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(Invited) Single Photon Detectors and Metrology

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For quantum applications, it is important to generate quantum states of light and detect them with extremely high efficiency. For future applications, it also important to do this at scale. This presents many engineering and metrology challenges. This paper discusses some of the open challenges and opportunities in single photon detector efficiency measurements, including the challenges of metrology for waveguide-integrated detectors on photonic circuits.

1. Introduction

As quantum optics experiments have matured in the past several decades, there is now a push to move them from academic research into commercial applications[1]. Examples of new quantum industries include quantum cryptography[2], secure random number generation[3], quantum computing[4], quantum networking[5], quantum sensing[6] as well as the commercial development of individual quantum components such as quantum light sources[7] and detectors[8]. The challenges of developing technology for commercial applications are different from initial research challenges. There is now a need for standardization, metrology, miniaturization, and scaling. In this article, we focus specifically on single photon detector efficiency metrology.

Single photon detectors are ubiquitous throughout many of the most important quantum technologies. Important figures of merit for these detectors include efficiency, wavelength, timing jitter, dead time and photon number resolution. In particular, very high efficiency is needed for quantum applications. For example, a recent loophole-free Bell test[9] required at least 72.5% total system efficiency to close the detector loophole. Quantum cryptography requires high efficiency to ensure security, and many of the protocols cease to be secure below a certain efficiency threshold. Typically, a higher detector efficiency will increase the length of the fiber link that can be implemented. For example, an important recently proposed quantum key distribution protocol requires greater than 85% total throughput efficiency[10], therefore making component efficiency one of the major practical barriers to implementation in fiber networks. Some proposed photonic quantum computing applications have even more stringent system efficiency requirements.

This presents a challenge for detector metrology. Great care must be taken to avoid embarrassment when measuring detectors with efficiencies approaching 100%, as any errors can lead to measurements of greater than 100% efficiency, a not-uncommon result for a first attempt. A typical optical fiber power meter calibration from a national metrology institute such as NIST has a standard uncertainty of around 0.55%[11] at the specified wavelength and power (typically in the 100 μW range), while the best optical radiometry measurements[12] at these power levels are accurate to 1 part in 10^5. To perform measurements of similar accuracy on single photon detectors requires transferring these calibrated measurements around ten orders of magnitude lower in power.

Furthermore, for many future applications, hundreds of detectors may be integrated on chip and accessed via on-chip waveguides. This will provide further challenges in terms of accurate measurements as well as in terms of scaling measurement procedures for fast and accurate measurements of hundreds of components. Integrated photonic metrology will need to be commonplace in a future with quantum networks and cryptography that rely on quantum photonic signals for communication.

2. High efficiency single photon detectors and applications

The main classes of single photon detectors in use are solid-state single photon avalanche diodes (SPADs), superconducting detectors, and photomultiplier tubes (PMTs). PMTs were historically the first technology with single photon detection capabilities but are rarely used today. SPADs are operated in Geiger-mode where they can only distinguish between zero or more photons, i.e. they do not have photon number resolution. Silicon based SPADs are the most commonly used detectors in the visible to near infra-red wavelength regimes below the silicon bandgap, with efficiencies typically in the 40-70% range depending on the precise type of detector[8]. SPAD development has been much more difficult in the infrared (IR), with high efficiency and low noise difficult to achieve simultaneously. This has led to the development of superconducting detectors that can work over a very broad wavelength range, due to the very small superconducting bandgap.

Superconducting single photon detectors have been demonstrated with single photon sensitivity from the ultra-violet at 250 nm[13] all the way to 10 μm[14] (although not simultaneously). Although the cryogenic operation required for superconducting detectors does increase the cost and complexity of experiments, the high efficiencies, high timing resolution and low dark counts still make these detectors the best option for many quantum experiments. Superconducting detectors come in several different types, the most important for single photon detection being transition edge sensors (TESs) and superconducting nanowire single photon detectors (SNSPDs). TESs work as very sensitive bolometers, operating at the edge of the transition from superconducting to normal, maintained by electro-thermal feedback. In practice, a superconducting material, such a tungsten, is deposited and lithographically patterned as a rectangular thin film with 25 μm sides on an insulating substrate. The resistance change due to heating by even a single photon can be measured due to the sensitivity around the superconducting phase transition. TES detectors are some of the few detectors that naturally exhibit photon number resolution. The disadvantage of TESs is that the response is slow relative to other detectors, and so the maximum count rate is relatively low without multiplexing techniques. Additionally, the transition edge temperature is typically around hundreds of millikelvin, requiring the use of a dilution refrigerator or similar.

Superconducting nanowire single photon detectors also use the superconducting to normal transition, but in a discrete rather than analog way. A thin film of a superconducting material is patterned into a narrow meandering wire. This material is typically either NbTiN or an amorphous silicide such as WSi or MoSi. The wire is cooled down below the superconducting transition temperature and current biased below the critical current. Unlike the TES, when a photon hits the wire, the hotspot it generates spreads via joule heating to the entire width of the wire, thus generating a normal region across the wire. This causes a voltage to be developed across the wire. Unlike TESs, this process is not sensitive to photon number, as multiple hotspots do not appreciably change the measured voltage. However, the recovery time is relatively fast (tens of nanoseconds), and count rates on these detectors can be as high as tens of MHz, while maintaining very low dark count rates. Another advantage of SNSPDs is that they typically operate at a higher temperature than TESs, in the 1-10K range, allowing operation in closed cycle or sorption pump cryostats. There have been very high efficiency demonstrations with both TES and SNSPD detectors with 98% total system efficiency demonstrated[15,16]. These ultra-high efficiencies do present measurement challenges, as we will discuss in the following section.

3. Single photon detector efficiency metrology

For optical metrology, at high powers, photon momentum can be used as a primary standard to measure the optical radiation pressure, with optical power traceable through the kilogram[17]. At lower powers, highly absorptive materials and electrical substitution is used. State-of-the-art measurements at the microwatt to milliwatt levels are made using optical radiometers[18]. A typical optical fiber power meter calibration is traceable to a measurement on an optical radiometer at a national metrology institute (NMI). The calibrations are typically only valid at a single optical power and wavelength. However, there is no primary standard that works at powers of the single photon level, which are generally in the attowatt to picowatt level. For example, one thousand photons per second at 1.5 um is around 150 aW, while one million photons per second is around 150 fW. The most commonly used method for calibrations at these powers is to translate the power from a calibrated power meter at higher powers, using one of the two techniques described below. However, for both techniques, care must be taken to ensure the calibration of the power meter used in the comparison. It is recommended that the power meter be calibrated at an NMI directly, as variations in commercial power meters are common.

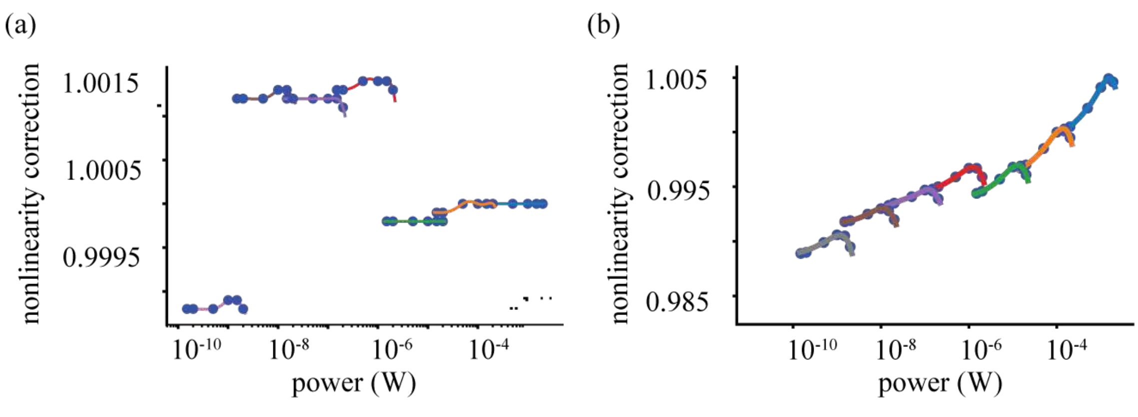

Figure 1. Nonlinearity correction for the same InGaAs power meter at (a) 1550 nm and (b) 850 nm. The lines are interpolated fits at each range on the power meter.

It is well known that the response of most power meters is spectrally dependent. However, it is less widely known that there is also a deviation from linearity with optical power. If the power meter is to be trusted at powers other than the power at which it received its absolute calibration, a nonlinearity correction must be made to the calibration factor[19]. Metrology institutes offer nonlinearity corrections for power meters, typically down to 150 pW. The nonlinearity correction for a commercial power meter is shown in Fig. 1 at (1) 1550 nm and (b) 850 nm. This power meter consists of an InGaAs photodiode with an associated amplifier. There is a nonlinearity effect within each range setting of the amplifier that is a combination of the photodiode nonlinearity and any amplifier nonlinearity. There are also discontinuities at range changes in the amplifier. For an accurate calibration, the photodiode must be calibrated with the amplifier. Note that the correction factors at 1550 nm are much smaller than at 850 nm. This highlights the importance of choosing the correct power meter at the correct wavelength; InGaAs detectors have a rapidly changing spectral responsivity around 850 nm, which also affects the power meter nonlinearity, and could additionally cause the calibration to be less stable over time and changing environmental factors.

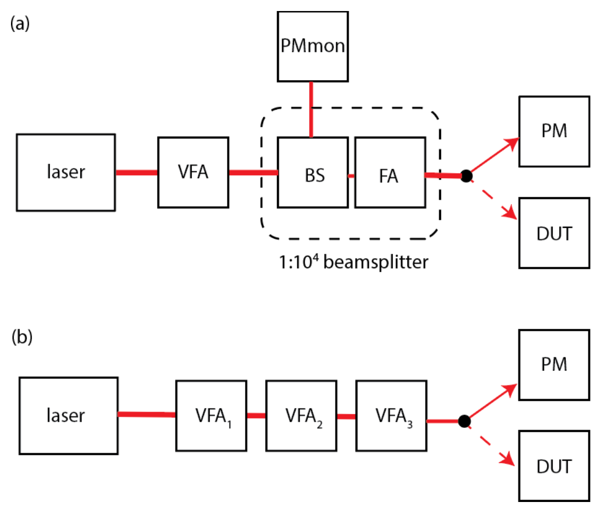

Figure 2. Overview diagram of (a) the beamsplitter technique and (b) attenuator technique for single photon detector calibration. FA = fiber attenuator. VFA = variable fiber attenuator. DUT = device under test. PM = power meter.

There are two main techniques for single photon detector efficiency calibration, shown in Fig. 2. Note that components used for stability and monitoring have been left out for clarity. The first technique is the “beamsplitter method”, shown in sketch part (a). In essence, a high ratio beamsplitter divides the power between a monitor power meter (PMmon) and a second power meter (PM), which can be directly substituted for the device under test. The beamsplitter is accurately characterized at high input powers, where both power meters are within calibration. The input power is then reduced with the input variable fiber attenuator, and the DUT is either spliced in or translated in place of PM. The beamsplitter method requires two power meters which have been calibrated at the wavelength of interest and with a nonlinearity correction. It has been demonstrated at 1550 nm with 0.7 % uncertainty, and 850 nm with 1.8 % uncertainty (k=2)[20].

A second method involves measurement of three independent attenuators and direct substitution of the DUT with a calibrated PM. The technique is shown in sketch in Fig 2b. The first basic principle is that each attenuator is measured in turn, and it is assumed that the attenuators sum linearly without any interference terms. The second important point is that the nonlinearity of the PM can be calibrated in situ in the setup, without the requiring the nonlinearity corrections done by an NMI. This is done by assuming that the first range on the power meter, around 100 microwatts, where it received its absolute calibration, is correct. The attenuators are each calibrated within that first range. For example, each attenuator is set to in turn to the 3 dB setting, while the others are set to zero. The actual attenuation value at that attenuator setting will then be measured within the first range. Once 3 dB has been calibrated on each attenuator, attenuator 1 and attenuator 2 are both set to 3 dB, such that the optical power is in the portion of overlap between the first two ranges. In this way the ranges can be compared at the same input optical power using the attenuators calibrated using the first range setting. The calibration can be transferred down through the ranges using this technique. Finally, once the attenuators and nonlinearity have been measured accurately, the DUT can be directly substituted for the PM. The major advantage of this technique is that requires only a single power meter calibrated at one power, which is a significant cost savings over the beamsplitter technique, which requires one absolute power calibration and two power meters with nonlinearity corrections (each calibration and correction costs several thousand dollars from most NMIs). The triple attenuator technique has been demonstrated with a standard uncertainty of 0.5% (note this is 1% at k=2, for fair comparison to the beamsplitter method uncertainty) at 1550 nm, and over a 40 nm bandwidth[21]. The broadband calibration was made possible by the relatively fewer power meter calibrations required. A disadvantage of this technique is that it relies on the repeatability of each attenuator, as attenuation values will be measured individually with a single power meter. The disadvantage of this technique is that the validity of the assumptions for the attenuators may be brand or model dependent and are not well characterized.

As a final aside, it is interesting to note that the precision of optical radiometry is significantly less than that of other physical values such as voltage and frequency, which can be measured absolutely close to 1 part in 10^{10} and 1 part in 10^{18} respectively[22,23]. While current methods for measuring single photon detector efficiency rely on primary standards at higher optical powers, the prospect of developing a primary standard at the single photon level could improve low power calibrations, and potentially lead to the development of lower uncertainty measurements at higher optical powers by using a bottom-up approach. There have been other single photon detector efficiency calibration techniques that show promising results for this type of bottom-up approach, including spontaneous parametric downconversion[24] based calibrations or using synchrotron radiation[25].

4. Integrated quantum photonics

Many of the more exciting future applications of single photon detectors involve integration into complex photonic circuits. For example, several companies are developing linear photonic quantum computing platforms[26] that will require hundreds of detectors on a single chip. Other companies are developing quantum modems that will necessarily contain photonic components, with the goal of transferring quantum data between different types of quantum computers, in what is being dubbed the quantum internet. SNSPDs, SPADs and TESs have all been demonstrated in on-chip waveguides compatible with this type of system. Fig. 3a shows the principle of operation of a waveguide-coupled SNSPD. The nanowire is patterned on top of waveguide, for example in silicon-on-insulator. The mode of the waveguide is evanescently absorbed as it travels through the part of the waveguide with the detector. If the detector is long enough, the light will be completely absorbed. Fig. 3b shows an example of a complex integrated photonic circuit with fifteen SNSPDs. The device shown is cooled in a cryostat, with light coupled into the on-chip waveguides via grating couplers[27]. The bow-tie like structures near the gratings are SU-8 collars designed to hold the fiber. Coupling light into waveguides in a cryostat with high coupling efficiency is a major challenge. The metrology of waveguide coupled detectors in general is an ongoing challenge, due to the difficulties in characterizing coupling losses well enough to accurately measure the absolute power levels in on-chip waveguides.

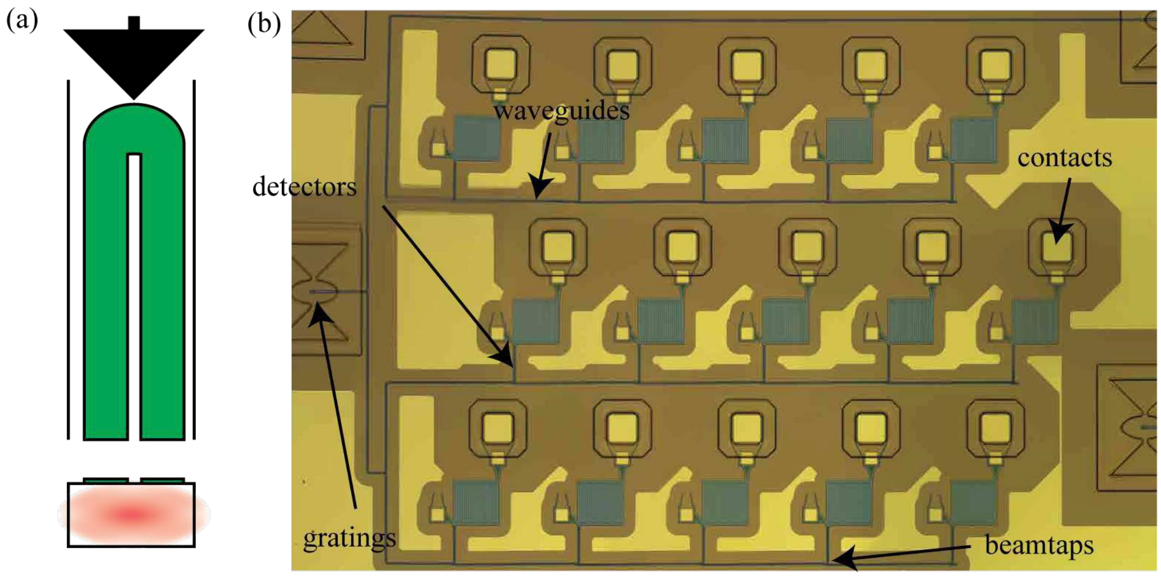

Figure 3. Principle of operation of a waveguide coupled superconducting nanowire single photon detector. (b) Example of a photonic integrated circuit with superconducting nanowire single photon detectors.

5. Conclusions and outlook

In this paper, we discussed the challenges involved in single photon detector efficiency metrology. Very high efficiency detectors are key for many quantum applications. The development of high efficiency detectors will require low uncertainty metrology, which poses challenges due to the lack of availability of a primary standard at the power levels required for calibration. Carefully measuring detector efficiencies by comparison with NMI calibrated power meters can give uncertainties of less than 1%. However, the development of new primary standards at the single photon level could improve the accuracy of radiometry measurements both at the single photon level and at higher power levels, as well as providing a better method for calibration of detectors on photonic integrated circuits.

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