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Efficient detection of an ultra-bright single-photon source using superconducting nanowire single-photon detectors

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ABSTRACT

We investigate the detection of a single-photon source using highly efficient superconducting nanowire single-photon detectors (SNSPDs) at telecom wavelengths. Both the single-photon source and the detectors are characterized in detail. At a pump power of 100 mW (400 mW), the measured coincidence counts can achieve 400 kcps (1.17 Mcps), which is the highest ever reported at telecom wavelengths to the best of our knowledge. The multi-pair contributions, the experimental and theoretical second order coherence functions, and the saturation property of SNSPD are analyzed in detail. The experimental data and theoretical analysis should be useful for the future experiments to detect ultra-bright down-conversion sources with high-efficiency detectors.

1. Introduction

Over the last two decades, quantum information science has become an attractive field in physics, and many experimental efforts have been devoted in order to demonstrate complicate quantum information protocols [1,2]. For further development of this field, more sophisticated photon engineering and detection technologies are indispensable, but it is limited by the performance of conventional photon source and detectors. In this paper, we provide state-of-art technologies of our photon source and detectors in order to overcome such difficulties.

From the perspective of single-photon detectors, many different kinds of detectors have been developed for quantum information applications [3]. At the near-infrared (NIR) wavelength range (around 800 nm), since the existence of highly efficient silicon avalanche photodiodes (APD, e.g., SPCM, PerkinElmer), many important experiments have been demonstrated at this wavelength range [2]. At the telecom wavelength range (around 1550 nm), however, experiments suffered from the low performance of the detectors [4]. The recent dramatic development of superconducting nanowire single-photon detectors (SNSPDs) [5] with high system detection efficiency (SDE) can solve this problem. For example, the NIST group has demonstrated SNSPDs with tungsten silicide (WSi) with a 0.93 SDE at a temperature around 0.12 Kelvin (K) [6]. The MIT group has shown a niobium nitride (NbN) SNSPDs array with a 0.76 SDE at 2.5 K [7]. The NICT group has reported SDE of 0.76 in niobium titanium nitride (NbTiN) SNSPDs [8], and 0.61–0.80 SDE SNSPDs with low filling-factor at 2.3 K [9]. Such SNSPDs are promising for quantum information applications because they have the merits of high efficiency, wide spectral response, short recovery time (high speed), low dark count rate, low timing jitter, and free-running operation [5].

Although the performance of these high-efficiency SNSPDs has been widely characterized [6–9], in all these reports, SNSPDs were tested and characterized with a classical weak coherent state, never exploiting its high performance with a quantum light source. The weak coherent states follow a Poisson distribution, while the single-photon state from a down-conversion source follows a geometric distribution. These two statistics affect the performance of SNSPDs differently, especially at high pump power regime. Therefore, the first motivation of our experiment is to investigate the performance of such high-efficiency SNSPDs with a single-photon source. We measure the spectral range, analyze the saturation of the SNSPDs with thermal light and coherent light, and compare the performance of SNSPDs with commercial APDs.

From the perspective of single-photon sources, the one based on a spontaneous parametric down-conversion (SPDC) process from periodically poled $KTiOPO_4$ (PPKTP) crystal has been proved to be very promising in many experiments [10–22]. The PPKTP

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crystal has a high nonlinear efficiency and a high damage threshold. At telecom wavelength, PPKTP crystal satisfies not only the quasi-phase matching condition, but also the group-velocity matching (GVM) condition [23,24]. The single-photon source from a GVM-PPKTP crystal may have a high spectral purity [10–12,18,21] and wide spectral tunability [18].

In all the previous experiments [10–20], however, this highly efficient photon source was detected by low-efficiency or low-speed detectors. For example, in Refs. [10–16], the photons were detected by InGaAs APDs with less than or equal to 25% quantum efficiency; and in Refs. [10,14], to match the low speed of the InGaAs APDs, the repetition rate of the pump laser was decreased from 76 MHz to around 4 MHz, so the performance of this source was not fully demonstrated. Therefore, the second motivation of this experiment is to fully characterize the performance this highly efficient single-photon source. We detect the photons with high-efficiency (quantum efficiency over 70%) and high-speed (dead time around 40 ns) SNSPDs. We pump the PPKTP crystal with a pump power up to 400 mW, measure the second order coherence function, and investigate the multi-photon contribution in this single-photon source.

This paper is organized as follows. In Section 2, we describe the detection efficiency, dark count rate and spectral range of our SNSPDs. In Section 3, the single and coincidence counts of a single-photon source from PPKTP crystal are measured with the SNSPDs. Then, in Section 4, the multi-pair components in the single-photon source are analyzed. To investigate the second order coherence function, $g^{(2)}(0)$, we experimentally measure it in Section 5 and theoretically analyze several different coherence functions in Section 6. In Section 7, we consider the different responses of SNSPDs with a coherent state and a thermal state. After that, we compare the performance of SNSPDs and two kinds of commercial InGaAs APDs in Section 8. Finally, the discussion and conclusion are in Sections 9 and 10.

The detailed characterization of the SNSPDs and the PPKTP source in this paper is of great importance for their future applications. We believe the combination of high brightness single-photon sources and high performance detectors is the road one must follow in the future development of quantum communication and information technologies.

2. Measuring the detecting efficiency and spectral range of SNSPD

Our SNSPDs are fabricated with 5–9 nm thick and 80–100 nm wide NbN or NbTiN meander nanowire on thermally oxidized silicon substrates [8,9]. The nanowire covers an area of 15 μm × 15 μm. The SNSPDs are installed in a Gifford–McMahon cryocooler system and are cooled to 2.1 K. The measured timing jitter and dead time (recovery time) were 68 ps [8] and 40 ns [25], respectively.

We measured the system detection efficiency (SDE, including the fiber coupling efficiency, transmission efficiency and quantum efficiency of the SNSPD chip) and dark count rates (DCR) as a function of the bias currents. Fig. 1(a) shows typical results measured at 1550 nm, where the SDE can be over 0.60 (0.78) with a dark count rate of around 180 cps (2 kcps). DCR in the low bias current region in Fig. 1(a) is caused by black body radiation at room temperature [26]. In our previous work [8,9], the DCR was suppressed to several tens of cps in the high SDE region.

Spectral range is another important parameter for detectors. Here, we report our measured results of the SDE at different wavelengths. Our method is similar to that of Ref. [3]. Wavelength tunable laser (Agilent 81980A and Santec ECL-200) with a power of less than 6 dBm is attenuated by about 100 dB by two attenuators (Agilent 81570A). The attenuated laser is detected by an SNSPD, which is connected to a counter (Tektronix TDS2014). The SDE is calculated as $SDE = SC/(p\lambda/hc)$, where SC is the single count; h is the Plank constant; c is the speed of light; p is the light power; and λ is the wavelength. By changing the central wavelength and repeating the measurement, we can obtain the spectral range of SNSPD from 1470 nm to 1630 nm. The measured results are shown in Fig. 1(b). The corresponding dark counts are around 180 cps. The measured SDEs are between 0.55 and 0.63 for all the wavelengths from 1470 nm to 1630 nm, which is consistent with our previous simulation results [8]. This result implies that our SNSPDs have a wide spectral response range that covers at least the S-, C-, and L-bands in telecom wavelengths.

3. Measuring single and coincidence counts

Fig. 2 shows the experimental setup for the detection of our single-photon source. To avoid the oscillation of the count rates in high SDE and high DCR regions, we set the bias current at the DCR of less than 1 kcps, and the corresponding SDE of SNSPD1, SNSPD2, and SNSPD3 were 0.70, 0.68, and 0.56, respectively. First, we measured the single counts and coincidence counts as a function of the pump power, as shown in Fig. 3(a) and Table 1. The single counts (coincidence counts) achieved 214 kcps (45 kcps), 1.91 Mcps (406 kcps), and 5.23 Mcps (1.17 Mcps) at pump power of 10 mW, 100 mW and 400 mW, respectively. As far as we know, these are the highest coincidence counts ever reported at telecom wavelengths. These count rates were one order higher than our

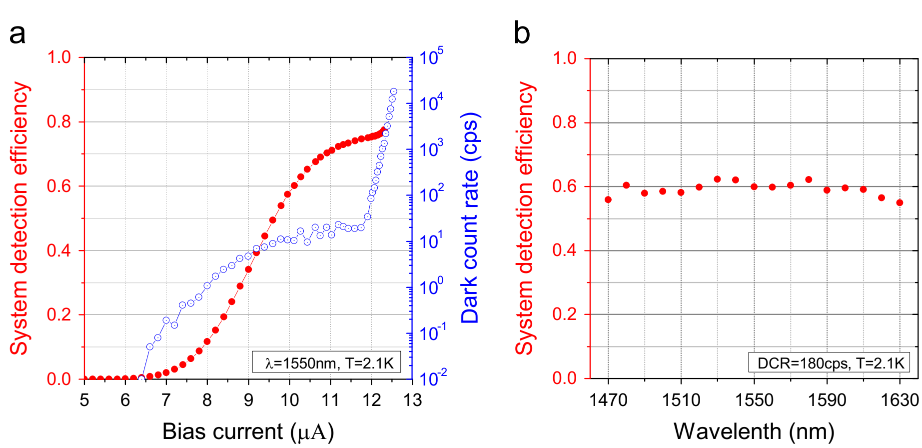

Fig. 1. (a) Measured system detection efficiency (SDE) and dark count rate (DCR) as functions of the bias current, with 1550 nm wavelength at 2.1 K. (b) Measured system detection efficiency (SDE) as a function of the wavelength, with dark counts of around 180 cps at 2.1 K.