Calibration of InGaAs/InP single-photon avalanche detectors

Robin Eßling, Helmuth Hofer, S. M. F. Raupach, Hristina Georgieva, Beatrice Rodiek, Justus Christinck, Stefan Kück and Marco López

Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
Corresponding e-mail address: marco.lopez@ptb.de

We present our latest results on the calibration of the detection efficiency of free-running and external-gated InGaAs/InP single-photon avalanche detectors at the wavelength of 1550 nm. This includes the characterisation of the gate window temporal response and the after-pulse probability, which, depending on the detector operation mode, significantly affect the detection efficiency.

INTRODUCTION

InGaAs/InP- single-photon avalanche detectors (SPADs) operated in external-gating and free-running mode are frequently used in many quantum technologies, such as quantum communication, quantum key distribution, etc. The precise characterization of relevant parameters such as, among others, detection efficiency, dead time, after-pulse probability, temporal photon detection probability profile and dark count probability, is mandatory for their use in quantum-sensitive detection systems. Therefore, several National Metrology Institutes (NMIs), such as PTB, and standardisation organisations such as the European Telecommunications Standards Institute (ETSI) are currently undertaking large efforts in developing and standardizing measurement methods and procedures, which will allow the traceable characterisation of all relevant parameters. From radiometric point of view, the detection efficiency is the parameter that can be determined with traceability to the primary standard for optical power, the cryogenic radiometer.

MEASUREMENT METHOD AND SETUP

The detection efficiency η of an InGaAs/InP SPAD detector is obtained by determining the probability P_i to detect a photon at each illuminated gate as a function of the mean number of photons per laser pulse, $<\mu>$. That is,

$$\eta = \frac{P_i - P_d}{<\mu>} \cdot \frac{1}{1+P_{after}} \quad (1)$$

where P_d is the dark count probability and P_after is the after-pulse probability. The mean number of photons per laser pulse $<\mu>$ is given by,

$$< \mu > = \frac{P}{f \cdot (h \cdot c/\lambda)} \cdot A \quad (2)$$

where P is the optical power of the laser, f is the repetition rate of the laser pulses, hc/λ is the photon energy and A is the attenuation factor required to attenuate the laser source down to single-photon levels (fW).

The setup used for the calibration of the detection efficiency of the free-running and gated fiber-coupled InGaAs/InP SPAD detectors is shown in Figure 1. In this setup, a strongly attenuated short-pulsed laser with a pulse duration of approx. 300 ps operating at a wavelength of 1550 nm, triggered with a frequency of f_Trigger = 90 kHz, is used as a radiation source. The optical power of the laser is attenuated down to single-photon levels (fW) by two attenuators, which attenuation factors A_1 and A_2 are previously calibrated at a higher optical power by using the double attenuator technique [1]. Thus, the attenuation factor A is calculated by $A_1 \cdot A_2$. A low noise InGaAs photodiode (Hamamatsu G8605-23) cooled to -20 °C and traceable to the PTB´s primary standard for optical power (cryogenic radiometer) is used as reference standard for the measurement of the optical power. The photocurrent generated by the InGaAs photodiode is directly measured with a Femto/Pico-ammeter (Keysight B2981A, see Figure 1(b)). When a SPAD operated in external gating mode is calibrated, a delay generator is used to precisely synchronise the photon detection time within the gate.

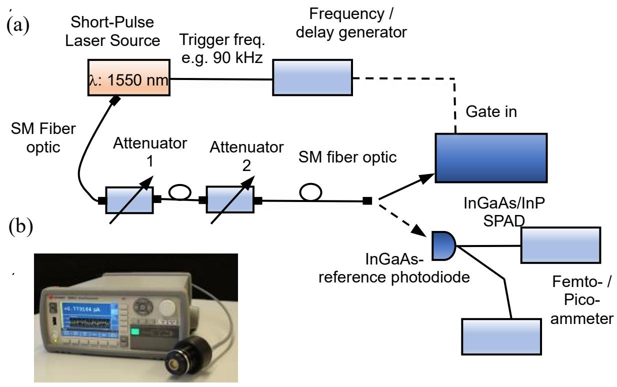

Figure 1. (a) Setup for determining the detection efficiency of fibre optic coupled InGaA/InP SPAD detector. (b) InGaAs reference photodiode (Hamamatsu G8605-23) and Femto/Pico-ammeter (Keysight B2981A) used as photocurrent meter.

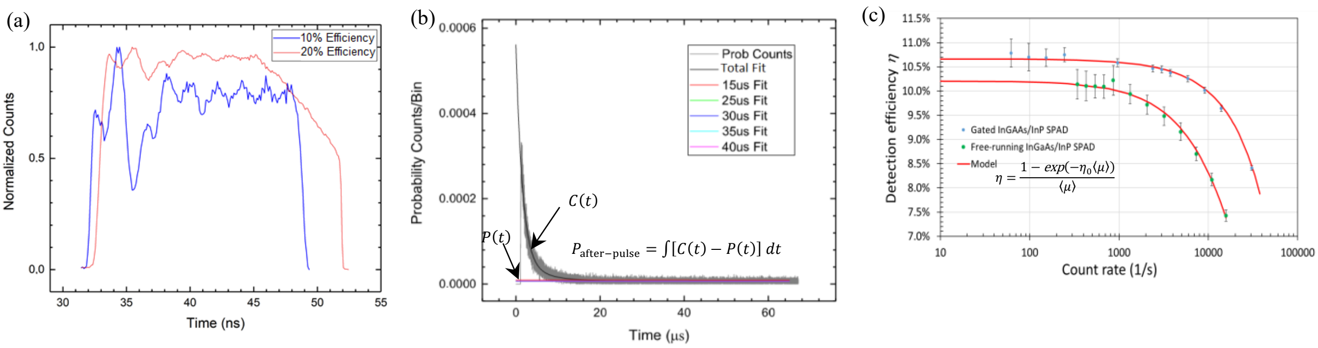

Figure 2. (a) Normalized gate window temporal response of the gated InGaAs/InP SPAD (ID201) for different detection efficiency configurations. (b) Histogram of the probability counts obtained for determining the after-pulse probability of the free-running InGaAs/InP SPAD (ID220). (c) Detection efficiency of the gated and the free-running InGaAs/InP SPAD detector (ID201 and ID220, respectively) as a function of the count rate. Solid points: measurement results, error bars: standard uncertainty, solid line (red): fitted model.

The after-pulse probability of the SPADs is determined as described in [2]. This method consists in determining the time-correlation between two consecutive output pulses generated by the SPAD detector in absence of light. The after-pulse probability is quantified by fitting a model function $C(t)$ und $P(t)$ to the registered time-correlation events for a timing period range with and without after-pulses events, respectively. Both fitting model functions $C(t)$ and $P(t)$ have the form $x_0 \cdot e^{-R \cdot t}$, where x_0 and R are the photon detection probability per unit time slot and the average photon counting rate, respectively. Finally, the after-pulse probability is calculated by $P_{\text{after-pulse}} = \int [C(t) - P(t)]\,dt$.

RESULTS

The measurement of the gate window temporal response of the external-gating SPAD detector (ID201), set to a nominal detection efficiency of 10 % and 20 %, respectively, is shown in Figure 2(a). As can be observed, the detector count rate strongly depends on the photon detection within the gate window. The count rate changes, relative to the maximum value measured, up to approx. 60 % and 10 %, for a detector efficiency setting of 10 % and 20 %, respectively.

Figure 2(b) shows the histogram of the probability counts and the corresponding fitted functions for the free-running SPAD detector (ID220). The after-pulse probability obtained, for a setting detector dead time of 10 us, is to be 7.43 %, which results in a correction factor $\frac{1}{1+P_{after}} = 0.931$ in equation (1).

The detection efficiency measurements of the gated and free-running InGaAs/InP SPAD detector (ID201 and ID220, respectively) as a function of the count rate is shown in Figure 2(c). The detection efficiency of the gated SPAD detector was determined by gating it at approx. 43 ns within the gate window shown in Figure 2(a). The dead time and efficiency of both detectors were configured to 10 µs and 10 %, respectively. As can be observed, the detection efficiency decreases once the saturation of the detectors is reached, as described in [2]. The relative standard uncertainty achieved is less than 1.2 %. The maximal deviation of the detection efficiency of the gated SPAD obtained within its gate window, and relative to an efficiency of 10 %, is to be 7.97 %.

In summary, the calibration of the detection efficiency of an external gating and a free-running InGaAs/InP SPAD detector was presented. The after-pulsing probability correction obtained for the free-running SPAD was approx. 7.0 % @10 µs dead time. For the external gating SPAD, a variation of the detection efficiency of up to approx. 8.0 % was obtained within its gate window.

Acknowledgment: The work reported on this paper was funded by project EMPIR 17FUN06 SIQUST. This project received funding from the EMPIR program co-financed by the Participating States and from the European Union Horizon 2020 research and innovation program.

REFERENCES

1. Marco López, et. al. "Detection efficiency calibration of InGaAs/InP single-photon detectors", NewRad 2017 Proceedings, Tokyo 13 - 16 June, 2017.
2. Hee Jung Lee et. al. "Wavelength-scanning calibration of detection efficiency of single photon detectors by direct comparison with a photodiode", Metrologia 53, 908-917, 2016.