Superconducting Nanowire Single-Photon Detectors for Quantum Communication Applications

Chandra M. Natarajan[1], Martin M. Härtig[1], Ryan E. Warburton[1], Gerald S. Buller[1], Robert H. Hadfield[1], Burm Baek[2], Sae Woo Nam[2], Shigehito Miki[3], Mikio Fujiwara[3], Masahide Sasaki[3], and Zhen Wang[3]

[1] Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom
[2] National Institute of Standards and Technology, Boulder, CO 80305, USA
[3] NICT, Tokyo, 184-8795, Japan
`cmn10@hw.ac.uk`

Abstract. Single-photon detectors are a key enabling technology for optical quantum information processing applications such as quantum key distribution. A new class of single-photon detectors have emerged based on superconducting nanowires. These detectors offer sensitivity at telecommunication wavelengths (1310nm and 1550nm) with low dark counts and excellent timing resolution at an operating temperature of ~4 K. We have integrated four independent fibre-coupled detectors into a practical closed-cycle refrigerator and plan to employ this multichannel detector system in advanced quantum information processing experiments.

Keywords: Superconducting nanowire single photon detectors, SSPD, SNSPD.

1 Introduction

Photons have been widely used in Quantum communication systems due to low noise (or decoherence). High speed single-photon detectors with very low dark counts and high quantum efficiency at the wavelength of interest are ideal requirements for quantum communication systems [1]. At wavelengths below 1000 nm, Silicon Avalanche Photodiodes are the detectors of choice offering high efficiency (~40% at 850 nm) combined with low dark counts (100 Hz). However, for long distance transmission over optical fibre, the ideal operating wavelengths are 1310 nm and 1550 nm. At these wavelengths, Quantum Key Distribution (QKD) experiments have employed InGaAs detectors to achieve distances up to 120km [2]. These detectors typically require cooling to 200 K and offer reduced detection efficiency (~10%). Afterpulsing from InGaAs detectors necessitates long dead times, reducing count rates. Also gated operation is required to reduce the high dark count rate. A new class of single-photon detectors based on superconducting nanowires hold considerable promise for QKD, offering single photon sensitivity at telecom wavelengths, combined with low dark counts, short recovery times (<10 ns) and picosecond timing resolution (<100 ps).

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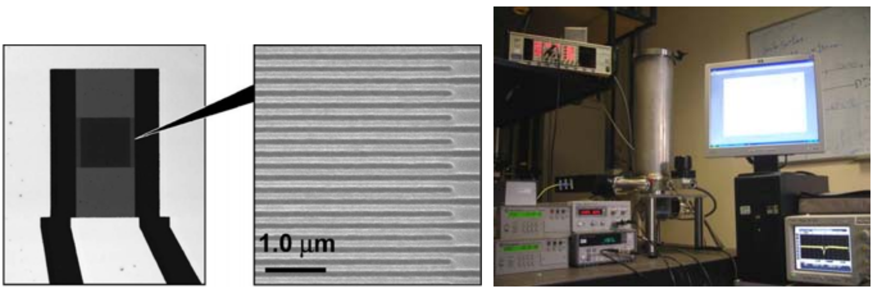
2 Detector System Design and Construction

2.1 Detector Technology

The basic operating principle of the superconducting-nanowire single photon detector (SNSPD) is as follows [3]: A 100 nm width wire is defined in a 4 nm thick niobium nitride film. The wire is cooled to ~4 K (below the superconducting transition temperature) and biased close to its critical current. When a visible or infrared photon strikes the wire, the current distribution is perturbed and a short voltage pulse is triggered. To improve the optical coupling efficiency a meander-type geometry is used [4] – the wire is folded back on itself to cover an area up to 20µm x 20µm [5] with a 50% fill factor. The meander pattern is embedded in a 50 Ω coplanar waveguide structure (Fig. 1a). Efforts are also underway to boost the efficiency further using optical cavity designs [6], although these detectors are not yet in widespread use.



(a) (b)

Fig. 1. (a) Scanning electron micrograph (SEM) of SNSPD device [5], (b) Superconducting nanowire single-photon detector system based on a closed-cycle Gifford-McMahon refrigerator at Heriot-Watt University, UK

2.2 Closed-Cycle Refrigerator

Over the past decade, commercially available closed-cycle cryocoolers have improved both in terms of attainable base temperature and reliability [7]. The smallest available unit (Gifford-McMahon type), provides 0.1 W of cooling power at 4 K. This runs off a 13A electrical outlet and requires only air cooling. This is sufficient to cool multiple superconducting detector packages [8]. A passive standoff stage with a long thermal time constant is implemented for temperature stability, with a modest increase in base temperature (2.9 K versus the cold head base temperature of 2.5 K) [8]. Several versions of this system have now been constructed by the authors and are now in use in the USA, Japan and Europe. The current version at Heriot-Watt University, UK has four detectors channels (Fig. 1b), and is capable of accommodating up to eight detector channels – required for advanced quantum information processing experiments.

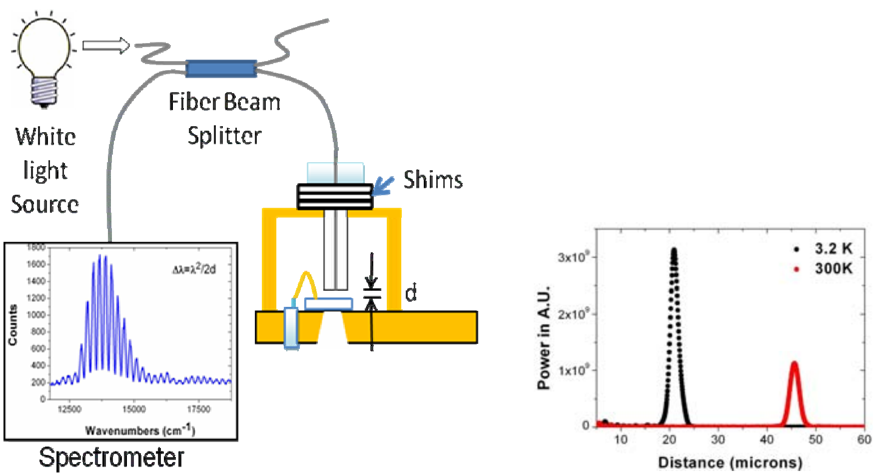
2.3 Optical Alignment

Photons are fibre-coupled to the meander nanowire devices. Proper alignment is essential for the efficiency of the system as in any other optics setup. The challenge lies in aligning the device at room temperature and subsequently cooling the package down to ~3K without affecting the alignment. It is important that two parameters, firstly the separation between the fibre ferrule and the device (*d*) and secondly the x-y alignment, are precisely controlled and maintained over repeated thermal cycling in order to avoid the need for realignment after every thermal cycle.

In our setup (Fig 2.a) white light interferometer [9] is used to study and control the separation between the fibre ferrule and the device. Light from a broad spectrum light source is launched through a fibre coupler (50:50 @ 700 nm) that splits it into two halves, one of which is dumped and the other half is coupled to the device using a polished ferrule. A fraction (~4%) of the light is reflected back from the polished end of the ferrule, 33% of the remaining light is reflected back from the device surface and the rest of the light gets transmitted through the device. The two reflected signals interfere at the coupler and a spectrometer (350-1000nm) is used to study the interference intensity profile over the broad spectrum. The separation (*d*) can be retrieved from the frequency of the interfered signal using the equation (Fig. 2b)

$$\Delta\lambda = \lambda^2 / 2d \,. \tag{1}$$

While packaging the device and the ferrule, precisely machined shims are introduced to vary *d*. At room temperature, *d* is set to ~50µm and as the package is cooled down to ~3K, it contracts and *d* reduces to about ~25µm (Fig. 2b).



(a) (b)

Fig. 2. (a) White light interferometry setup, (b) distance (d) at 300K and 3.2K

In order to achieve accurate x-y alignment, the sample holder and the ferrule holder are secured onto a platform and a sub-micron x-y alignment stage respectively (Fig. 3). A 1550nm beam from a diode laser is sent through the fibre ferrule, the beam emanating from the ferrule is transmitted through the device and is viewed using a long working distance near-infrared objective (50x). Acceptable alignment is achieved via careful positioning of the x-y alignment. Thereafter the ferrule holder and sample holder are fixed together using screws. The alignment is performed at room temperature and the package is attached to the standoff stage in the cryostat, which is maintained at about 3.2K. This robust packaging scheme enables the alignment to be preserved over repetitive thermal cycling between room temperature and cryogenic temperatures.

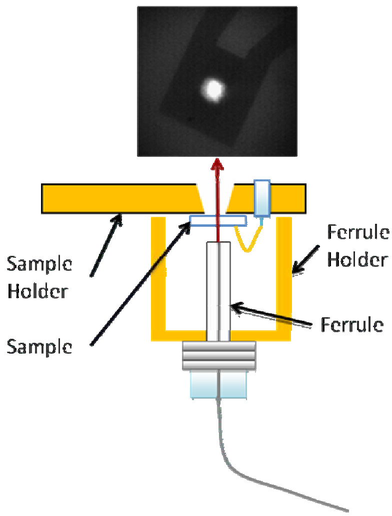


Fig. 3. Fibre ferrule – device alignment setup

3 Practical Detector System Performance

3.1 System Detection Efficiency at 830nm, 1310nm and 1550nm

System detection efficiency (η) of the detector is determined by calculating the ratio of number of photons detected to number of photons sent into the system, without subtracting the losses in the optical path inside the system. The schematic setup used to determine η at a given wavelength for a fibre coupled detector, is shown in figure 4. A laser diode, gain switched by a pulse pattern generator (PPG), generates optical pulses at the drive frequency f, which are attenuated using two programmable digital attenuators. Each attenuator is calibrated upto 60dB, therefore resulting in a range of 0-120dB attenuation when used in series. The device is current biased at various bias points and the corresponding dark counts (D) of the device are measured. An average number of photons per pulse (μ) is controlled by varying the output power of the diode and the attenuation. The incident photon flux is varied and the corresponding response from the device is recorded as R counts per second. η is extracted by fitting the data to the following curve [8]:

$$R = D + f\left(1 - e^{-\eta\mu}\right). \tag{2}$$

η improves at shorter wavelengths due to higher photon energy (Fig. 5a). As the bias current approaches the critical current of the nanowire, the device become more sensitive, picking up electronic and thermal fluctuations resulting in higher dark count rates. The device can be operated at an appropriate bias point depending on the signal-to-noise and detection efficiency requirements of the experiment.

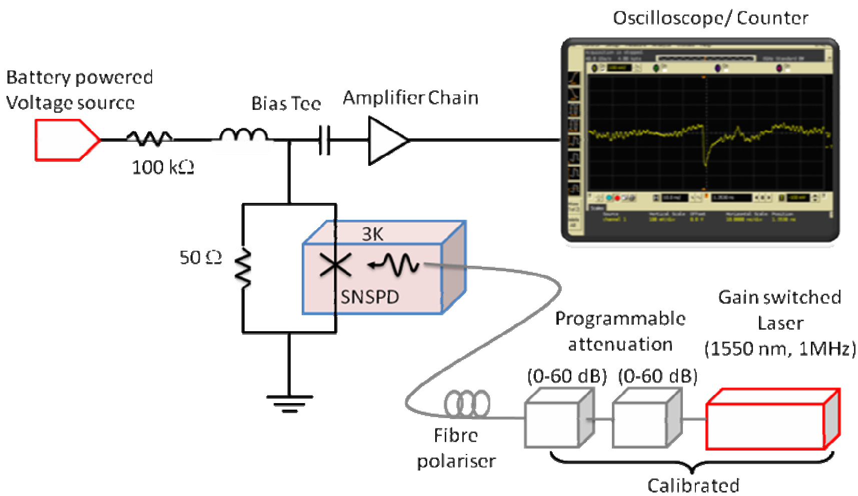
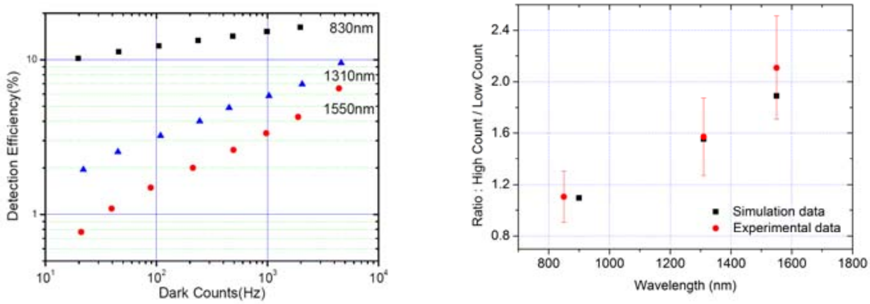


Fig. 4. System detection efficiency characterization setup

3.2 Polarization Dependence

The meander SNSPD device is observed to possess noticeable polarization sensitivity. It has been reported [10] that the count rate from the detector displays a maximum and a minimum value depending on the orientation of the electric field being either parallel or perpendicular to the orientation of the nanowire. In our setup, the polarization dependence is observed by varying the polarization of the incident photons using a fibre polarizer. The fibre polarizers are adjusted either to high or low count rate and the η is subsequently measured. The experimental ratios of the high count rate η_{high} to that of low count rate η_{low} are well in accordance with results from simulations (Fig. 5b). However, the measurements from the 830nm experiment were taken using the same single mode telecom fibre. This could affect the polarization control of the 830nm photons owing to the possible multimode nature of the fibre below 1200 nm.



(a) (b)

Fig. 5. (a) Practical SNSPD system detection efficiency η versus ungated dark count rate D for a fibre-coupled detector at wavelengths 830nm, 1310nm and 1550nm, (b) Comparison of experimentally-determined polarization sensitivity (η_{high}/η_{low}) versus wavelength, plotted with simulations

3.3 Detector Timing Jitter

In QKD experiments, timing jitter of the detectors plays a major role in determining the total key transmission rate [11]. Jitter is usually given by the full width half maximum (FWHM) of the histogram of the detection time of photons. In our setup (Fig. 6), a picosecond diode laser (1550nm) driven by a pulse/pattern generator is used to generate photon pulses. The pulses are attenuated to single photon per pulse regime and coupled to the SNSPD. Sync pulses from the laser driver and output pulses from the detector are used to start and stop the time-correlated single-photon counting (TCSPC) card respectively. The TCSPC card generates a histogram of the start-stop intervals (Fig. 7). The data was recorded with a TCSPC card with a timing resolution of 10ps and the binning width of 4ps. The histogram has a Gaussian profile and a FWHM of ~70ps.

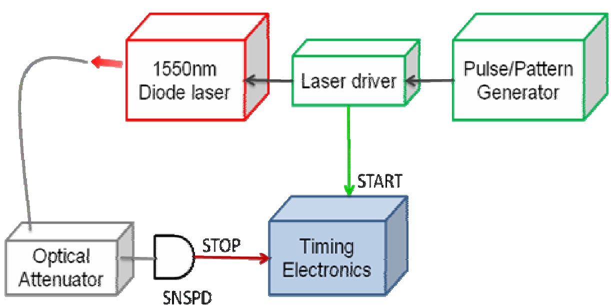


Fig. 6. Instrument response curve of a fibre-coupled detector (1550nm laser diode excitation)

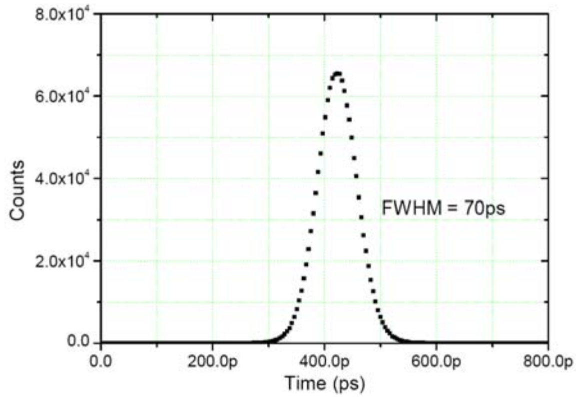


Fig. 7. Instrument response curve of a fibre-coupled SNSPD (1550nm picosecond laser diode excitation)

4 Conclusion and Outlook

Superconducting nanowire single-photon detectors (SNSPDs) are a promising new technology for telecom wavelength quantum key distribution. The detectors can be implemented into closed-cycle refrigerator systems for practical operation. Record bit rates and transmission distances have been achieved in QKD experiments exploiting this detector technology [11-15]. In the near future, there are plans to employ these devices in various experiments such as (i) characterization of single photon sources at telecom wavelengths [16], (ii) long distance, high bit rate QKD experiments and (iii) to operate these devices with quantum waveguide circuits [17]. Considerable improvements in practical detector performance are anticipated [6] and we expect these detectors to play a significant future in the field of quantum information processing.

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