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Low-Energy Optical-to-Electrical Converters Based on Superconducting Nanowire for Single-Flux-Quantum Circuits

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SUMMARY We report the energy-efficient optical input interface using NbN superconducting nanowire-based optical-to-electrical (SN-OE) converters for a single-flux-quantum (SFQ) data processing system. The SN-OE converters with small active areas ranging from 1×1 to $10 \times 10\,\mu\text{m}^2$ were fabricated to improve the recovery time by reducing the kinetic inductance of the nanowire. The SN-OE with the smallest area of $1 \times 1\ \mu\text{m}^2$ showed the recovery time of around 0.3 ns, while its detection efficiency for a single photon was reduced below 0.1% due to insufficient coupling efficiency with a single-mode optical fiber. However, the optical power dependence of the error rate of this device showed that the required optical power to achieve the error rate below 10^{-12} at 10 GHz operation is as large as 70 μW, which is still one order of magnitude lower than semiconductor photo diodes. We also demonstrated the operation of the SN-OE converters combined with the SFQ readout circuit and confirmed the operating speed up to 77 MHz.

key words: *superconductor, single photon detector, single-flux-quantum circuit, optical interface, cryocooler implementation*

1. Introduction

Single-flux-quantum (SFQ) circuits [1] that can integrate over ten thousand of niobium-based Josephson junctions have been demonstrated at clock frequencies of tens of gigahertz with a power consumption of only a few milliwatts [2]. Owing to their high-speed and low-power operation, SFQ circuits could be a promising candidate as an alternative technology for semiconductor CMOS devices, even including the cooling cost. To realize a practical system using this technology, the input/output (I/O) links between the SFQ circuits and the room-temperature electronics are one of key issues to be developed.

So far, a total I/O data rate of 40 Gbit/s (10 Gbit/s × 4) has been successfully demonstrated using copper-based coaxial cables [3]. However, these coaxial cables are also good thermal conductors and provide a thermal load of approximately 25 mW per channel, making it difficult to maintain a low operation temperature with an increase in the number of I/O links. Thus, optical I/O links are desirable because they can drastically reduce the thermal load to the cooling system. To realize optical I/O links with a high data rate and low energy consumption, energy-efficient and high-speed optical-to-electrical (O/E) converters are an essential component at the input link. Although optical input links using uni-traveling-carrier photodiodes (UTC-PDs) and metal–semiconductor–metal photodiodes (MSM-PDs) have been demonstrated [4], [5], the required optical input powers to achieve a sufficiently small bit-error rate were 4.5 mW and 0.75 mW, respectively, which are almost comparable with the power dissipated by the SFQ circuits with ten thousand of Josephson junctions. More energy-efficient O/E converters are required for the realization of future large-scale systems.

Superconducting nanowire single-photon detectors (SSPDs) [6] are promising single-photon detectors with a high system detection efficiency (SDE) of 80% at a wavelength of 1550 nm [7]–[9]. Their high photosensitivity is very attractive for energy-efficient O/E converters operating in a cryogenic environment. However, the counting rate of conventional SSPDs is limited by a large kinetic inductance L_k due to the long meandering nanowire to realize a large active area for efficient optical coupling and a high SDE [10]. Further, practical SSPDs with active areas of 10×10 to $15 \times 15\ \mu\text{m}^2$ have L_k = 1–2 μH [8], [9], [11], and their maximum counting rate is approximately several tens of megahertz, which is far from the gigahertz rate expected intrinsically. Therefore, a reduction in L_k is necessary to realize fast O/E converters with a data rate greater than 1 Gbit/s per channel. Although the simplest way to reduce L_k is to reduce the active area as much as possible, this will cause a degradation in the optical coupling efficiency and SDE. To realize low energy consumption and high-speed O/E converters by using SSPDs, the actual nanowire structure should be optimized for the O/E converters with design guidelines that are different from those of conventional SSPDs.

In this paper, we report a systematic investigation of the properties of superconducting nanowire-based O/E (SN-OE) converters. We characterize the recovery time and required optical power for error-free operation of the SN-OE converters with various active areas. We also demonstrate the operation of an SN-OE converter connected with an SFQ readout circuit.

2. Experimental Setup

First, we deposited a 9-nm-thick niobium nitride (NbN) film on a 2-inch thermally-oxidized silicon wafer by reactive dc-magnetron sputtering [12]. The wafers were then patterned into a meandering nanowire structure by direct electron-beam lithography and reactive ion etching. We fab-

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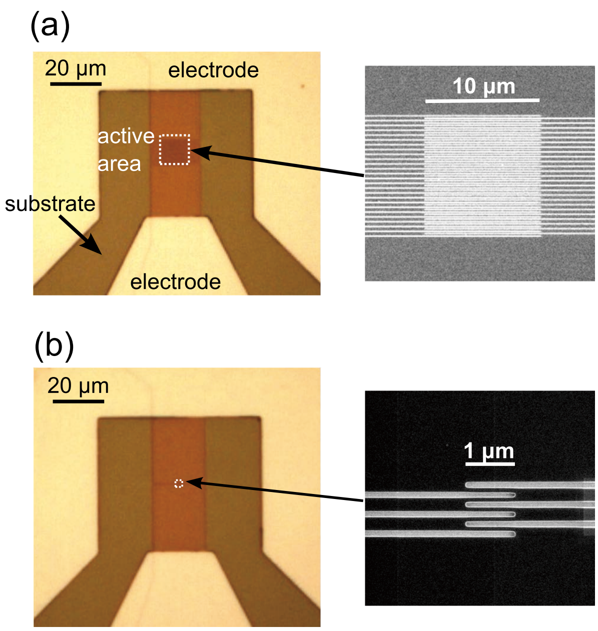

Fig. 1 Optical photomicrographs of the SN-OE converter devices and scanning electron microscopy (SEM) images of the meandering nanowires with active areas of (a) $10\times10\,\mu$m^2 and (b) $1\times1\,\mu$m^2.

ricated devices with active areas of 1×1, 2×2, 3×3, 5×5, and 10×10 μm^2 on the same wafer. The line width and the space between the nanowires were 100 nm for all devices. For simplicity, an optical cavity structure, as reported elsewhere, was not employed in this experiment [11], [13]. Figure 1 shows an optical photomicrograph of the SN-OE converters and a scanning electron microscopy (SEM) image of the meandering nanowire pattern with an active area of (a) $10\times10\,\mu$m^2 (b) $1\times1\,\mu$m^2. Further details of the fabrication process are described elsewhere [12]. Table 1 summarizes the electrical properties of the fabricated devices in the present work. The relatively small distributions of the critical temperature T_c and the critical current I_c suggest that the uniform superconducting properties of the fabricated devices do not depend on the size of the active area.

The fabricated SN-OE converters were mounted into compact fiber-coupled packages using fiber-spliced graded index (GRIN) lenses. Because the GRIN lenses are designed for efficient optical coupling with our conventional SSPDs at $15\times15\,\mu$m^2, the beam waist at the active area is approximately 9 μm in diameter [14]. The detailed device packaging and implementation procedures are described elsewhere [13]. The fiber-coupled packages were then implemented in a Gifford–McMahon (GM) cryocooler with a cooling capacity of 0.1 W. During the measurement, the temperature of the workspace was maintained at 2.3 K.

3. Experimental Results

3.1 Characterization of the Recovery Time with Various Active Area Sizes

In order to characterize the recovery time of the SN-OE converters with various active areas, we measured the dependencies of L_k on the nanowire length of the SN-OE converters, as shown in Fig. 2. In this figure, the open circles indicate values of L_k obtained from fitting the observed output waveforms of the SN-OE converters by using a simple equation with a recovery time constant τ (= L_k/R_L, where R_L is the input impedance on the load side) [10]. To observe the output waveform accurately, the output signals were amplified by two broadband amplifiers (SHF100AP) with a bandwidth of 30 kHz–23 GHz and acquired by a digital oscilloscope with an 8-GHz bandwidth (Agilent DSO80804A). The closed circles in Fig. 2 indicate values of L_k obtained from measurements of the phase of the reflection coefficient $S_{11} = (i\omega L_k - 50\Omega)/(i\omega L_k + 50\Omega)$ by using a network analyzer [15]. From these results, it is clear that L_k is proportional to the nanowire length and could be reduced to 10 nH by reducing the active area to $1\times1\,\mu$m^2. Furthermore, the pulse widths of the observed output waveforms are apparently reduced, as shown in the insets in Fig. 2, and the recovery time for the smallest $1\times1\,\mu$m^2 SN-OE converter was reduced to 0.3 ns.

Table 1 Nanowire lengths, critical temperatures, and critical currents of SN-OE converters with various active areas.

Active area (μm^2)	Nanowire length (μm)	T_c (K)	I_c (μA)
10×10	500	7.76	22.6
5×5	125	7.74	22.1
3×3	45	7.74	21.8
2×2	22	7.64	20.6
1×1	5	7.75	21.4

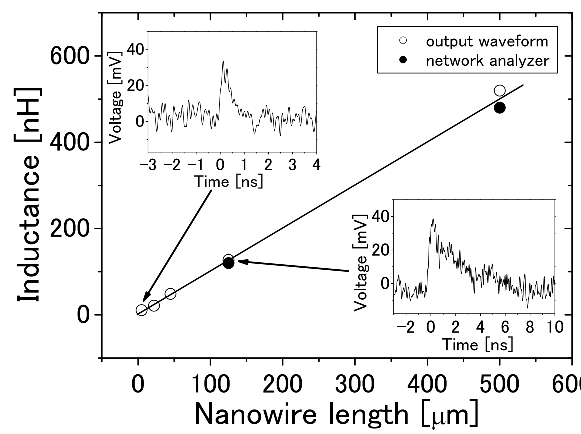

Fig. 2 Kinetic inductances as a function of the nanowire length obtained from the waveform (open circles) and those by using a network analyzer (closed circles). The solid line is a guide for the eye. Inset: Output pulse waveforms of SN-OE converters with active areas of $5\times5\,\mu$m^2 and $1\times1\,\mu$m^2.

3.2 Verification of the Required Optical Power for Error-Free Operation

Next, we measured the photon-number dependence of the error rates (ERs) of our SN-OE converters to estimate the optical input power required to achieve error-free operation. In this measurement, the ER is given by the probability that

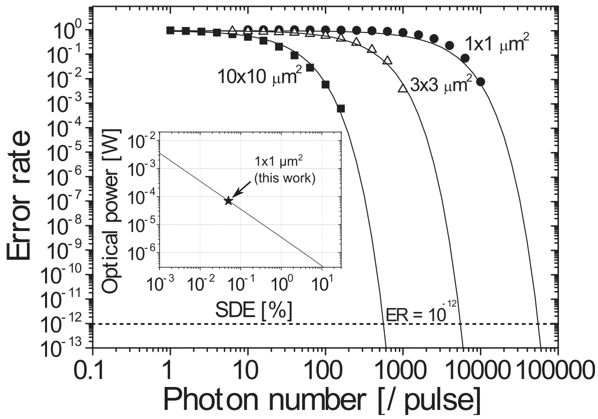

Fig. 3 Error rates of $10 \times 10\,\mu$m^2 (closed squares), $3 \times 3\,\mu$m^2(open triangles), and $1 \times 1\,\mu$m^2 (closed circles) SN-OE converters as a function of the input photon number per pulse at a bias current of 18 μA. The solid curves are theoretical curves [Eq. (1)] with SDEs of 4.8%, 0.5%, and 0.05%. Inset: The optical power as a function of the SDE, where the SN-OE converter operates at 10 GHz with an ER of 10^{-12}.

the device does not respond to an optical signal, and we define error free as an ER less than 10^{-12} [5]. Prior to the ER measurement, we measured the SDE for a single photon at a wavelength of 1550 nm [15]. The SDEs for the active areas of $10 \times 10\,\mu$m^2, $3 \times 3\,\mu$m^2, and $1 \times 1\,\mu$m^2 were 4.8%, 0.5%, and 0.05% at a bias current of 18 μA with a dark count rate lower than 1 c/s, respectively. The reduction in the SDE for smaller active areas is simply due to the reduction in the optical coupling efficiency by reducing the active area.

Then, we measured the photon-number dependence of the ERs. A 20-ps-wide pulsed laser diode with a repetition frequency of 1 MHz was used as the input source. The number of incident photons per pulse was controlled by an optical attenuator, and the output pulses from the SN-OE converter were measured by a pulse counter. ERs were then obtained by $1 - q/f$, where q and f are the number of output pulses per second and the repetition frequency of the input optical pulses, respectively. The results for the SN-OE converters with active areas of $10 \times 10\,\mu$m^2, $3 \times 3\,\mu$m^2, and $1 \times 1\,\mu$m^2 are plotted in Fig. 3, where the bias current was set at 18 μA for all devices. Here, the ER is theoretically given by

$$\mathrm{ER} = (1 - \mathrm{SDE})^m, \tag{1}$$

where m is the input photon number per pulse. The solid lines in Fig. 3 are the curves calculated using Eq. (1), where we employed the experimentally obtained values of the SDEs for the devices with each active area. As clearly shown in this figure, the experimental results are well explained by the theoretical curves without any fitting parameters. Focusing on the result for the smallest active area of $1 \times 1\,\mu$m^2, the required value of m to achieve an ER of 10^{-12} is estimated to be 54,000 photons per pulse. If we assume an operating frequency of 10 GHz, the optical power consumption P, which is given by $P = E_{photon} \times m \times f$, is estimated to be 70 μW at 1550 nm. Even for the SN-OE converter with an SDE of 0.05%, the optical power required to achieve an ER less than 10^{-12} is as large as 70 μW, which is still one order of magnitude lower than that of semiconductor photodiodes. This higher SDE will provide a lower optical power for error-free operation. The required optical power to achieve error-free operation at 10 GHz as a function of the SDE is shown in the inset of Fig. 3. The beam-spot diameter in our experimental setup is 9 μm [14], which is much larger than our smallest active area of $1 \times 1\,\mu$m^2. Even if the center of the beam spot is perfectly aligned with the active area, the optical coupling efficiency is as large as 2.4% according to a simple calculation using a Gaussian beam profile [13]. O'Connor et al. has reported that the full width at half maximum spot size was reduced to 1.3 μm using a confocal microscope system with an aspheric lens [16]. If we apply this configuration to our $1 \times 1\,\mu$m^2 SN-OE converter, the coupling efficiency will be improved to 77%. In addition, we employed no cavity structure to simplify the fabrication process; however, the SDE of our SN-OE converters will be further improved by employing a cavity structure. We have already demonstrated an SDE of 80% for SSPDs with a double-sided cavity structure [8], [9], which is significantly higher than the SDE below 10% for the SSPD without a cavity structure. By employing these techniques to enhance the SDE of the small-area SN-OE converter, an optical power less than 10 μW will be possible to realize an ER less than 10^{-12} at 10-GHz operation.

3.3 Operation of the Small-Area SN-OE Converter Connected to an SFQ Readout Circuit

To verify the correct operation of SN-OE converters connected with SFQ circuits, we implemented the SN-OE converter with an SFQ readout circuit in a cryocooler system and observed the output signals from the SFQ circuit. The SFQ readout circuit was fabricated using a clean room for analog–digital superconductivity (CRAVITY) and a 2.5-kA/cm^2 Nb standard process [17]. The output pulses from the SN-OE converter were converted into SFQ pulses by the front-end circuit called the magnetically coupled DC/SFQ (MC-DC/SFQ) converter, which has an input transformer with a 50-Ω load resistor in series to enhance the input current sensitivity [18]. After an appropriate signal processing, the SFQ pulses are converted into the voltage pulses with the amplitude of approximately 1.8 mV and the duration of 0.8 ns to be detected by the room temperature electronics. The SFQ circuit with a simple merging function of four input channels was used in this experiment, whose detailed operation is described in [18]. The SN-OE converters with an active area of $3 \times 3\,\mu$m^2 and the SFQ chips are implemented in the same workspace in the GM cryocooler and connected via 10-cm coaxial cables, as illustrated in Fig. 4 [19]. In this measurement, a continuous-wave laser was used as the input source. The incident photons sporadically arrive to the device. In this case, the incident photons sporadically arrive to the device, and the period of arriving photons can be regarded as the inverse of incident photon rate in average. Therefore, the operating speed of the SN-

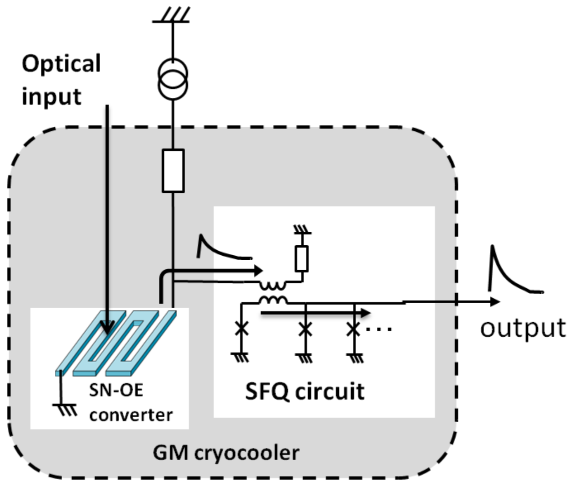

Fig. 4 Schematic of the experimental setup of an SN-OE converter and SFQ readout circuits in a GM cryocooler.

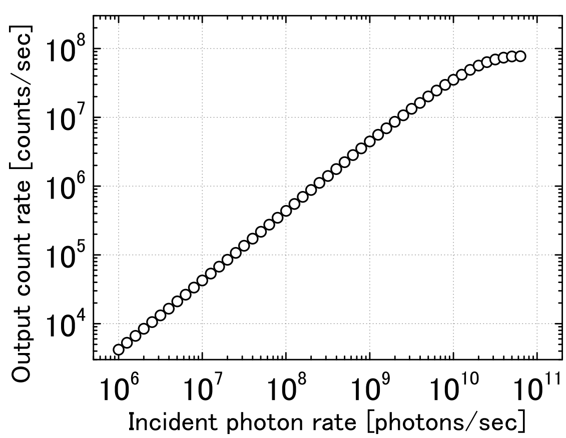

Fig. 5 Output count rate as a function of the incident photon rate for a $3\times3\,\mu$m^2 SN-OE converter connected with the SFQ readout circuit for a bias current of 18 μA.

OE converter can be estimated by statistical measurement of the output counting rate from the SFQ readout circuit as a function of incident photon rate [9].

Figure 5 shows the output count rate as a function of the incident photon rate, where the bias current to the SN-OE converter was set to 18 μA. For the low-incident-photon-rate region, the output count rate is proportional to the incident photon rate, indicating that the mean time interval of each incident photon is longer than the recovery time of the SN-OE converters. Because an SDE of 0.5% can be obtained in this region, which agrees with those without the SFQ circuit, the SN-OE converter correctly functioned as an optical input link for the SFQ circuit. In addition, a deviation from the linear dependence can be observed in the region with a high incident photon rate around 100 MHz because the SN-OE converter cannot follow the photons that arrive when its time interval becomes as short as the recovery time. The 3-dB roll-off operating speed f_{3dB} can be estimated from the counting-rate measurement, and this operating speed was estimated to be f_{3dB} = 77 MHz for our $3\times3\,\mu$m^2 SN-OE converter, which is faster than that of conventional SSPDs with larger active areas [9]. However, the L_k of the $3\times3\,\mu$m^2 SN-OE converter estimated from Fig. 2 is as large as 40 nH, which gives the recovery time of 0.8 ns. If the counting rate of our $3\times3\,\mu$m^2 SN-OE converter is simply limited by the recovery time, the f_{3dB} is expected to exceed 500 MHz, which is significantly larger than 77 MHz actually observed in our experiment. This suggests that the counting rate of the small-area SN-OE converter is limited not only by the recovery time but also the other mechanism. Further effort to reveal this mechanism will be necessary for improving the operating speed of SN-OE converter.

4. Conclusion

In this work, we systematically fabricated and characterized NbN SN-OE converters for the energy-efficient optical input interface for SFQ readout circuits. SN-OE converters with the active areas ranging from 1×1 to $10\times10\,\mu$m^2 were measured in a GM cryocooler system. The observed recovery time was improved by reducing the kinetic inductance, and a time constant of 0.3 ns was obtained for the smallest SN-OE converter area of $1\times1\,\mu$m^2. The photon-number dependence of the ER revealed that the input optical power required for the error free operation was approximately 70 μW assuming 10-GHz repetitive frequency, which is over one order of magnitude lower than conventional semiconductor photodiodes. Further improvements in the energy efficiency can be achieved by improving the optical coupling efficiency and/or adopting an optical cavity structure. We also tested a $3\times3\,\mu$m^2 SN-OE converter connected with an SFQ readout circuit and confirmed the successful operation at maximum operating frequency of approximately 77 MHz.

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