, the average value and the expanded uncertainty reported by the participants are shown in Table 1.

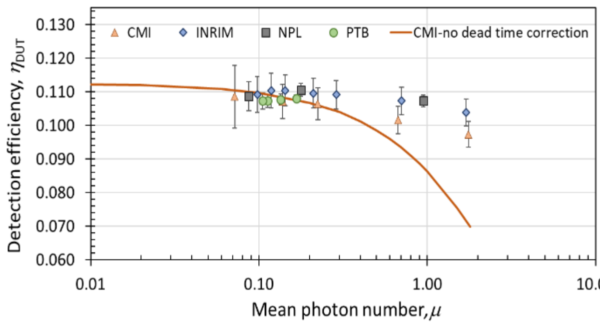

Figure 2. Detection efficiency of the InGaAs/InP SPAD detector measured by all participants between the mean photon number per pulse from 0.07 and 1.8, which correspond to a photon rate of approx. 16250 photons/s and 203 000 photons/s, respectively. Error bars: expanded uncertainty (k=2). Solid line: detection efficiency without detector dead time correction.

Table 1. Average and expanded uncertainty of the detection efficiency reported by each participant laboratory.

Laboratory	Participant detection efficiency, η_p	Expanded uncertainty
CMI	0.1042	0.0054 (5.2%)
INRIM	0.1086	0.0050 (4.7%)
NPL	0.1089	0.0026 (2.4%)
PTB	0.1076	0.0024 (2.2%)

CONCLUSIONS

A pilot study on the measurement of the detection efficiency of fibre-coupled free-running InGaAs/InP-SPAD detectors was presented. The evaluation of the detection efficiency included the correction of the dead time of the device under test. The measured values reported by all participants are within the expanded uncertainty of the mean.

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