# 4-2 Development of Superconducting Nanowire Single-Photon Detector

Hirotaka TERAI

Superconducting nanowire single-photon detector (SSPD) has attractive features such as high detection efficiency, high maximum count rate, low dark count rate, low jitter, and so on. Due to those excellent features, SSPD have been employed in many experiments in quantum information field such as fundamental researches on quantum optics and system demonstrations of quantum key distribution. In this paper, we will introduce our current status on the development of SSPD system mainly for the application in quantum information field and also introduce our recent research activities toward further expansion of application fields and improvement of its performance.

## 1 Introduction

A superconducting nanowire single photon detector (SSPD) is sensitive to a broad wavelength region from deep ultraviolet to mid-wavelength infrared and has advantages in many characteristics such as detection efficiency (value of output count divided by incident photon number), maximum count rate (countable photon number in a certain time interval), dark count rate (output count without incident photon) and jitter (temporal deviation of output signal) over an avalanche photo diode (Avalanche Photo Diode: APD) that is a semiconductive photon detector sensitive to the communication wavelength band of 1,550 nm (1 nm is 1/1000000 of 1 mm) [1]–[5]. We started research and development of SSPD aiming at practical use in a quantum key distribution system (QKD: Quantum Key Distribution) and have developed a multi-channel SSPD system that is mounted on a small mechanical cryocooler operable with 100 V power on which a 6-channel SSPD can be mounted [6]. The detection efficiency of the SSPD system we have developed reached 80% at 1,550 nm [7] and the system has been contributing to many excellent results such as an experiment to verify the Tokyo QKD network [8] and fundamental experiments in quantum optics [9][10]. On the other hand, the application field of photon detectors is widespread, from communication and measurement to biology and medical treatment. In most cases of these applications, the wavelength of the detection target is less than 1,000 nm, so the silicon APD and photo multiplier tube (Photo Multiplier Tube: PMT) have been used as photon detectors. The detection efficiency of a silicon APD in the visible wavelength range reaches 70%, which means that it is necessary for SSPD to compete with these photon detectors in the future and to extend its application field to achieve total performance in not only detection efficiency but also in maximum count rate, dark count rate, and jitter, etc. that are superior to those of other detectors.

In this paper, we summarize the research and development of SSPD we have conducted focusing on the light of 1,550 nm, and introduce other research we are implementing now such as broadening of the wavelength band and a multi-pixel detector for the purpose of extension of the application field and higher performance.

## 2 Development of multi-channel SSPD system

### 2.1 Structure of SSPD device and its functional principle

The structure of the SSPD device (a) and the principle of photon detection (b) are shown in Fig. 1. Briefly explaining the principle of photon detection of the SSPD, one incident photon destroys the superconducting state. In order to realize the phenomenon, it is necessary to minimize the volume of the superconductive substance to its limit. Hence, a superconducting nanowire manufactured from a superconducting membrane of 5 nm thickness to a wire of 100 nm width is used. When this superconducting nanowire absorbs a photon, a hot spot where the superconducting state is locally destroyed is generated. If sufficient bias current is supplied to this superconducting nanowire, the superconducting state of the whole cross-section of the nanowire collapses because the superconducting current density around the hot spot exceeds the critical value (the value over which the superconducting state collapses) by the trigger of hot spot generation. As a result, the resistance between both sides of the nanowire increases to several kΩ and the bias current flows through the load of 50 Ω. Then, Joule heat around the hot spot diffuses over the substrate and the hot spot area returns to the superconducting state. Finally, the area recovers to the initial state where bias current flows through the superconducting nanowire. When the superconducting nanowire absorbs a photon, a spike-like pulse is observed by monitoring the voltage of both sides of the nanowire. Hence, a photon can be detected by monitoring this pulse by measurement apparatus at room temperature.

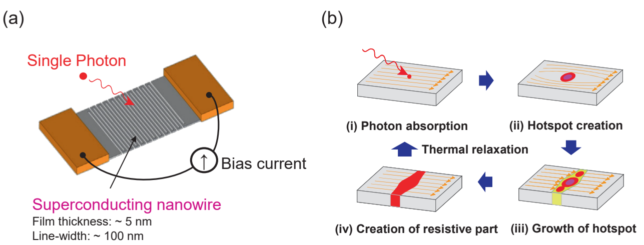



**Fig. 1** (a) Device structure of SSPD, (b) Photon detection mechanism

## 2.2 Development of high detection efficiency SSPD system

Although the theory of operation of SSPD is quite simple, there are some technical barriers to overcome to achieve high detection efficiency. There are three factors that determine the detection efficiency of SSPD. They are coupling efficiency with optical fiber, optical absorptance of nanowire, and pulse generation probability (Fig. 2). We developed a special fiber package so that the light from single mode (SM) fiber used for the communication wavelength band irradiates on the entire photosensitive area without loss. The photosensitive area of the SSPD is 15 × 15 μm$^2$ which is larger than the diameter of core of the SM fiber (about 10 μmØ). We succeeded in achieving fiber coupling efficiency of almost 100% by fusing a Graded Index (GRIN) lens at the terminal of the fiber to focus on the sensitive area [11].

The thickness of the superconducting nanowire membrane is about 5 nm, which is relatively thin, so it is difficult to realize high optical absorptance due to transmission and reflection of light in a single layer membrane. Hence, we adopted a device structure called a double side cavity in order to optimize the device structure so that the photoelectric field intensity become maximum near the nanowire by enclosing a photon in between the silicon substrate and metal reflection layer. As a result, optical absorptance over 90% for light of wavelength is 1.550 nm was realized. Normally, the ratio of the area of the superconducting nanowire to the entire detector (filling factor)

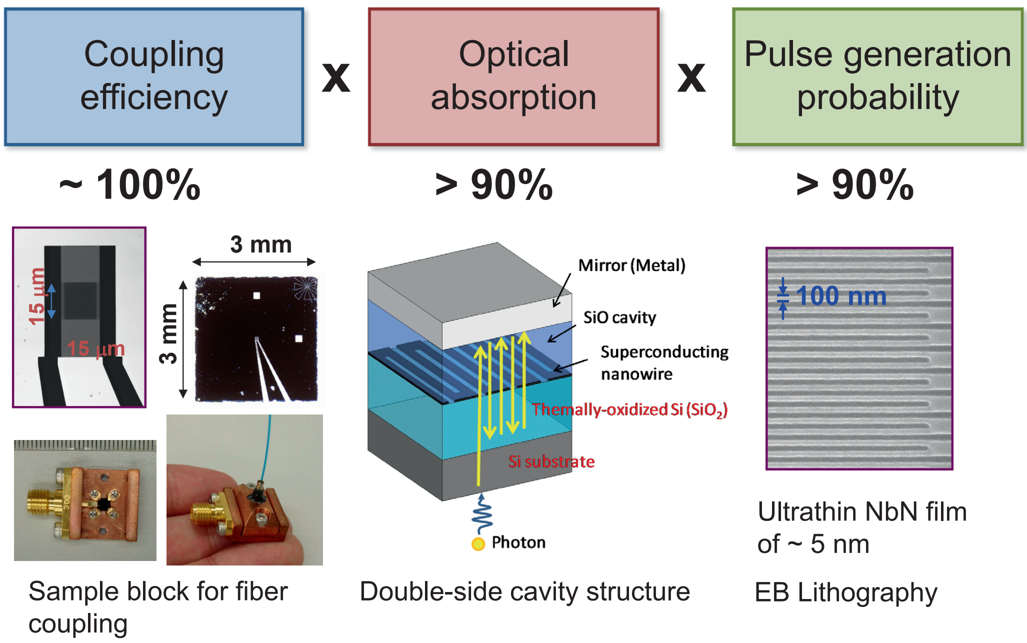
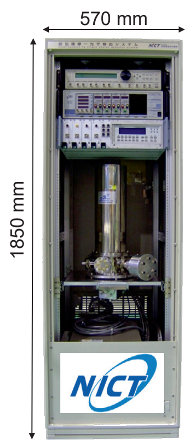



**Fig. 2** Three major factors determining detection efficiency of SSPD

is about 50%, and we found that the optical absorptance does not decrease with a double side cavity structure even when the filling factor is less than 25%[7][12]. The length of the nanowire become shorter if the filling factor becomes smaller, so a higher count rate can be achieved.

The last pulse generation probability is the probability that the superconducting state of the nanowire collapses due to photon absorption according to the theory shown in Fig. 1. If there is nonuniformity in the quality of the membrane or line width somewhere in the superconductive nanowire on a photosensitive area, the superconducting critical current density become lower, hence sufficient bias current cannot be supplied to other normal areas because the bias current supplied to the nanowire is limited at this minimum area of critical current. In this case, the probability that the superconducting state does not collapse due to absorption of a photon by the superconductive nanowire becomes higher. In order to achieve high pulse generation probability, it is important to manufacture a very thin, fine, and long superconducting nanowire uniformly. We used a nitride (NbN, NbTiN) superconducting substance whose thin-membrane surface is not easily oxidized and realized a super-thin membrane with a thickness of 5 nm of which uniformity of properties is excellent. Electron beam drawing of acceleration voltage of 125 kV was adopted for patterning and we succeeded to manufacture nanowire of width 100 nm with high patterning accuracy. As a result, pulse generation probability reached over 90%.

The view and performance of the 6-channel SSPD system developed by NICT is summarized in Fig. 3. We achieved detection efficiency of 80% at 1,550 nm by maximizing the value of each of the three factors mentioned above [7]. This value is much superior compared with 20%




| | Specification & performance |
|---|---|
| System DE (λ=1550nm) | 80% @1550nm |
| Dark CR (c/s) | 100 cps |
| Timing jitter | 68 ps |
| # of channel | 6 |
| Gate operating | Not required |
| Refrigerator | Air cooling compact GM |
| Driving voltage and power consumption | AC 100V・Max. 1.2 kW |
| Liquid helium | Not required |

**Fig. 3** 6-channel SSPD system and its specification and performance

of the APD made of InGaAs. As for dark count rate; it is more than 10,000 (counts/sec) for InGaAs APD; however, it is less than 100 (counts/sec) for SSPD that is much smaller than APD.

There exists a noise called after-pulse in InGaAs APD that has correlation with detector response. In order to suppress this noise, gate bias is necessary that synchronizes with the photo signal. On the other hand, the dark count is small and the after-pulse does not exist in SSPD, so this device can be driven by bias current of direct current, which is a large advantage.

In order to supply SSPD to users in a more convenient manner by maximizing its performance, we mounted the 6-channel SSPD on a small mechanical cryocooler (0.1 W Gifford McMahon cryocooler) that operates by 100 V power and developed a multi-channel SSPD system enclosed in a 19-inch rack [6]. This mechanical cryocooler does not require a water cooling system and it can cool SSPD down to 2.5 K only by turning on the cryocooler. As it is a mechanical cryocooler, coolant such as liquid helium is not necessary. So, long-time continuous running is possible without maintenance. The system is already used in many experiments in the quantum information field such as the Tokyo QKD network system, as a photon detection system that anybody can use easily at anytime and anywhere [8]–[10].

## 3 Challenge of extending application field

### 3.1 Broadband detection

Although we have optimized the device structure of SSPD for optical absorptance at the 1,550 nm wavelength assuming to be applied in the quantum information field, the photon detector is applied in various fields from communication and measurement to biology and medical treatment (Fig. 4). Because the wavelength used in such applications varies by field, it is important for an SSPD to be sensitive to not only at 1,550 nm but to other various wavelengths in order for it to be applied in other fields. Considering the theory of photon detection of SSPD where the superconducting state collapses by photon energy, shorter wavelength light with high energy is advantageous to realize higher pulse generation efficiency. However, as incident light irradiates from the backside of the silicon substrate in the case of the double-side cavity structure shown in Fig. 2(b), light of a wavelength shorter than 1μm is absorbed in the substrate because the energy of the photon is larger than the band gap of silicon. Then, we

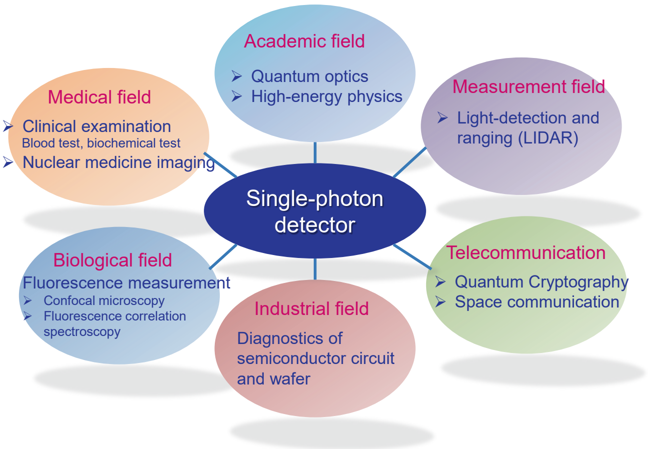



**Fig. 4** Application field of single-photon detector

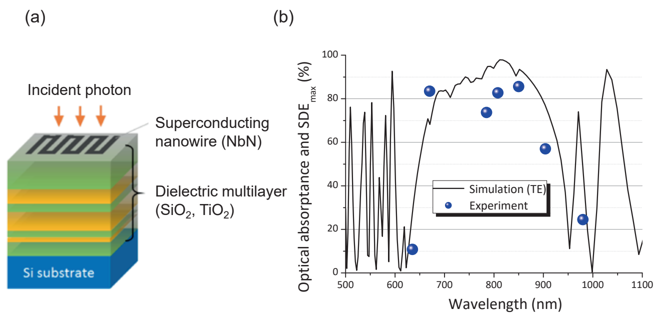



**Fig. 5** SSPD with dielectric multilayer and its optical wavelength dependence of optical absorptance

designed a device structure using a dielectric multilayer membrane shown in Fig.5 which enables flexible design to be sensitive to light of wavelengths shorter than 1μm [13][14]. The wavelength of light absorbed by the superconducting nanowire can be freely designed by varying the thicknesses of two kinds of dielectric membrane of different refractive indexes (we used $SiO_2$ and $TiO_2$).

In order to save time spent on optimization of structure, we designed an optimization method by combining a matrix method and a finite element method. First of all, the thickness and period of $SiO_2$ and $TiO_2$ is optimized so that high optical absorptance is achieved at the desired wavelength for the structure with NbN thin film that is not processed as a mono layer nanowire on the dielectric multilayer membrane, using the matrix method (for example, software to optimize optical thin film, Essential MacLeod, etc.). Then, light wavelength dependency of optical absorptance covering polarization dependency of the nanowire made of NbN thin film which is a part of the real SSPD structure is calculated using the finite element method (using software such as COMSOL, etc.). A larger amount of time for calculation is reduced using both the matrix method and finite element method rather than using only the finite element method. The light wavelength dependency of optical absorptance is obtained by optimization of the structure of a dielectric multilayer, targeting wavelength of 650 ~ 900 nm by this method. The light wavelength dependency of optical absorptance obtained by optimizing structure of dielectric multilayer targeting wavelength of 650 ~ 900 nm by this method is shown in Fig. 5. It is seen that high optical absorptance is achieved in the wavelength range of 650-900 nm and low at other wavelengths. The optical absorptance obtained for the SSPD we manufactured and evaluated is presented in Fig. 5. The optical absorptance obtained from the experiment coincides well with the result obtained from calculation, which means that our optimization method is effective [13][14].

There are many theories for the origin of dark count rate of SSPD. The dark count rate of SSPD in a low bias region is mostly due to black body radiation at room temperature incident from optical fiber [15]. As photon absorption at wavelengths other than that to be detected can be suppressed by using a dielectric multilayer, it is expected to be useful to decrease the dark count rate by black body radiation. We will apply a device structure using a dielectric multilayer to various light wavelengths in the future and verify the effectiveness from the viewpoint of decreasing the dark count rate.

## 3.2 Multi-pixel detector

The detection efficiency of Si APD for light wavelength of less than 1μm achieves 70%. So, in order for SSPD to extend its application fields, it is necessary to verify its advantages in not only high detection efficiency but total performance such as maximum count rate, dark count rate, and jitter over other existing techniques.

One of the merits of SSPD is the high maximum count rate. In principle, it is determined by the relaxation time of a quasi-particle of a hot spot generated by photon absorption and it is supposed to be possible to operate at 1 GHz. However, in order to couple it with single-mode fiber with a core diameter of about 10 μm, a photosensitive area of 15 μm × 15 μm is necessary. If the sensitive area is covered with superconducting nanowire of 100 nm width in meander, the kinetic inductance of nanowire $L_K$ reaches 1 μH. Hence, the dead time (time needed to recover to the state of next photon detection after detecting a photon) of the SSPD is constrained by the ratio of $L_k$ to load resistance R ($L_k$/R time constant) and the maximum count rate of the

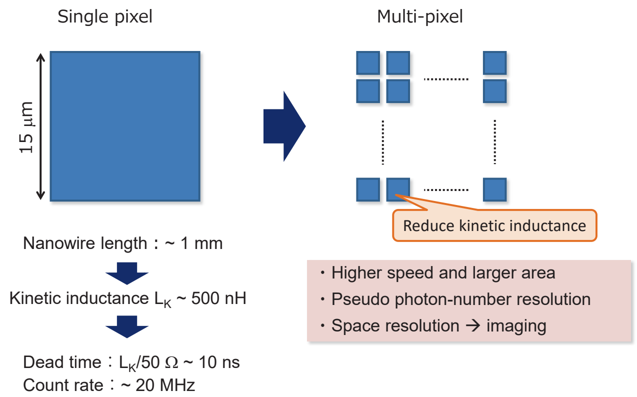



**Fig. 6** Benefit of multi-pixel SSPD

present SSPD is several tens of MHz. This value is not advantageous comparing with other competing techniques such as APD, etc. Also, in some application cases (especially used in visible wavelength), it is necessary to couple it with multimode fiber of core diameter 50 μm that is larger than SM fiber, so a larger sensitive area is necessary. As a result, the dead time increases and maximum count rate decreases.

In order to overcome the limit of maximum count rate by $L_K$, a multi-pixel SSPD is proposed [16]. The merits of multi-pixel are summarized in Fig. 6. It is possible to shorten the dead time without deteriorating the detection efficiency by downsizing each pixel and keeping the sensitive area necessary for coupling with fiber by multi-pixel. Multi-pixel is effective to suppress increase of dead time due to large area.

Also, a single pixel SSPD cannot count incident photons, but a multi-pixel SSPD can detect multiple photons incident into individual pixels simultaneously, so photon counting is possible in a pseudo way.

Multi-pixel of a million-pixel class would enable realization of an ultimate camera with photon-counting-level sensitivity in the future. The most severe bottleneck to realize a multi-pixel SSPD is read-out of the output signal. In general, broader-band coaxial cable is a better thermal conductor. Hence, the number of cables installed in a small mechanical cryocooler is limited due to thermal load to the cryocooler. In order to reduce the number of readout cables, NICT proposed cryogenic signal processing consists of a single flux quantum (Single Flux Quantum: SFQ) logic circuit for the first time in the world [17]. We have succeeded in signal readout of SSPD and multiplexing [18] [19], cross-talk free operation of an SFQ circuit of a 4-pixel SSPD covering signal multiplex [20], demonstration of signal readout with lower timing jitter compared with

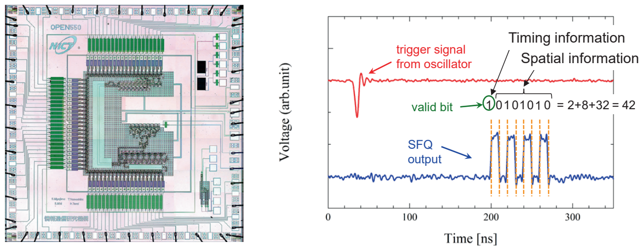



**Fig. 7** Photograph of 64-bit event-driven SFQ encoder chip and it output waveform

the conventional method using readout circuit [21]. Also, as a larger-scale multi-pixel device, we are developing a 64-pixel SSPD imaging system. We have already evaluated the individual detection efficiency of each pixel of the SSPD and succeeded in reproducing a beam profile of fiber irradiation [22]. Now, we are developing an encoder circuit for a 64-pixel SSPD. The encoder circuit is a circuit to read out coded position information of a pixel that detected a photon by one coaxial cable. This enables real-time imaging of a 64-pixel SSPD. It is designed so that not only position information of a photon but also time information can be detected by applying an event driven circuit that generates a clock in the circuit every time it detects a photon. Flying time can be measured by measuring the round-trip time of a photon from a certain measuring point and then the distance to the target can be calculated. It is information on the depth of the target, so a three-dimensional image can be constructed using the information on the depth direction in addition to a two-dimensional image reconstructed from the information of a pixel that detected a photon.

One of the features of an SFQ circuit is that it operates with low power consumption and the impedance of the circuit is very low. A bias current of about 1 A is necessary to drive a circuit containing ten thousand Josephson junction. Figure 7 shows a microscopic photo of a 64-bit type event driven SFQ encoder circuit. For the preliminary circuit design, bias current of 370 mA was needed to drive the circuit. We tested the circuit by installing it in a cryocooler and found temperature increase of the cryocooler due to Joule heat generated in a bias cable [23]. Then, we revised the circuit design and succeeded in operating with a small cryocooler by reducing bias current to 150 mA. This 64-bit encoder circuit was installed to the same sample block as the 64-pixel SSPD. We observed output of the SFQ encoder by illuminating light on the SSPD. As a result, information on the address of the pixel that detected a photon (binary code) was output synchronously with the photon signal input. So, it was confirmed that a multi-pixel SSPD operates in combination with an SFQ encoder [24]. In the future, we plan to verify real-time imaging operation including signal processing at room temperature and continue to develop larger pixel detectors [25] by making the best use of SFQ signal processing of NICT, taking the method of a readout signal with 2N outputs from an N × N pixel SSPD that the National Institute of Standards and Technology (NIST) group proposes [26].

The ultimate goal of SFQ signal processing is monolithic integration with a multi-pixel SSPD. We have already started to develop monolithic integration of a 16-pixel SSPD and SFQ multiplexing circuit and succeeded to read out a photon detection signal from the SSPD via the SFQ circuit that is integrated on the same substrate as the multi-pixel [27]. However, the present detection efficiency is 0.25% which is much smaller than the detection efficiency of 80% obtained for a single-pixel SSPD. There are many problems in the manufacturing process to be improved in the future such as generation of separation of SiO silicon thin film that constructs the photo cavity of SSPD by stress of thin film in the manufacturing process of the SFQ circuit. Improvement of fitting of film, relaxation of thin film, etc. should be made.

## 4 Future prospects

The performance of SSPD increased dynamically in these five years and the detection efficiency already has reached 80%. It is important to realize high detection efficiency for various wavelengths to extend application fields and to differentiate the performance of the SSPD photon detector from the other photon detectors in terms of detection efficiency such as high count rate, low dark count rate and low level of jitter. In this case, it is important to know how accurately we understand users' demand for research and development. NICT is attempting to apply SSPD to fluorescence correlation spectroscopy (FCS) for the purpose of applying it to biology and medical treatment, but which cannot be introduced in detail in this article. This is an application focusing on the low-noise and high-speed property that SSPD has no after-pulse. We have developed an SSPD for visible light used in FCS [28], and succeeded to observe rotation dispersion of a molecule that has been difficult for silicon APD [29][30]. Also, we are developing a large-area multi-pixel targeting application for deep space communication, in collaboration with researchers of Space Communications. We believe that it will be a key to discovering new demand, to compete with other existing photon detectors and to widen application fields in the future.

## Acknowledgments

We thank Drs. Shigehito MIKI, research scientist, Taro YAMASHITA, research scientist, Shigeyuki MIYAJIMA, researcher, Masahiro YABUNO, researcher, Akira KAWAKAMI, research scientist and Saburo IMAMURA, technologist, members of the Frontier Research Laboratory. Also, we thank Drs. Shuichi NAGASAWA and Mutsuo HIDAKA of the National Institute of Advanced Industrial Science and Technology for manufacturing the SQC circuit, Dr. Tokuko HARAGUCHI, research scientist of the Frontier Research Laboratory, Prof. Yasushi HIRAOKA of the Graduate School of Frontier Biosciences, Osaka University, Prof. Masataka KINJO of Hokkaido University, Faculty of Advanced Life Science, and Dr. Jotaro YAMAMOTO for useful discussion on FCS. A part of this study was funded by Grants-In-Aid for Scientific Research (Creative, pioneering research conducted by individual researcher (A) No. 26249054).

### *References*

1 G. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, "Picosecond superconducting single-photon optical detector," Appl. Phys. Lett.79, pp.705–707 2001.

2 E. Dauler, M. Grein, A. Kerman, F. Marsili, S. Miki, S. W. Nam, M. Shaw, H. Terai, V. Verm, and T. Yamashita, "Review of Superconducting Nanowire Single Photon Detector System Design Options and Demonstrated Performance," Opt. Engineering 53, 061907, 2014.

3 F. Marsili, V. Verma1, J. Stern, S. Harrington1, A. Lita, T. Gerrits, I. Vayshenker, B. Baek, M. D. Shaw, R. P. Mirin1, and S. W. Nam, "Detecting single infrared photons with 93% system efficiency," Nature Photonics 7, pp.210–214, 2013.

4 D. Rosenberg, A. J. Kerman, R. J. Molnar, and E. A. Dauler, "High-speed and high-efficiency superconducting nanowire single photon detector array," Opt. Express 21, 1440, 2013.

5 S. Miki, T. Yamashita, H. Terai, and Z. Wang, "High performance fiber-coupled NbTiN superconducting nanowire single photon detectors with Gifford-McMahon cryocooler," Opt. Express 21, 10208, 2013.

6 S. Miki, T. Yamashita, M. Fujiwara, M. Sasaki, and Z. Wang, "Multichannel SNSPD system with high detection efficiency at telecommunication wavelength," Opt. Lett. 35, pp.2133–2135, 2010.

7 http://www.nict.go.jp/press/2013/11/05-1.html

8 M. Sasaki, M. Fujiwara, H. Ishizuka, W. Klaus, K. Wakui, M. Takeoka, S. Miki, T. Yamashita, Z. Wang, A. Tanaka, K. Yoshino, Y. Nambu, S. Takahashi. A. Tajima, A. Tomita, T. Domeki, T. Hasegawa, Y. Sasaki, H. Kobayashi, T. Asai, K. Shimizu, T. Tokura, T. Tsurumaru, M. Matsui, T. Honjo, K. Tamaki, H. Takesue, Y. Tokura, J. F. Dynes, A. R. Dixon, A. W. Sharpe, Z. L. Yuan, A. J. Shields, S. Uchikoga, M. Legre, S. Robyr, P. Trinkler, L. Monat, J.-B. Page, G. Ribordy, A. Poppe, A. Allacher, O. Maurhart, T. Langer, M. Peev, and

A. Zeilinger, "Field test of quantum key distribution in the Tokyo QKD Network," Opt. Express 19, 10387, 2011.
9 T. Kobayashi, R. Ikuta, S. Yasui, S. Miki, T. Yamashita, H. Terai, T. Yamamoto, M. Koashi, and N. Imoto, "Frequency-domain Hong-Ou-Mandel interference," Nat. Photonics 10, pp.441–444, 2016.
10 R. Ikuta, T. Kobayashi, K. Matsuki, S. Miki, T. Yamashita, H. Terai, T. Yamamoto, M. Koashi, T. Mukai, and N. Imoto, "Heralded single excitation of atomic ensemble via solid-state-based telecom photon detection," Optica 3, 1279, 2016.
11 S. Miki, M. Takeda, M. Fujiwara, M. Sasaki, and Z. Wang, "Compactly packaged superconducting nanowire single-photon detector with an optical cavity for multichannel system," Opt. Express 17, pp.23557–23564, 2009.
12 T. Yamashita, S. Miki, H. Terai, and Z. Wang, "Low-filling-factor superconducting single photon detector with high system detection efficiency," Optics Express 22, 27177, 2013.
13 T. Yamashita, K. Waki, S. Miki, R. Kirkwood, R. Hadfield, and H.Terai, "Superconducting nanowire single-photon detectors with non-periodic dielectric multilayers," Scientific Reports 6, 35240, 2015.
14 http://www.nict.go.jp/press/2016/10/24-1.html
15 T. Yamashita, S. Miki, K. Makise, W. Qiu, H. Terai, M. Fujiwara, M. Sasaki, and Z. Wang, "Origin of intrinsic dark count in superconducting nanowire single-photon detectors," Appl. Phys. Lett.99, 161105, 2011.
16 E. A. Dauler, B. S. Robinson, A. J. Kerman, J. K. W. Yang, K. M. Rosfjord, V. Anant, B. Voronov, G. Gol'tsman, and K. K. Berggren, "Multi-Element Superconducting Nanowire Single-Photon Detector," IEEE Trans. Appl. Supercond. 17, (2007) 279.
17 H. Terai, S. Miki, and Z. Wang, "Readout electronics using single-flux-quantum circuit technology for superconducting single-photon detector array," IEEE Trans. Appl. Supercond. 19, 350, 2009.
18 H. Terai, S. Miki, T. Yamashita, K. Makise, and Z. Wang, "Demonstration of single-flux-quantum readout operation for superconducting single-photon detectors," Appl. Phys. Lett.97, 112510, 2010.
19 S. Miki, H. Terai, T. Yamashita, K. Makise, M. Fujiwara, M. Sasaki, and Z. Wang, "Superconducting single photon detectors integrated with single flux quantum readout circuits in a cryocooler," Appl. Phys. Lett.99, 111108, 2011.
20 T. Yamashita, S. Miki, H. Terai, K. Makise, and Z. Wang, Opt. Lett., "Crosstalk-free operation of multielement superconducting nanowire single-photon detector array integrated with single-flux-quantum circuit in a 0.1 W Gifford McMahon cryocooler," Opt. Lett.37, 2982, 2012.
21 H. Terai, T. Yamashita, S. Miki, K. Makise, and Z. Wang, "Low-jitter single flux quantum signal readout from superconducting single photon detector," Opt. Express 20, 20115, 2012.
22 S. Miki, T. Yamashita, H. Terai, and Z. Wang, "High detection efficiency fiber-coupled NbTiN superconducting nanowire single photon detectors with Gifford-McMahon cryocooler," Opt. Express 21, 10208, 2013.
23 H. Terai, K. Makise, T. Yamashita, S. Mik, and Z. Wang, "Design and testing of SFQ signal processor for 64-pixel SSPD array," Applied Superconductivity Conference 1EOr1A-03, 2014.
24 S. Miyajima, T. Yamashita, S. Miki, and H. Terai, "A Cryogenic Event-Driven Encoder Based on Single-Flux-Quantum Circuit for Multi-Pixel Superconducting Single-Photon Detectors," Applied Superconductivity Conference 3EOr1B-05, 2016.
25 M. Yabuno, S. Miyajima, S. Miki, T. Yamashita, and H. Terai, "Design for Building the Large-scale Superconducting Nanowire Single-photon Detector Imaging Array," International Superconducting Electronics Conference We-SQE-19, 2017.
26 M. S. Allman, V. B. Verma, M. Stevens, T. Gerrits, R. D. Horansky, A. E. Lita, F. Marsili, A. Beye, M. D. Shaw, D. Kumo, R. Mirin, and S. W. Nam, "A near-infrared 64-pixel superconducting nanowire single photon detector array with integrated multiplexed readout," Appl. Phys. Lett.106, 192601, 2015.
27 H. Terai, S. Nagasawa, S. Miyajima, T. Yamashita, S. Miki, M. Yabuno, and M. Hidaka, "Design of large-scale superconducting nanowire single-photon detector array monolithically integrated with cryogenic single-flux-quantum signal processor," Applied Superconductivity Conference 3EOr1B-03, 2016.
28 T. Yamashita, D. Liu, S. Miki, J. Yamamoto, T. Haraguchi, M. Kinjo, Y. Hiraoka, Z. Wang, and H. Terai, "Fluorescence correlation spectroscopy with visible-wavelength superconducting nanowire single-photon detector," Opt. Express 22, 28783, 2014.
29 J. Yamamoto, M. Oura, T. Yamashita, S. Miki, T. Jin, T. Haraguchi, Y. Hiraoka, H. Terai, and M. Kinjo, "Rotational diffusion measurements using polarization-dependent fluorescence correlation spectroscopy based on superconducting nanowire single-photon detector," Opt. Express 23, 32633, 2015.
30 https://www.nict.go.jp/press/2015/12/22-1.html

**Hirotaka TERAI, Dr. Eng.**

Excutive Researcher, Frontier Research Laboratory, Advanced ICT Research Institute
Superconducting electronics, Quantum information and communication