Development of fiber-coupled four-element superconducting nanowire single-photon detectors

Shigehito Miki*, Taro Yamashita, Hirotaka Terai, Kazumasa Makise, Mikio Fujiwara, Masahide Sasaki, and Zhen Wang

Abstract

We report on the development of fiber-coupled 4-element superconducting nanowire single photon detector arrays. The SNSPD arrays consist of four nanowire elements which are placed into a sensitive area with 15 \times 15 \mu m^2 square. The device was mounted into a small chip-mounting block with four tiny connectors which can pass high frequency signals up to 110 GHz, and each element was connected to each connector through CPW line. The single-mode optical fiber with GRIN lens was fixed to fiber-holding block and was joined to chip-mounting block from back side and aligned accurately so that the light spot irradiate to the center of device sensitive area. The fiber coupled package is then installed into closed-cycle cryocooler system and cooled down to 2.3 K. All four elements were able to detect single photon event, and total system DE reached to 8.07 %.

1. Introduction

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 dark count rate (DCR) [2-5]. In addition, they are capable of turnkey, continuous, and stable operation without any liquid cryogen or the need for a

* Corresponding author.
E-mail address:s-miki@nict.go.jp.
wavelength conversion and gating system, making them more attractive. Practical multi channel SNSPD systems have been employed in a wide range of applications such as quantum key distribution, optical communications, and quantum optics studies [6-9]. Further improvements in system performance are highly desirable and the primary concern of these efforts is to resolve the trade-off between the maximum counting rate and detection efficiency (DE) related with the size of the active area[5,10].

Dividing the active area into independent multi arrays is an attractive alternative to avoid this trade-off, because this configuration can not only simultaneously achieve a high counting rate and DE, but in addition allow spatial and pseudo-photon-number resolution [3]. The realization of large format SNSPD arrays will have a great impact on various application fields such as biomedical, fluorescent imaging, light detection and ranging (LIDAR). To utilize SNSPD arrays into practical applications, development of compact fiber-coupled packaging technique, which is suitable for installing into practical multichannel cryocooler system, is essential.

In this work, we report on the development of fiber-coupled 4-element SNSPD arrays. We describe the fabrication of 4-element SNSPD arrays, and the development of compact fiber-coupled packaging technique.

2. Experimental procedure

Figure 1(a) shows the SEM image of SNSPD arrays. The SNSPD arrays consist of four element nanowire which is connected to Coplanar waveguide (CPW) lines, respectively. The NbN thin films for nanowire were deposited on single crystal MgO (100) substrate by reactive dc-magnetron sputtering in a mixture of Ar and N² gases at ambient temperature. The deposition procedure in detail is described elsewhere [11]. The NbN thin films were then formed to the nanowire by direct e-beam lithography and reactive ion etching (RIE) processes. Covering area of each element is 15 × 3.75 µm and each element placed linearly so that the total active area becomes 15 × 15 µm square. The nanowire thickness, width and space were set to 4.5 nm, 100 nm and 80 nm, respectively. 100-nm-thick NbN CPW lines with an input impedance of 50 Ω were then fabricated by standard photolithography and lift-off process. Optical cavity structure as reported in [12,13] was not applied this time.

Fig. 1. (a) Scanning electron micrograph (SEM) of 4-element SNSPD arrays. (b) Photograph of fiber-coupled packaged for 4-element SNSPD arrays.
Figure 1(b) shows the fiber-coupled package for 4-element SNSPD arrays. This compact fiber-coupled packaging technique was modified from the one used for a single element SNSPD [2], 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 SNSPD arrays chip was 20 μm at low temperatures. SNSPD arrays chips were mounted on chip-mounting blocks which had a through hole at the center of the chip-mounting area. Chip-mounting block has four tiny connectors which can pass frequency signals up to 110 GHz, and each element was connected to each connector through CPW line. An MU-type fiber ferrule was inserted through this hole from the rear. To achieve efficient optical coupling, small-gradient index (GRIN) lenses were directly fusion-spliced to the end of the optical fiber. The lenses were designed so that the beam waist (2\(\omega_0\)) at device area is 8-10 μm. 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) × 15 mm (width) × 10 mm (thickness), which are sufficiently compact to install multiple packages into the GM cryocooler system.

For characteristics measurement, 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 packages was connected to the second stage through a stainless steel plate to reduce thermal fluctuation. The sample stage could be cooled to 2.3 K within a thermal fluctuation range of 5 mK. After careful adjustment, the SNSPD packages were set on the sample stage. Continuous laser diodes with 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. Each element 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 low noise amplifiers. The system DE was defined as the output count rate divided by the photon flux rate input into the system.

3. Results

Table 1 lists the critical current (I\(_c\)), normal resistance at 300 K (R\(_{300K}\)), and system DE at a 100 Hz DCR of a 4-element SNSPD arrays. Since there are small variations in I\(_c\) and R\(_{300K}\) among each element, further improvement in tolerances of I\(_c\) and R\(_{300K}\) are desired. However significant differences were not seen and we confirmed that all elements can detect single photon event successfully. In terms of system DEs, element "B" had highest value of 5.07 %, and "A" and "C", which are both sides of "B" respectively, have a similar value of ~1-2%. On the other hand, element "D" has extremely low DE of ~0%. These results means the illuminate light spot shifted slightly from the center of a device sensitive area, and the spot center was positioned to the element "B". Since the diameter of light beam waist is ~8-10 μm, the incident photon rarely entered to element "D". The total system DE, which is sum of each element's DE, is 8.06 %, if there is no cross talk.

Figure 2 shows the system DE and DCR of element "B" as a function of bias current. System DE at 100 Hz DCR was 5.07 % as already shown, and the maximum value, at which the bias current was just below I\(_c\), reached to ~7.5 %. Since the plateau in the bias current dependencies could not be seen, pulse generation probability after photon absorption (P\(_{\text{pulse}}\)) still did not reached to 100 %. To improve P\(_{\text{pulse}}\) further, optimization of device design and fabrication process are necessary. In addition, optical cavity structure can enhance absorption efficiency, leading to the improvement of system DE further.
Table 1. Characteristics of 4-element SNSPD arrays

| Element | Ic (mA) | R_{300K} (kΩ) | System DE at 100 Hz DCR (%) |
|---------|---------|---------------|----------------------------|
| A       | 37.2    | 936           | 1.79                       |
| B       | 39.0    | 912           | 5.07                       |
| C       | 39.8    | 886           | 1.20                       |
| D       | 36.0    | 873           | ~0                         |

Fig.3. System DE and DCR of element "B" as function of bias current.

4. Conclusion

We have developed fiber-coupled 4-element SNSPD arrays. To utilize SNSPD arrays to quantum information processing experiments, compact fiber-coupled packaging techniques that employ GRIN lenses has been developed. The beam waist on the nanowire arrays achieved 8-10 μm, and has been successfully installed into 0.1 W GM cryocooler system. All the elements showed a single photon detection sensitivity and total system DE reached to 8.07% at a DCR of 100 Hz and wavelength of 1550 nm. We believe that these results are important first step to develop practical SNSPD arrays in near future.

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