INVITED PAPER   *Special Section on Superconducting Signal Processing Technologies*

Enhancing Detection Efficiency by Applying an Optical Cavity Structure in a Superconducting Nanowire Single-Photon Detector

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SUMMARY   We report on the enhancement of system detection efficiency in a superconducting nanowire single-photon detector (SNSPD) by applying the optical cavity structure. The nanowire was made using 4-nm-thick NbN thin films and covered with an SiO cavity and Au mirror designed for 1300–1600 nm wavelengths. The device is mounted into fiber-coupled packages, and installed in a practical multichannel system based on GM cryocoolers. System detection efficiency depends on the absorptance of cavity structure, and reached 28% and 40% at 1550 nm and 1310 nm wavelengths, respectively. These values were considerably higher than an SNSPD without optical cavity.
key words: *single photon detector, superconducting nanowire, quantum information and communications, NbN thin films*

1. Introduction

Single-photon detectors for telecommunication wavelengths are one of the most important components in the field of quantum information and communications technology. Ideally, they should feature high speed, high quantum efficiency, a low dark count rate (DCR), and low timing jitter. These factors are to be directly reflected in the overall performance of many protocols, typically for example, in the distance, speed and security level of quantum key distribution (QKD). In recent times, multichannel superconducting nanowire single-photon detector (SNSPD [1]) systems based on closed-cycle cryocoolers have been recognized as promising instruments; this is because SNSPDs potentially have broadband sensitivity from the visible to the near-infrared wavelengths, excellent timing resolution, high counting rate, and low DCR [1], [2]. In addition, they are capable of turnkey, continuous, and stable operation without any liquid cryogen or the need for a wavelength conversion and gating system, making them more attractive. Practical multi channel SNSPD systems have been employed in many QKD experiments and quantum optics studies, and demonstrated their superiority [3]–[9].

However, further improvements in system performance are highly desirable and will broaden the impact of SNSPDs in QKD and other quantum information processing applications. In particular, significant effort is being directed to increasing system detection efficiency (DE). An effective method of improving the system DE is enhancing the photon absorption coefficient by integrating an optical cavity structure with the SNSPD device (OC-SNSPD) [10]. Moreover, efficient optical coupling to the meander nanowire area simultaneously with photo absorption coefficient is crucial, and a primary concern is how to implement the OC-SNSPDs in a practical multichannel system. Recently, we successfully developed a high optical coupling OC-SNSPD packaging technique, and developed a practical multi-channel system with high system DE [11], [12].

This paper focuses on the verification of photon absorption enhancement by applying an optical cavity structure, and contributing to the enhancement of system DE. We describe in detail the fabrication of NbN SNSPD devices with an optical cavity structure, optical packaging technique, and practical multichannel system. Next, we report on the experimental and simulated results of absorptance of the optical cavity, and verified the effect on system DE by applying the optical cavity.

2. Experimental Procedure

2.1 SNSPD Device with Optical Cavity Structure

The NbN thin films for nanowire were deposited by reactive dc-magnetron sputtering in a mixture of Ar and N_2 gases at ambient temperature. The background pressure was below 8×10^{-8} Torr, and the total pressure was set at 2 mTorr to elevate the sputtering energy. The relative amounts of argon and nitrogen introduced for sputtering were carefully controlled to 5:1 using mass-flow controllers. The target was 99.99% pure niobium and the target size was 8 inches in diameter. Single-crystal MgO (100) substrates with a thickness of 0.4 mm were used to promote the epitaxial growth of the films. A direct-current power supply was used to stabilize the discharge state [13], and the bias current was set to 3.0 A. A detailed explanation of the deposition process to find the optimum bias conditions is described elsewhere [14]. After optimization of bias conditions, NbN thin films with a fine crystal structure and good superconducting properties were able to be obtained [15].

The NbN thin films were then formed to the nanowire by direct e-beam lithography and reactive ion etching (RIE) processes. We fabricated 100-nm-wide NbN meander nanowires covering an area of $15 \times 15 \, \mu m^2$ with a filling
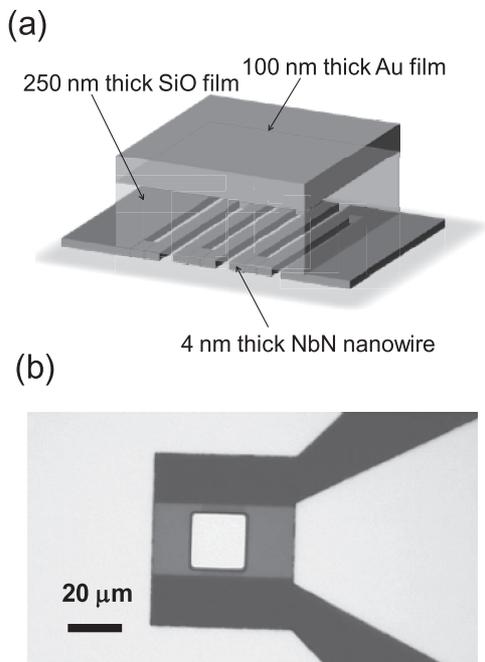
Fig. 1 (a) Schematic layout and (b) microphotograph of OC-SNSPD device.

Fig. 2 (a) Schematic layout for OC-SNSPDs. (b) configuration of GRIN lenses connected to optical fiber.

factor of 62.5%. The superconducting critical temperature T_C and critical current density J_C of nanowires were 10.2–10.5 K and 4–7×10^{10} A/m^2, respectively. Coplanar waveguide (CPW) lines with an input impedance of $50\,\Omega$ were connected to the nanowire to read the output signal. These were fabricated by standard photolithography and a lift-off process. Since NbN ultrathin films break easily from damage during fabrication and thermal stress near the electrodes [15], 150-nm-thick NbN thin films were used for the CPW lines. These introduce minimal stress on the contact area of NbN ultrathin film and have relatively strong adherence.

Figure 1(a) shows the schematic layout and (b) micrograph of the OC-SNSPD device. An optical cavity structure consisting of an Au mirror and SiO cavity was covered on the NbN nanowire area. We chose SiO thin films deposited by high vacuum thermal evaporation as the $\lambda/4$ dielectric cavity, because there was almost no damage to NbN thin films [16]. The SiO and Au films were sequentially deposited after patterning a square window on the active area of the nanowire by photoresist masking. The cleaning process was intentionally not performed prior to the deposition of SiO thin films, to prevent damage to the nanowire. To enable these structures to act as an optical cavity at 1550 nm, the thicknesses of the Au and SiO films were set to be 100 and 250 nm, respectively.

2.2 Device Packaging

Figure 2(a) shows the schematic layout of the fiber-coupled packaging for OC-SNSPDs. This compact fiber-coupled packaging technique was modified from the one used for a single-layer SNSPD [17], [18], which is simple and very
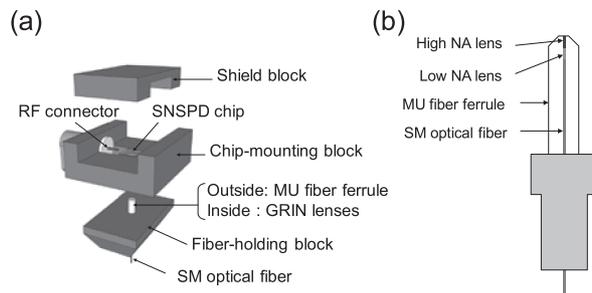
reliable. A fiber ferrule was fixed to the fiber-holding block in advance by using an adhesive so that the distance from the exit end to the rear surface of the OC-SNSPD chip was $20\,\mu$m at low temperatures. OC-SNSPD chips were mounted on chip-mounting blocks which had a through hole at the center of the chip-mounting area. An MU-type fiber ferrule was inserted through this hole from the rear. Prior to cooling, the fiber-holding block was joined to the chip-mounting block from the rear, and the two blocks were accurately aligned so that the incident light spot illuminated the center of the meander area. The dimensions of the packaged blocks are 15 mm (length) $\times$ 15 mm (width) $\times$ 10 mm (thickness), which are sufficiently compact to install multiple packages into the GM cryocooler system.

To achieve efficient optical coupling, the light beam waist on the meander nanowire area must be smaller than the size of the nanowire area. Since the OC-SNSPDs need to be illuminated from the rear through the substrate, small-gradient index (GRIN) lenses were used to reduce the beam waist at a distant from the exit end. To embed lenses into the compact packages, GRIN lenses with a diameter of $125\,\mu$m, which is equal to the clad diameter of a single-mode (SM) optical fiber, are directly fusion-spliced to the end of the optical fiber. Since the fiber-spliced lenses were inserted into the MU fiber ferrule, the shape of the end of fiber did not change at all from that without lenses, as shown in Fig. 2(b). The numerical aperture and length of the two lenses are chosen so that the focal length is equal to the appropriate distance in the packaging and the beam waist becomes is made as small as possible. As a result, the beam waist ($2\omega_0$) at 1550 nm wavelength was estimated to be 8–$10\,\mu$m on the meander nanowire area, when the distance between the exit end and the substrate is $20\,\mu$m and the thickness of the MgO substrate is $400\,\mu$m. This beam waist is sufficiently small to allow efficient optical coupling with a meander nanowire area of $15 \times 15\,\mu$m^2.

2.3 Measurement Setup

Figure 3 shows the measurement setup of the SNSPD system. We used small, two-stage-type Gifford-McMahon (GM) cryocoolers to operate the SNSPD devices. The rated input power consumption was 1.5 kW at a driving frequency of 60 Hz. The sample stage for cooling SNSPD pack-
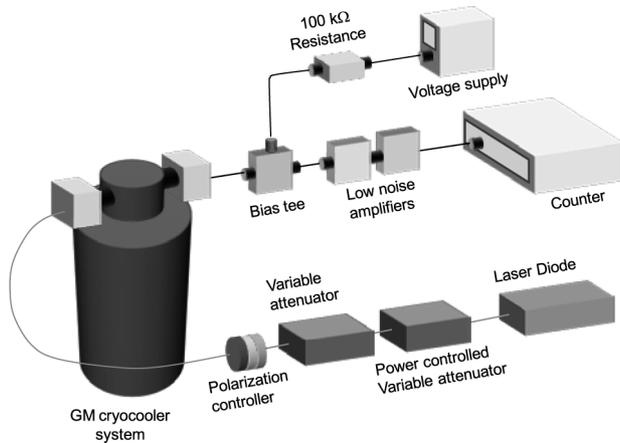
Fig. 3 Schematic diagram of SNSPD system and setup for system DE measurement.

Fig. 4 Optical absorptance of Au/SiO/NbN layers and NbN single layer versus wavelength. The thicknesses of each film were made the same as those of the OC-SNSPD device (Au: 150 nm, SiO: 250 nm, NbN: 4 nm). The dotted line shows simulated results using optical multilayer calculation software.

ages was connected to the second stage through a stainless steel plate and a lead block with large heat capacity to reduce thermal fluctuation [7], [18]. The sample stage could be cooled to 2.96 K within a thermal fluctuation range of 10 mK. After careful adjustment, the SNSPD packages were set on the sample stage. Up to six SNSPD packages could be set in a cryocooler, and we introduced brass semi-rigid coaxial cables and SM fibers for the telecommunication wavelength to each package.

Continuous laser diodes with 830, 1310, and 1550 nm wavelengths were used as the input photon source, and they were heavily attenuated so that the photon flux at the input connector of the cryostat was 10^6–10^7 photons/s. A fiber polarization controller was inserted in front of the cryocooler optical input to control the polarization properties of the incident photons so that their polarization sensitivity (maximizing the DE) matched that of each device. The output port was connected to a bias tee and two low noise amplifiers (LNAs) through a coaxial cable at room temperature. The device was current biased via the dc arm of the bias tee, and the output signal was counted through the ac arm of the bias tee and two LNAs. The system DE was defined as the output count rate divided by the photon flux rate input into the system.

3. Experimental Results

3.1 Absorptance of Optical Cavity Structure

To verify the effectiveness of the optical cavity structure, we examined the absorptance of the optical cavity structure using a spectrometer that can observe the reflectance R and transmittance T of target films. Then, the absorptance A can be obtained by $1 - (R + T)$. Figure 4 shows the obtained absorptance of unpatterned Au/SiO/NbN layers and the NbN single layer versus the wavelength. The absorptances of SiO and Au films were confirmed to be quite lower than few % by measuring each single film in advance. Although the real absorptance of OC-SNSPD cannot be seen from this
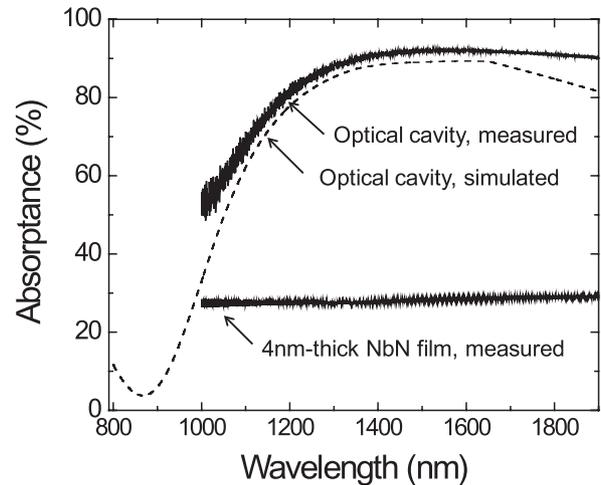
measurement because NbN films were not patterned to the nanowire, it can still be useful to know the qualitative behavior of the optical cavity structure. The thicknesses of each film were made the same as those of OC-SNSPD device (Au: 150 nm, SiO: 250 nm, NbN: 4 nm). Simulated results for the optical cavity structure using optical multilayer calculation software (Essential Macleod, Thin Film Center, Inc.) are also shown in Fig. 4. As is shown in the figure, simulated results showed absorptance exceeding 85% at aimed wavelengths of 1300–1600 nm. The measured results of the optical cavity layers nearly agree with the simulated result and exceed 90% at wavelengths of 1300–1600 nm. It should be noted that absorptance around 1300–1800 nm is about three times higher than that of an NbN single layer (~30%), which would certainly be effective for increasing the system DE of SNSPD devices. Although absorptance also decreased drastically at a wavelength of around 800 nm, it will be possible to achieve high optical absorptance at a short wavelength by optimizing the optical cavity design.

3.2 System Detection Efficiency

Figure 5(a) shows the system DE of OC-SNSPD versus the bias current normalized by I_C at three different wavelengths: 1550 nm, 1310 nm, and 830 nm, respectively. Figure 5(b) shows the maximum system DE at each wavelength as a function of the wavelength. The maximum system DE, at which the bias current was just below I_C (~0.99I_C), reached 40% and 28%, at wavelengths of 1310 nm and 1550 nm, respectively, and drastically decreased to 2.0% at a wavelength of 830 nm. The system DE is mainly determined by the product of the optical coupling efficiency between the incident light and the active area P_{couple}, the intrinsic photon-absorption coefficient of the superconducting nanowire P_{absorb}, and the probability of electrical pulse
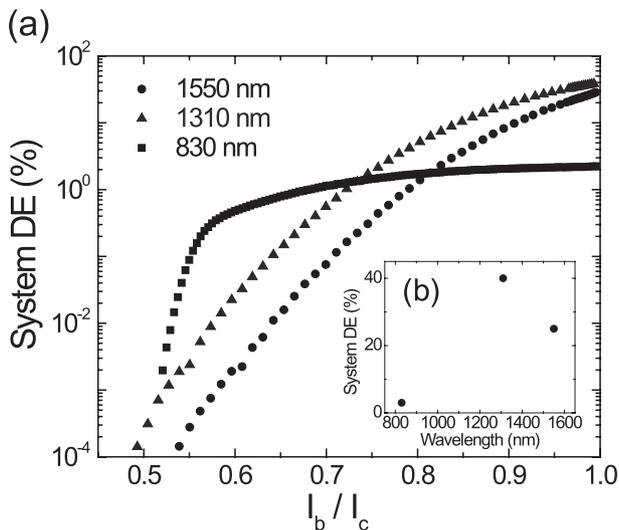
Fig. 5 (a) System DE versus normalized bias current of four-channel OC-SNSPDs at wavelengths of 830 nm, 1310 nm, and 1550 nm, respectively. (b) Maximum system DE versus the wavelength.

Fig. 6 System DE versus DCR at 1550 nm wavelength of the OC-SNSPD and a typical standard device.

generation after photon absorption P_{pulse}. Since we did not change alignment of packages in the measurements of three different wavelengths, P_{couple} must be constant. Therefore, these wavelength dependencies can be explained by P_{absorb} and P_{pulse} dependencies against single photons with different energies, as follows.

According to the absorptance measurement shown in Fig. 4, the absorptances of an optical cavity at 1310 nm and 1550 nm are sufficiently high and almost identical. Meanwhile, the P_{pulse} at 1310 nm must be higher than that at 1550 nm because the SNSPD is easier to produce output signals as the energy of single photons increases [2]. As a result, the system DE at 1310 nm becomes higher. It should be noted that no saturation region can be seen in the shape of the bias current dependencies at wavelengths of 1310 nm and 1550 nm, indicating that P_{pulse} did not reach its intrinsic value. Improving P_{pulse} is important for further gains at these wavelength regions.

On the other hand, the saturation region can be seen in the shape of bias current dependencies at 830 nm wavelength, indicating that P_{pulse} has almost reached its intrinsic value. It is clear that the low system DE in spite of the high P_{pulse} is caused by the considerably low absorptance of the optical cavity structure at the 830 nm wavelength. For further improvements in system DE in this wavelength region, optimizing optical cavity structure would be effective.

Figure 6 shows the system DE versus DCR of an OC-SNSPD and single-layer SNSPD. The single-layer SNSPD shown here is the best one of the 12 devices reported in [15], [18], and is a different device from the OC-SNSPD measured this time. It is apparent that the system DE can be increased by applying an optical cavity structure. The system DE at 100 Hz DCR of the OC-SNSPD and single-layer SNSPD were 21% and 2.5%, respectively. The enhancement ratio by applying an optical cavity structure was
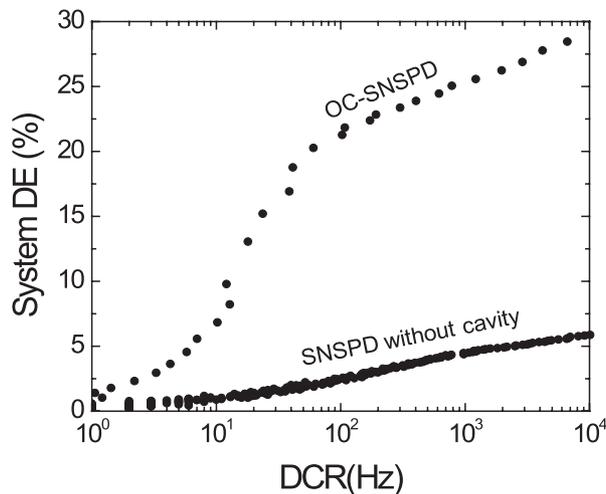
~8.5. This large enhancement is difficult to explain only by the enhancement of device absorptance or by variability from device to device. Although it is natural to consider that the P_{pulse} also improved by applying the optical cavity, we could not find a clear reason for P_{pulse} improvement at this time. Careful consideration of the effect of the optical cavity structure to P_{pulse} and a systematic investigation of different conditions such as operation temperature, applied magnetic field, and mechanical noise of the system will answer this open question.

4. Conclusion

We have verified that system detection efficiency in a superconducting nanowire single photon detector can be enhanced by applying an optical cavity structure. The OC-SNSPD device was successfully installed in a practical fiber-coupled package for an OC-SNSPD and operated at 2.9 K using the GM cryocooler system. The optical cavity structure worked efficiently at the target wavelengths of 1300–1600 nm, and enhanced the system DE of the device. The OC-SNSPD showed a system DE of 28% and 40% at wavelengths of 1550 nm and 1310 nm, respectively. These DE values are significantly higher than those of a standard multi-channel SNSPD system using a compact packaging technique [17], [18], and clearly have a great impact on the QKD and various applications.

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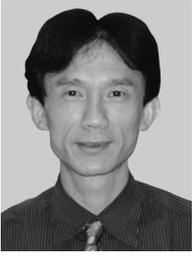
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