Calibration of free-space and fiber-coupled single-photon detectors

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We present our measurements of the detection efficiency of free-space and fiber-coupled single-photon detectors at wavelengths near 851 nm and 1533.6 nm. We investigate the spatial uniformity of one free-space-coupled silicon single-photon avalanche diode (SPAD) and present a comparison between fusion-spliced and connectorized fiber-coupled single-photon detectors. We find that our expanded relative uncertainty for a single measurement of the detection efficiency is as low as 0.7 % for fiber-coupled measurements at 1533.6 nm and as high as 1.8 % for our free-space characterization at 851.8 nm [1].

Future Optical Quantum Networks will need components based on single-photon quantum technologies and those components will require characterization. We start with single-photon detectors, which in turn can be used to characterize other quantum network components such as single-photon sources, fiber losses, network switches, etc.

We measure detection efficiency using a calibrated attenuation stage and a calibrated optical power meter as shown in Figure 1. Laser power is first roughly set using a variable fiber attenuator ($\mathrm{VFA_{input}}$) and then sent to a splitter/attenuator unit, which has a highly attenuated output and high-light-level monitor. The ratio of the output to the monitor ($R_{\mathrm{out/mon}}$) is $\approx 10^{-5}$ and is measured using an optical power meter (PM) and monitor optical power meter ($\mathrm{PM_{mon}}$). Both, PM and $\mathrm{PM_{mon}}$, require a nonlinearity (relative) calibration, whereas only PM requires an absolute responsivity calibration. Key to the measurements are the transmittance of the splitter/attenuator unit and the output-to-monitor ratio of the splitter/attenuator unit. Both are determined from the fiber beam splitter (FBS) splitting ratio and the attenuation of VFA, using the power meter and the monitor power meter. In addition, this method relies on the stability of the splitter/attenuator unit's output-to-monitor ratio, the polarization and wavelength of the light versus time, and the independence of the output-to-monitor ratio with input optical power. We verify each of these either during the measurement or by prior characterization.

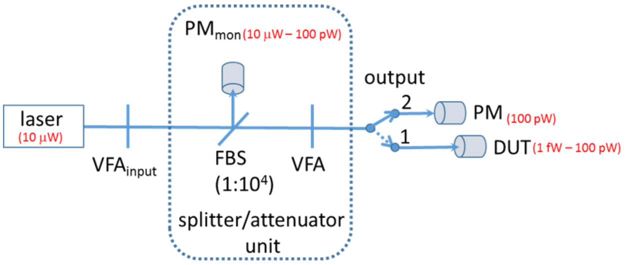

Figure 1. Schematic of the measurement setup.

Detection efficiency results are shown (fig. 2) for a free-space-coupled silicon single-photon avalanche detector (SPAD) measured in two modes. One using a continuous wave (CW) and another using a mode-locked Ti:sapphire laser. Detection efficiency (DE) is measured at a range of detector count rates so that the DE can be determined at 1 cnt/s and 10^5 cnt/s. Setup stability and repeatability is achieved for the extracted detection efficiencies at the two rates of 1 cnt/s and 10^5 cnt/s (fig. 2).

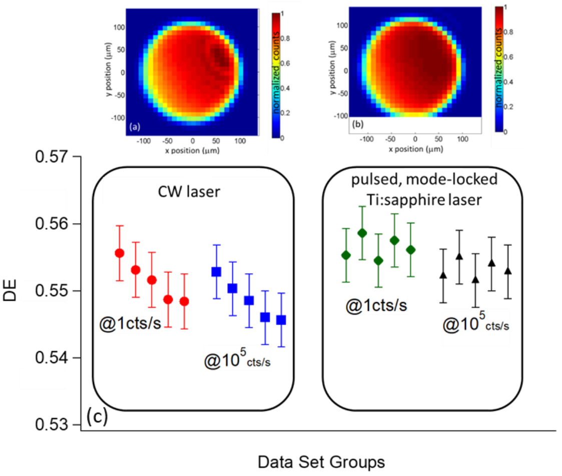

Figure 2. Measured DE for the NIST8103 detector at 1 cnt/s and 10^5 cnt/s made with CW laser and a pulsed Ti:sapphire laser, as labelled. Error bars represent the extracted standard uncertainties (k=1) for each measurement.

The CW laser results show a larger variation in the extracted DE at both count rates. The spatial response of the SPAD using the CW and Ti:sapphire laser, measurements are also shown. The CW laser results show fringes in the spatial response. Thus, it will have higher sensitivity to slight spatial misalignments than for the measurements made with the Ti:sapphire laser.

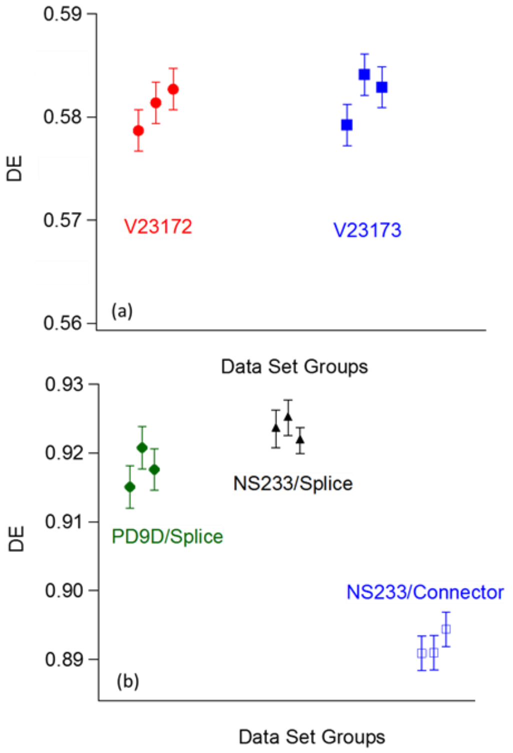

Figure 3. Summary of measurements for fiber-coupled detectors (a) V23172, V23173, and PD9D at 851.8 nm and (b) NS233 at 1533.6 nm. For detector NS233, fusion splicing and FC/PC connectors were used to connect the DUT fiber to the output of the FBS as indicated. Error bars are the extracted standard uncertainties (*k*=1) of each measurement

Figure 3 shows the extracted detection efficiencies at 10^5 cnt/s of three fiber-coupled detectors, two SPADs: V23172 and V23173 and one superconducting nanowire single photon detector (SNSPD): PD9D at a wavelength of 851.8 nm. The DEs for both SPADs were determined with an FC/PC fiber connector at the output fiber of the FPC, whereas the SNSPD's DE was determined by fusion splicing the detector fiber. Good setup reproducibility is observed for all three detectors. Figure 3 also shows the calibration results of an SNSPD optimized for 1550 nm (NS233) at a measurement wavelength of 1533.6 nm. The DE of NS233 was determined with an FC/PC fiber-to-fiber connector union and by fusion splicing the detector fiber to the output fiber of the FPC. The measured extracted DE at 10^5 cnt/s through a fusion splice is higher than that measured through an FC/PC connector, as expected. The repeatability between individual runs for both cases is comparable to the repeatability achieved for the 851.8 nm fiber-coupled measurement.

Table 1 summarizes the results of this work for all detectors at a count rate of 10^5 cnt/s. The DE and 95 % coverage intervals were calculated with the NIST consensus builder [2] and linear opinion pooling for the individual measurement outcomes for each detector. Relative expanded uncertainties as low as 0.70 % are achieved in the case of a fiber-coupled SNSPD at 1533.6 nm. Whereas for the free-space measurements at 851.8 nm, the relative expanded uncertainty is 1.8 % with a CW laser. The main source of uncertainty for the free-space measurements is the uncertainty in the detector response due to laser-beam-detector alignment. For all-fiber-coupled detectors this uncertainty is not relevant but is replaced with a connector and fiber-end reflection-loss uncertainty. In this study, we were not able to compare several FC/PC connectors to establish an uncertainty associated with different commercially available fiber connectors. However, we believe that for many different FC/PC connectors the loss uncertainty will be larger than our overall uncertainty budget. For the NS233 detector, we observe a ≈3.5 % lower system DE than when splicing the fibers. In the extreme case, an FC/PC connection may have very low losses (close to 0 %). Therefore, we speculate that this measurement already reveals a variation of at least 3.5 % in the extracted DE for the FC/PC connector method.

detector		DE at 10^5 cnt/s	95 % cov. int.	rel. exp. unc.(%)
NIST8103	fs, Ti:Sa	0.5532	[0.5449, 0.5615]	1.5
NIST8103	fs, CW	0.5490	[0.5397, 0.5587]	1.8
V23172	fc, FC/PC	0.5811	[0.5708, 0.5911]	1.8
V23173	fc, FC/PC	0.5821	[0.5735 0.5911]	1.6
PD9D	fc, splice	0.9178	[0.9066, 0.9292]	1.1
NS233	fc, FC/PC	0.8921	[0.8859, 0.8996]	0.73
NS233	fc, splice	0.9234	[0.9171, 0.9298]	0.70

Table 1. Summary of results for all measured single photon detectors. Quoted are the photon delivery method (fc: fiber-coupled, fs: free-space, Ti:Sa: Ti:sapphire laser, CW: CW laser, splice: fusion spliced, FC/PC: FC/PC fiber connector), mean DEs at 10^5 cnt/s, the 95 % coverage intervals and the relative expanded uncertainties (*k*=2).

REFERENCES

[1] T. Gerrits et al., Metrologia **57**, 015002 (2020)
[2] https://consensus.nist.gov/