Afterpulse-like phenomenon of superconducting single photon detector in high speed quantum key distribution system

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Abstract: We discuss our estimates of the performance of a superconducting single photon detector (SSPD) in a high speed quantum key distribution (QKD) system. We find that at high repetition operation reflections from the readout circuit at room temperature causes an afterpulse-like phenomenon, and drastically increases the quantum bit error rate (QBER). Such effects are not seen during low frequency operation. By using an amplifier with a small reflection coefficient S11, we succeed in reducing the afterpulse-like phenomenon and increasing a secure key rate.

OCIS codes: (040.0040) Detectors; (030.5260) Photon counting.

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1. **Introduction**

Quantum key distribution (QKD) [1,2] is a representative candidate enabling critical issue to be protected in network service. QKD allows users to communicate with absolute security by combining it with Vernam’s one-time pad. Unconditional security is guaranteed by the fundamental laws of physics. In 2010, we demonstrated the world’s-first secure TV conferencing in a metropolitan QKD network with trusted nodes [3], called the Tokyo QKD Network. Six different QKD systems were integrated into a mesh-type network. A gigahertz-clocked QKD system that has been developed by NEC and NICT in this network enabled us to demonstrate the information-theoretically secure TV conferencing over a distance of 45 km [3–5]. The system is designed for a multi-channel QKD scheme with wavelength division multiplexing (WDM). Each channel is operated at a clock rate of 1.25 GHz, and a maximum of eight channels can be installed in our system. A laser diode on the transmitting side releases 1550 nm photon pulses with a 50 ps width at a repetition rate of 1.25 GHz at each channel. A 2-by-2 asymmetric Mach-Zehnder interferometer (MZI) made of a polarization free planar-lightwave-circuit (PLC) splits these pulses into pairs of double pulses with a 400 ps delay with time-bin encoding.

At the receiver side, the quantum and the synchronization signals are divided through a WDM filter, and the quantum signals are input to a 2-by-4 asymmetric and totally passive PLC-MZI, and these are then detected by four-channel detectors. Superconducting single photon detectors (SSPD) [6,7] have recently been widely used for quantum experiments [8]. We have developed and demonstrated a three channel WDM QKD that is connected to two sets of SSPDs developed by NICT [9,10] and one set of semiconductor single photon detectors. In a single channel with SSPDs, the averaged sifted key and final secure key rates of our QKD system after 45 km transmission through a field installed fiber (14.5dB loss) are 268.9 kbps and 81.7 kbps respectively, under an averaged quantum bit error rate (QBER) of 2.7% [4,5]. The detection efficiency of the SSPDs themselves are about 15% at a dark count (DC) rate of 100 cps, but the total detection efficiency decreases to less than 10% when they are connected to the QKD system. One reason for this discrepancy is due to event selection with a time window of 400 ps. The active time window imposed on the time-bin signal cannot cover the whole pulse spreading after the fiber transmission. Moreover, the QBER increased drastically when the SSPD operated at high detection efficiency (DE) conditions (high bias current region).
This paper reports on the behavior of SSPDs when they are used in a high speed QKD system and the discrepancy between unit testing results and system performance. In contrast to the conventional belief that SSPDs are free of afterpulse phenomena, we observed an afterpulse-like phenomenon in SSPDs especially when they are operated at high repetition rate. We discuss its origin and present countermeasures against it deteriorating the improvements in QKD performance.

2. Afterpulse-like phenomenon of SSPD

We have applied a NbN SSPD [9,10] to our QKD system. We have developed a multi-channel SSPD system based on the Gifford McMahon (GM) cryocooler that can offer guaranteed performance, be cryogen free, and be capable of turnkey, continuous operation with low input power consumption. There is a photograph of the SSPD system in the inset of on the left of Fig. 1. We measured the DE of our whole system including the optical coupling efficiency. The incident photons are introduced through a single mode telecommunications fiber to the SSPD. The packaged device is cooled to 2.4 − 2.6 K with ~20 mK thermal fluctuation at the operating temperature. The output port from the nanowire was connected to a parallel shunt resistor (50 Ω) and a bias tee at room temperature through a 50 Ω co-axial cable. The shunt resistance is to prevent the biased device from latching and it is placed outside of the cryocooler to allow back-reflections to be attenuated. The cable length between the parallel shunt resistor and the bias tee is 50 cm. The SSPD is current-biased via the dc arm of the bias tee. The output signal from the ac arm of the bias tee is amplified using a series of two low noise amplifiers (RF Bay Inc., LNA-550 and LNA-1000), and it is then observed by using a pulse counter, an oscilloscope and a QKD discrimination system. A similar system was used in a QKD experiment through field-installed fibers in 2007 [8]. At that time, the single photon DE was around 1% at a DC rate of 100 c/s [11]. This time, however, we use the latest version with enhanced DE by applying an optical cavity structure [9,10]. Figure 2 plots the DE and DC rate of a typical SSPD as functions of bias current. The DE measured in a unit test is about 15% and 20% at dark cont (DC) rate of 50 −100 c/s and 800-1000 c/s respectively. A rapid increase of DC at the bias close to the critical current is different from the previous reported publication [12]. We suspect the speed and quantity of changing bias current affect the behavior of the SSPD. The DE in the higher bias current region in which the DC rate increases drastically is not accurate due to the oscillation in the SSPD. Continuous wave and pulse lasers have been used to estimate DEs and consistent results have been obtained.

It is noted that several approaches to improve the performances of SSPDs have been reported [13–15], and our SSPDs are also on the way for further improvement. Namely, we will try to make SSPDs on other substrates i.e. Si or SiO₂ to get higher affinity for fiber and silicon photonics. Moreover, DEs of our SSPDs have dependency on polarization of incident photons due to their meander structures. Amount of change in DE is about 3dB [16]. To apply SSPDs for a QKD system, we need polarization controllers in the QKD system. Or SSPDs with minimized polarization dependence [17] should be used.

Highly sensitive detectors are generally susceptible to grounding conditions. SSPDs are particularly vulnerable. When SSPDs are connected to the QKD system, we install an RF transformer to insulate the ground lines. Without this, the QKD system suffers from large noise of 50 Hz.
The Tokyo QKD Network consists of parts of the NICT open testbed network called the Japan Giga Bit Network 2 plus (JGN2plus) [18]. The percentage of aerial fibers is about 50% causing the links to be quite lossy and susceptible to environmental fluctuations. There are many splicing points resembling those in actual business situations. The total attenuation amounts to 14dB on average. Moreover, the fibers are also noisy, i.e. photon leakage from neighboring fibers causing inter-fiber crosstalk in the same cable is often observed [19]. Background count rate of the field installed QKD system is determined by stray light of about 2000 –3000 c/s. On the other hand, the DC of SSPD itself is set at 100 c/s, which is small enough compared to stray light. If we can use SSPDs in the high quantum efficiency region with a DC rate of several hundred c/s, the sift key rate will be increased by 50% with almost the same or slightly higher QBER. However, the QBER increases drastically from 2.5% to over 5%, when the SSPD is biased at a DC rate of 800- 1000 c/s. This implies that other noise different to that of DC appears in SSPDs. Actually, afterpulses are known to be major noise sources in InGaAs avalanche photodiodes. Afterpulses are particularly troublesome for high-speed QKD because the necessary high rate of detection for photons induces severe afterpulse noise. Therefore, we need to be suspicious of afterpulse-like phenomena in SSPDs. SSPDs are supposedly free from afterpulse phenomenon in principle. Indeed, our SSPDs were used in a QKD system and succeeded in generating secure keys after 97 km transmission without afterpulse phenomena. At that time, detection rate was about a few kbps. A new GHz-clocked QKD system, on the other hand, requires high speed operation in megahertz region. High speed operation would increase the electrical load on an SSPD system.
To measure the behavior of SSPDs at high detection rates, we use 50-ps-wide and 10-MHz-repetition periodic weak laser pulses at 1550 nm and a time interval analyzer (TIA: YOKOGAWA TA-520). The average photon number per pulse is adjusted from 0.1 to 1. Figure 3 shows histograms of photon counting rates at DC rates of 50–100 c/s and 800–1000 c/s with and without illumination. The peaks in Fig. 3 correspond to detection events for input photon pulses. The temporal axis is opposite to the real time flow. The average photon number per pulse is 0.1, and DC levels are increased due to stray light. At DC rate of 50–100 c/s, the floor levels are almost equal with and without illumination as seen in Fig. 3(a). Here, the counting rate of photon detection events is about 100k c/s. However, at a DC rate of 800–1000 c/s, the floor level increases about tenfold when it is illuminated with counting a rate of about 150k c/s, which is shown in Fig. 3(b). Moreover, periodical fluctuations in the count rate can be observed. This is specifically an “afterpulse” phenomenon, which has been observed in our SSPD system at the first time. This phenomenon is consistent with the rapid increase of QBER in the QKD system in the region of high current bias.

Fig. 3. Temporal histograms for photon counting rates with and without illumination. (a) Biased at DC rate of 50–100 c/s, and (b) at DC rate of 800–1000 c/s.

To clarify the conditions for afterpulses, we provide histograms of the photon counting rate at a DC rate of 50–100 c/s for various photon numbers per pulse in Fig. 4. At least, when the average photon number exceeds 0.7, an afterpulse is observed. At that time, the photon detection rate is about 700k–1M c/s. Therefore, the high repetition rate of detection events induces afterpulses. To assess whether the high detection rate changes the characteristics of the superconductor itself, histograms are measured for various background photon levels from 50 to 2000 c/s, as shown in Fig. 5. Background photons are adjusted by changing brightness of a room light. The average photon number per pulse is 0.7 and bias is set at a DC rate of 50 c/s. The DCs (measured as counts between the pulses of the laser) increase to (a) 383, (b) 1220, and (c) 2725 c/s. The afterpulse–like phenomena are difficult to recognize. If the afterpulse emanates from the superconductor itself, i.e., the superconductor induces DCs by itself, the increase rate in the floor level would be liner to background photon numbers.
However, the percentages for growth decrease when the background level increases. For that reason, we suspect the readout circuit as the cause of afterpulses.

Fig. 4. Temporal histograms for various photon numbers per pulse, (a) dark, (b) 0.1, (c) 0.7, and (d) 1.

Fig. 5. Temporal histograms for various background levels. Background photon counting rate levels are (a) 51 c/s, (b) 590 c/s, and (c) 2000 c/s. Average photon number per pulse is 0.7. Signal photon detection rate is about 700k c/s.
3. Reflection from readout circuit

We have been used a series of two low noise amplifiers (RF Bay Inc., LNA-550 and LNA-1000) as the readout circuit of the SSPD system. To confirm interference to an SSPD, we measure the reflection coefficient $S_{11}$ of this readout circuit with a network analyzer (Agilent E5061A). Before measuring $S_{11}$, the influence of a cable is checked for lengths of 10, 30, and 50 cm. At the SSPD with low critical current ($I_c$) of around 10 µA, a QBER increases when the cable length is over 30 cm. However, for the SSPD with $I_c$ of around 20 µA, there is no change in the QBER. Therefore, we note below the performance of the SSPD with $I_c$ of over 20 µA with 50 cm cable to eliminate the influence of attenuation in the cable. The frequency properties of $S_{11}$ and waveforms with temporal histograms measured with an oscilloscope are shown in Fig. 6(a). Below 4 MHz, large reflections can be observed, and an afterpulse appears at about 175 ns (shown in Fig. 6(a): red circle in oscilloscope measurements) after a short dead time for the SSPD due to the bandwidth of the readout circuit. Such a high $S_{11}$ generally induces an undesirable standing wave effects. Moreover, back reflection voltage should influence the bias of the SSPD. Especially, a small increase of the bias would induce high DC in the region of high current bias. If this high $S_{11}$ induces the afterpulse, we can suppress this phenomenon using an amplifier with low $S_{11}$. We test the series of 5840A (Picosecond Lab.) and SHF 74B (SHF Communication Technology) amplifiers that are indicated in Fig. 1 (inside the dashed rectangle). The bandwidth of these amplifiers are around 10 GHz; therefore, two low frequency pass filters of 900 and 600 MHz are installed to reduce high frequency noise. Figure 6(b) shows the frequency properties and waveforms with a temporal histogram for this new combination. The value of $S_{11}$ in the low frequency region is about $-20$ dB and afterpulses are obviously suppressed. Figure 7 shows temporal histograms of the new readout circuit for several input pulse intensities at a DC rate of 50–100 c/s. When the average photon number is 1, despite the detection rate reaching 1M c/s, the increase of DC is suppressed to 130 c/s. To confirm the influence of the back reflection from the readout circuit, it would be desirable to see a change of the delay between the initial pulse from a photon and after-pulses by changing the length of the cable. However, this is not experimentally feasible, because QBER is strongly affected by attenuation in the cable. We measure a change of the delay of the reflection by increasing the cable length to 7 m. We observe a slight shift of the peak in the histogram, but caution is needed when drawing a definite conclusion, because the cable length of 7 m is too short to make a significant change in a broad peak of the 175 ns delay reflection, which corresponds to 35 m cable. Further increasing of a cable length induces serious attenuation of a signal pulse, and it hinders the measurement of meaningful data. Nevertheless, the fact that the afterpulse can be decreased by using a readout circuit with low $S_{11}$ implies that afterpulse of a SSPD can be identified as the back reflections of a readout circuit.
4. Performance gain of the QKD system

The performance of the SSPD system with a new readout circuit is estimated when it is connected to the QKD system. Comparison data are listed in Table 1, where at each bias
point, the QBERs for the new readout circuit are below those of the previous one. Especially, the difference increases at high current bias. When bias current in the previous circuit exceeds 23.8 µA, the QBER increases drastically. On the other hand, the new circuit maintains low QBER in the higher bias current region (not shown here). At least, the secure key generation rate can be improved more than 25%. Figure 8 plots the secure key generation rates for the decoy method [20] as functions of the distribution length. In this calculation, we use the following parameters in these calculations; a probability that signal photon hits a wrong detector due to an imperfection of detector: (measured results listed in Table 1), error correction efficiency: 1.22, a channel loss: 0.32dB/km (according to the attenuation rate in JGN2plus), photon per bit: 0.4, DE and DC: (measured results listed in Table 1). This result implies the new circuit would enable to obtain about 10 kbps of secure key rate after a transfer distance of 100 km, even in lossy field installed fiber.

Table 1. Comparison of Performances: Series of 5840B and SHF 74B (New) and Series of LNA-550 and LNA-1000 (Previous) for Two Bias Currents

| Bias | New | Previous |
|------|-----|----------|
| 23.5µA |     |          |
| QBER (%) | 1.26 ± 0.02 | 1.38 ± 0.05 |
| Dark count rate (c/s) | 200 | 200 |
| Counting rate (c/s) | 480 κ | 480 κ |
| Detection efficiency (%) | 11.95 | 11.95 |
| Secure key generation rate through 14.5 dB loss | 4.27 E-4 | 4.07 E-4 |

| Bias | New | Previous |
|------|-----|----------|
| 23.5µA |     |          |
| QBER (%) | 1.36 ± 0.08 | 2.43 ± 0.12 |
| Dark count rate (c/s) | 800 | 600 |
| Counting rate (c/s) | 660 κ | 660 κ |
| Detection efficiency (%) | 15.1 | 15.1 |
| Secure key generation rate through 14.5 dB loss | 5.13 E-4 | 3.98 E-4 |

Fig. 8. Simulation of secure key generation rates of a new readout circuit and a previous one for two current biases.
5. Conclusion

We report the behavior of an SSPD when it is used in a gigahertz-clocked QKD system. An “afterpulse” appears in the SSPD when the repetition rate of detection increases near 1 MHz, and it produces the discrepancy between a unit testing result and system performance. Such phenomena are caused by reflection from a readout circuit, and the SSPD itself is free of afterpulse. The secure key generation rate of our QKD system will be improved more than 25% by using a low S11 readout circuit.

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