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Low-temperature optical photon detectors for quantum information applications

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Abstract

There is increasing interest in using high-performance cryogenic optical photon detectors in a variety of applications in quantum information science and technology. These applications require detectors that have extremely low dark count rates, high count rates, high quantum efficiency, and moderate energy resolution for IR to optical photons. We describe three applications, quantum key distribution, quantum optics with spontaneous parametric down converters, and linear optical quantum computing. We also describe preliminary results using a superconducting tungsten transition-edge sensor in a quantum key distribution system and a quantum optics experiment with spontaneous parametric down converters.

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Keywords: Quantum information; Quantum optics; Quantum computing; Single photon detector; Photon number detector

1. Introduction

Quantum information science and technology is a fast-growing field of research where information is represented quantum mechanically. Typically, binary information is coded in the form of a two-state quantum mechanical system such as two polarization states of a photon, two energy levels of an atom, two spin directions of an electron, or two types of neutrinos. Coding information quantum mechanically has opened up a rich area of research in both information science and basic physics [1].

Development of low-temperature detectors such as superconducting tunnel junctions [2] and transition-edge sensors [3] has been motivated by astronomy and astrophysics applications where information such as time-of-arrival and photon energy is desired at the single photon level [4]. Now, similar performance is needed in many areas of quantum information science. In particular, it is desirable that photon detectors have no dark counts, high detection efficiency, and operate at visible and/or telecommunication wavelengths (300–1500 nm).

In this paper, we will discuss three possible quantum information applications for low-temperature detectors, quantum key distribution, quantum optics, and linear optical quantum computing.

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2. Quantum key distribution

In the early 1980s, Gilles Brassard and Charles Bennett recognized that information encoded in a quantum mechanical system could be transmitted in such a way that, in principle, it is impossible to eavesdrop without detection [5]. Their first protocol, known as BB84, and many protocols that have been developed since BB84 encode one bit of information in one photon and use concepts in quantum mechanics to provide unconditional security. The critical concepts are that it is impossible to clone a single photon in an unknown quantum state and that any attempt by an eavesdropper to measure the photon alters the photon and disrupts the communication channel in an easily detectable way.

Practically, quantum communication or quantum key distribution (QKD) systems that are unconditionally secure are difficult to implement because of limitations in photon sources and photon detectors. The dark count rates in conventional silicon and InGaAs avalanche photodetectors (APDs) limit the security and range of QKD systems. In addition, it is desirable in long distance communications to use detectors that can efficiently detect photons at the telecommunication wavelengths, 1310 and 1550 nm.

We have used a superconducting tungsten transition-edge sensor (W-TES) in a fiber QKD system to take advantage of its low dark count rate and sensitivity at the telecommunication wavelengths. In an experiment performed jointly with researchers at Los Alamos National Laboratory, we replaced conventional InGaAs APDs with W-TES detectors in a system to generate secure key material. Fig. 1 shows the distribution of photon arrival times from a faint, 1310 nm laser pulsed at 100 kHz. The photons that contribute to the main peak are encoded with the key material and the counts outside the peak correspond to stray light leaking into the fiber that effectively limits the performance of the link. In a real system, this stray light reaching our TES detector would limit the effective range of the QKD link. To simulate different lengths of fiber between the transmitter (Alice) and the receiver (Bob), different amounts of attenuation were inserted between Alice and Bob to mimic fiber losses. Preliminary analysis indicates that the effective range of the QKD system using TES detectors was similar to those based on APDs. We expect significant improvement in the performance of the TES system once stray light is eliminated from the system.

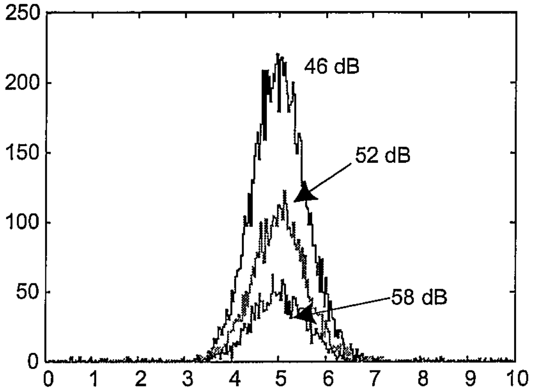

Fig. 1. Distribution of photon arrival times from a faint laser at 1310 nm pulsed at 100 kHz in a QKD system. The different curves represent different amounts of attenuation between "Alice" and "Bob". Counts outside the main Gaussian peak indicate stray light leaking into the system.

A significant drawback of using low-temperature detectors in a QKD system is the intrinsic speed (rise and fall time) of the devices. Fast rise times are necessary to timestamp the arrival of the photon accurately and to take advantage of time gating to effectively reduce the background count rate. Fast decay times are needed so that the photon source can be pulsed at a high rate. These disadvantages could be overcome by engineering devices with sufficient bandwidth to count photons at rates greater than 1 MHz.

3. Quantum optics

There are a variety of applications in quantum optics that need detectors with high quantum efficiency at visible and telecommunication wavelengths, very low dark count rates, and photon number resolution (the ability to count the number photons in a weak pulse of light). Photon-number-resolving detectors have been demonstrated with low-temperature detectors at both visible wavelengths [6] and telecommunication wavelengths [7]. In quantum optics, optical detectors with high quantum efficiency and number resolving capability are desired for a full accounting of the distribution of photons at all the detection points. For example, in a Hong-Ou-Mandel interferometer [8], two indistinguishable photons incident on a simple beam splitter emerge from the splitter as a pair out of the same output port. Because conventional single-photon detectors cannot distinguish one photon from multiple photons, evidence of the photon pairing at the output ports of a beamsplitter has always been observed indirectly as a reduction in coincident counts in detectors positioned at the outputs. Recently, we have demonstrated for the first time direct measurements of the pairing of two photons in a Hong-Ou-Mandel interferometer with a tungsten transition-edge sensor [9].

The optical circuit in Fig. 2 is another example of an experiment now possible with a photon number resolving detector. In this experiment, photon pairs are generated using a 351 nm laser to pump a BaB_2O_4 (BBO) nonlinear crystal aligned to generate two orthogonally polarized, collinear photons. A dichroic mirror and colored glass filter are used to filter the pump beam. Polarizers are placed at the output ports of a conventional beam splitter and rotated. In Fig. 3, we observe directly for the first time the modulation of the rate of photon pairs hitting one of the photon number resolving detectors as a function of relative polarizer angles.

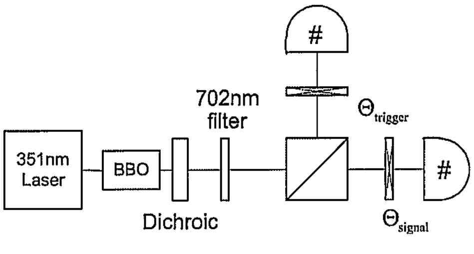

Fig. 2. Optical diagram of a classical interference experiment using a spontaneous parametric down converter crystal and a low-temperature detector used to count photons in a weak pulse of light.

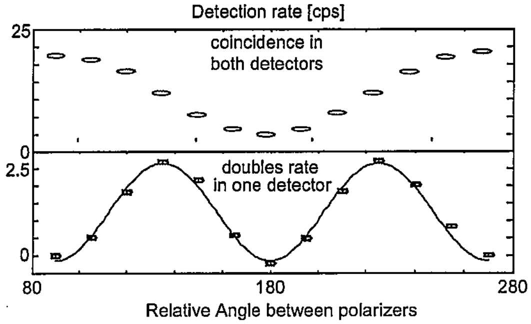

Fig. 3. The upper figure is the rate of one photon reaching each detector (coincidence rate) as a function of relative angle between polarizers. The lower figure is the rate of two photons detected by one detector. The predicted modulation is drawn as a guide.

4. Linear optical quantum computing

Quantum computing or quantum information processing promises to greatly increase the efficiency of solving classically difficult problems such as factoring [10] and searching [11]. Many experimental systems are being explored as the basic technology for building a quantum computer [12] utilizing "qubits", where the state of the qubit is encoded as a superposition of two states. Recently, schemes have been proposed for implementing a quantum computer with linear optical components and photon-number-resolving detectors [13,14].

In the schemes proposed, detectors with extremely high quantum efficiency (>99.99%), photon-number-state resolving capability, and high count rate (>1 MHz count rate) are needed to perform efficient and scalable linear optical computing. Despite high detector performance requirements, many basic building blocks in quantum computing can be built and studied probabilistically with non-ideal detectors. However, it is necessary to use detectors that have the ability to count the number of photons in a weak pulse of light. Consequently, low-temperature detectors are potentially very useful in exploring quantum computing with photons.

The minimum set of components required to build a quantum computer are arbitrary single qubit operations (rotations) and a controlled-not gate. An arbitrary single qubit operation is basically a rotation of bases, so for a photon qubit encoded with polarization states where

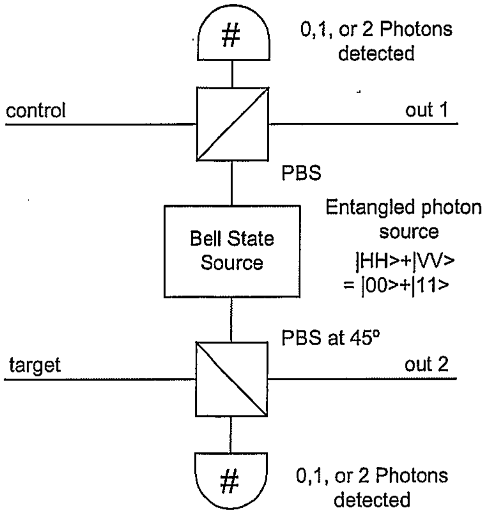

Fig. 4. Controlled-not gate implemented with photon-number-resolving detectors and a source of entangled photon pairs (Bell state source). When one and only one photon is detected in each detector, the circuit has successfully implemented a controlled-not gate. The probability of success ignoring photon loss mechanisms is 0.25.

horizontal polarization corresponds to "0" and vertical polarization corresponds to "1" a half wave-plate would be a qubit operation. A controlled-not gate is a two input and two output qubit gate where a "not" operation is applied to one of the inputs (target) if the other input (control) has a logical value of "1".

Fig. 4 is an example of a proposed controlled-not gate using the previously described polarization basis that uses two photon-number-resolving detectors [15]. The operation of this gate requires two ancilla photons that are an entangled photon pair in one of the Bell states. The output of this gate is not deterministic, but probabilistic. When one and only one photon is detected in each of the detectors, a controlled-not operation has been successfully performed. In this optical circuit, the operation is successfully performed one-fourth of the time ignoring photon losses.

5. Summary

We have described three applications in quantum information science that can effectively use low-temperature optical photon detectors. These applications are only a small sampling of possible opportunities in quantum information. Further improvements in quantum efficiency, energy resolution, and speed of low-temperature detectors such as TESs and STJs will accelerate the use of these detectors in this new field of science.

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