Superconducting nanowire single-photon detectors for quantum key distribution

Robert H Hadfield, Chandra Mouli Natarajan, (1) Burm Baek, Sae Woo Nam (2) Shigehito Miki, Mikio Fujiwara, Masahide Sasaki, 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, Japan
Contact email: r.h.hadfield@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 infrared sensitivity with low dark counts and excellent timing resolution at an operating temperature of 4 K. We have integrated these detectors into practical closed-cycle refrigerator systems and employed them in a succession of quantum information processing experiments.

Introduction

The ideal single-photon detector for quantum key distribution (QKD) would have high speed, zero dark counts and high quantum efficiency at the wavelength of interest [1]. At wavelengths below 1000 nm, Silicon Avalanche Photodiodes are the detectors of choice offering high efficiency (up to 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. Long transmission distances (up to 120 km) have been achieved in QKD experiments using InGaAs detectors [2]. These detectors typically require cooling to 200 K, offer reduced detection efficiency (20-30 %), and are limited to count rates of ~100 kHz. Furthermore, gating is essential to reduce the high dark count rate. A new class of 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).

Detector technology

The basic principle of the superconducting nanowire single photon detector 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 20 µm x 20 µm [5] with a 50 % fill factor. Efforts are also underway to boost the efficiency further using optical cavity designs [6], although these detectors are not yet in widespread use.

Practical performance at 1310 nm and 1550 nm

The most important question for end-users is the following: what is the practical efficiency of the detector, inclusive of coupling losses? In our packaging scheme [7], we use single-mode telecommunications fibre (Corning SMF28, 9 µm core diameter). A polished fibre is aligned to the detector at room temperature with micrometre precision, and fixed in place mechanically in a robust package that will survive thermal cycling to cryogenic temperatures. The performance of a typical fibre-coupled detector is shown in figure 1. Measurements of practical detection efficiency and ungated dark count rate are shown at 1310 nm and 1550 nm. The input polarization is controlled (as the meander device has noticeable polarization sensitivity). Note that the detector also has extremely low timing jitter (below 100 ps FWHM). In the context of QKD, this means that the ratio of dark counts to detected photons per time bin (the dominant contribution to the error rate, QBER, with large link loss) can be driven down, either by aggressive time stamping or by moving to very high clock rates.

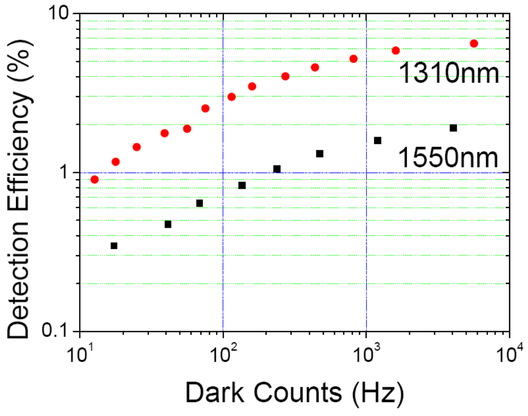

Figure 1: Practical system detection efficiency versus ungated dark count rate for a fibre-coupled detector at 1310 nm and 1550 nm wavelength.

Closed-cycle detector system

Over the past decade, commercially available closed-cycle cryocoolers have improved both in terms of attainable base temperature and reliability. The smallest available unit (Gifford-McMahon type), provides 0.1 W of cooling power at 4 K. This is sufficient to cool multiple detector packages. 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) [7]. Several versions of this system have now been constructed by the authors and are now in use in the USA, Japan and Europe. The most recent versions are capable of accommodating four or even eight detector channels – required for advanced quantum information processing experiments.

QKD implementations

Superconducting nanowire single-photon detectors packaged in practical closed-cycle refrigerator systems have been used in a succession of QKD experiments in collaboration with leading international groups. The first successful implementation of superconducting nanowire single-photon detectors in QKD was carried out at BBN technologies, USA [8]. In a phase-encoding system operating at 1550 nm clocked at 3.3 MHz, secure key was transmitted (using the BB84 protocol) over 12 dB channel loss (42 km optical fibre). In the first high clock rate demonstration [9] (B92 protocol, polarization encoding, $\lambda = 850$ nm, 3 GHz clock rate) a low enough error rate was achieved for secure key distillation up to 25 km range. Shortly afterwards, the detectors were implemented in a long range, high bit rate experiment [10] (DPS-QKD protocol, λ=1550 nm, clock rate 10 GHz) achieving an overall range of 40 dB (200 km in fibre). In a recent field trial [11] (BB84 protocol, λ=1550 nm, clock rate 625 MHz) a low enough error rate was achieved for secure key transmission over 97 km of installed fibre. In another recent demonstration [12] (decoy state, phase encoding, λ=1550 nm, clock rate 10 MHz) secret key was distilled at a maximum range of 145 km in fibre.

Conclusion and outlook

Superconducting nanowire single-photon detectors 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 [10]. Considerable improvements in practical detector performance are anticipated [6] and we expect these detectors to play a significant enabling role in the field of quantum information processing.

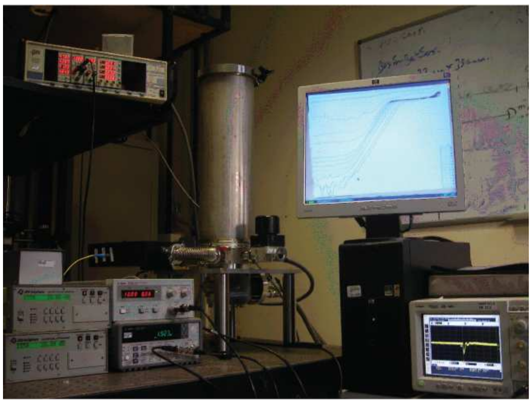

Figure 2: Superconducting nanowire single-photon detector system based on a closed-cycle Gifford-McMahon refrigerator at Heriot-Watt University, UK

Acknowledgements

RHH acknowledges support from the Royal Society of London and the Engineering and Physical Sciences Research Council (UK). We thank our many collaborators (BBN Technologies, Heriot-Watt, Stanford, NTT, NEC, LANL) and G. N. Gol’tsman for providing detectors for many of the experiments.

References

1. N. Gisin, *et al.* Rev. Mod. Phys. **74,** 145-196 (2002).
2. C. Gobby *et al.* Applied Physics Letters **84** 19 3762 (2004)
3. G. Gol’tsman *et al* Applied Physics Letters **79** (6) 705 (2001)
4. Verevkin *et al* Applied Physics Letters **80** (25) 4687 (2002)
5. Miki *et al* Applied Physics Letters **92** 061116 (2008)
6. K. Rosfjord *et al* Optics Express **14** (2) 527 (2005)
7. R. Hadfield *et al* Optics Express **13** (26) 10846 (2005)
8. R. Hadfield *et al* Applied Physics Letters **89** 241129 (2006)
9. R. Collins *et al* Electronics Letters **43** (2) (2007)
10. H. Takesue *et al* Nature Photonics **1** (6) 343 (2008)
11. A. Tanaka *et al* Optics Express **16** (15) 11354 (2008)
12. Rosenberg *et al* arXiv:0806.308