Establishment of single-photon detection efficiency calibration system at NRC

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The advent of single-photon detection capabilities has enabled rapid advancements in many areas including quantum measurements and quantum communication [1-2]. Recently, numerous national metrology institutes have established their own detection-efficiency calibration methodologies for single-photon detectors (SPDs) [3-4]. Here, we report the establishment of a free-space SPD efficiency calibration system at NRC utilizing an attenuation-based substitution technique [3]. The measured detection efficiencies of commercial silicon single-photon avalanche photodiodes are traceable to the NRC optical power scale. To validate this new system, SPD detection efficiencies were also measured at NIST, using a calibration set-up described in Ref. [4]. The results of these measurements will be presented.

SI-TRACEABLE QUANTUM RADIOMETRY

The substitution and attenuation technique for measuring detection efficiency enables a single-photon detector (SPD) to be directly compared to a transfer standard detector (TSD), making the calibration traceable to the absolute cryogenic radiometer, the primary standard for the NRC optical power scale (Fig. 1).

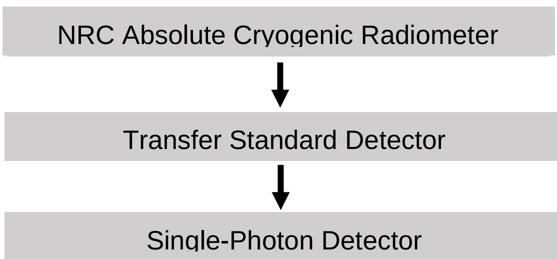

Fig. 1. Traceability chain of a SPD detection-efficiency calibration.

NRC CALIBRATION APPARATUS

Our experimental setup is depicted in Fig. 2. In this calibration method, multiple filters are used to attenuate the incident power of the input laser beam at 850 nm to a level measurable by the SPD, on the order of femtowatt.

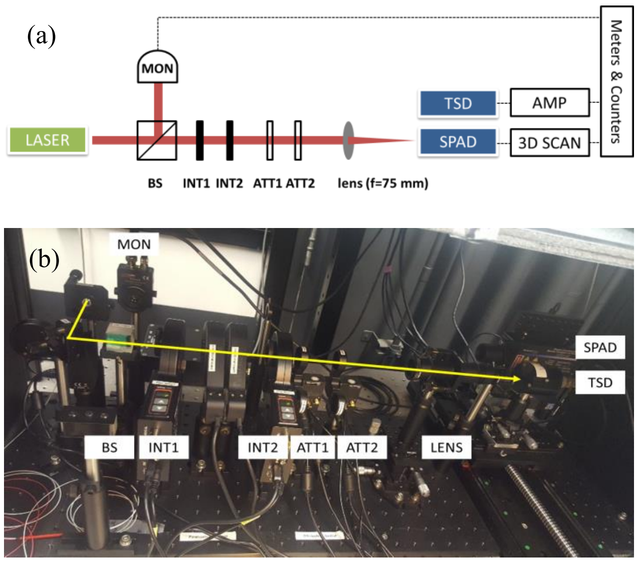

Fig. 2. Measurement setup: (a) a schematic diagram and (b) a photo. AMP: amplifier, BS: beam splitter, MON: laser intensity monitoring detector, INTs: intensity controllers, ATTs: neutral density filters, SPAD: single-photon avalanche diode.

The SPAD under test is mounted on a 3-dimensional computer-controlled stage, allowing the single photons to be optimally positioned on the active area of the SPAD (Fig. 3).

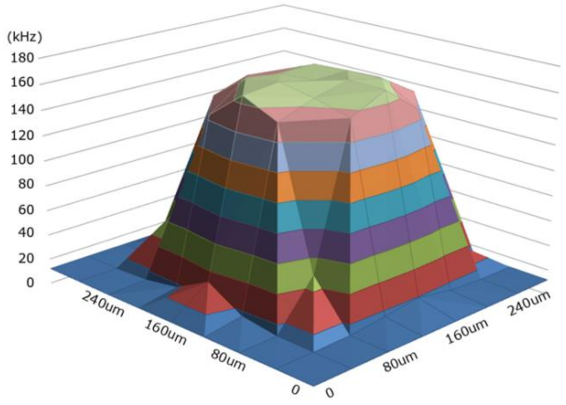

Fig. 3. Detection-response spatial uniformity. A laser beam with a focal size of 17 μm scans the SPAD detection window. An active area diameter (plateau) of 160 μm is measured.

COMPARISON TO NIST CALIBRATION

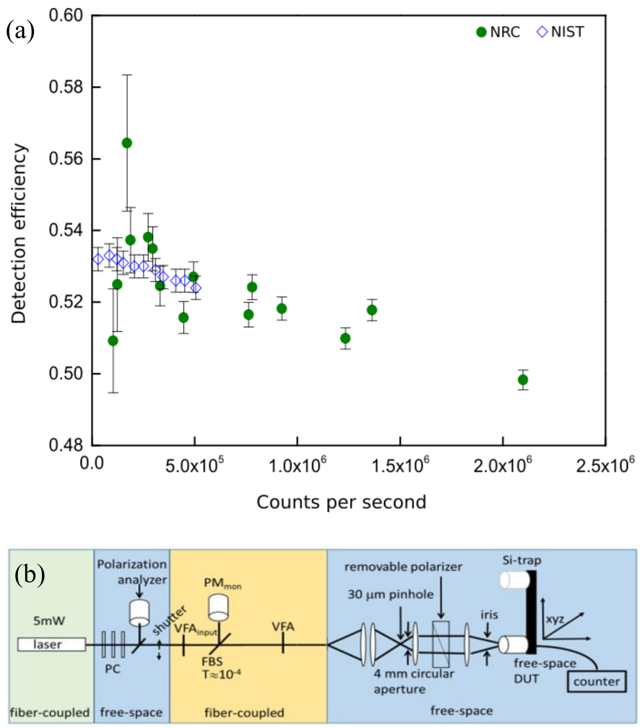

Fig. 4. Measurement results. (a) Detection efficiencies are measured at various input intensity levels, and compared to measurements performed at NIST. (b) The NIST SPAD calibration system [4].

Measurand	Symbol	Unit	Value	Uncertainty	Uncertainty (%)
Wavelength	λ	m	850.63×10^{-9}	6.00×10^{-11}	7.05×10^{-3}
TSD Spectral Responsivity	s	A/W	4.526×10^{-1}	5.93×10^{-4}	1.31×10^{-1}
Amplification	A	V/A	1.00×10^{9}	5.00×10^{6}	5.00×10^{-1}
Ratio $V_0/V_{0,\mathrm{mon}}$	Q_0	1	1.14×10^{1}	1.40×10^{-7}	1.23×10^{-6}
Ratio $V_1/V_{1,\mathrm{mon}}$	Q_1	1	2.25×10^{-1}	2.91×10^{-6}	1.30×10^{-3}
Ratio $V_2/V_{2,\mathrm{mon}}$	Q_2	1	2.64×10^{-2}	1.98×10^{-4}	7.49×10^{-1}
Ratio $N_{SPAD}/V_{\mathrm{SPAD,mon}}$	Q_{SPAD}	V·s	2.51×10^{6}	1.38×10^{-6}	5.51×10^{-11}
Efficiency (n=4)	η	1	0.522	1.03×10^{-3}	1.98×10^{-1}
Combined uncertainty (k=1)					0.93

Table 1. Uncertainty budget. Uncertainties are evaluated at the level of N_{SPAD}=102895 counts per second.

CONCLUSION

We demonstrate a newly constructed apparatus and results for SI-traceable detection-efficiency measurements of free-space single-photon detectors. Our automated system has the capability to measure the uniformity of the active area of the single-photon detector under test which increases measurement accuracy and reproducibility. The measured average detection efficiency agrees with measurements performed at NIST, within measurement uncertainty. Further improvement to reduce measurement uncertainties at the low photon-flux level can be made by utilizing low-noise and high-gain transfer standard detector amplifier and alternate attenuation technique.

REFERENCES

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