Superconducting microstrip single-photon detector with system detection efficiency over 90% at 1550 nm

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Abstract: Generally, a superconducting nanowire single-photon detector (SNSPD) is composed of wires with a typical width of ~100 nm. Recent studies have found that superconducting stripes with a micrometer-scale width can also detect single photons. Compared with the SNSPD, the superconducting microstrip single-photon detector (SMSPD) has smaller kinetic inductance, higher working current, and lower requirement in fabrication accuracy, providing potential applications in the development of ultra-large active area detectors. However, the study on SMSPD is still in its infancy, and the realization of its high-performance and practical use remains an opening question. This study demonstrates a NbN SMSPD with a saturated system detection efficiency (SDE) of ~92.2% at a dark count rate of ~200 cps, a polarization sensitivity of ~1.03, and a timing jitter of ~48 ps at the telecom wavelength of 1550 nm when coupled with a single fiber and operated at 0.84 K. Furthermore, the detector’s SDE is over 70% when operated at a 2.1-K closed-cycle cryocooler.

1. Introduction

Superconducting nanowire single-photon detectors (SNSPDs) [1] have been proven as one of the most attractive single-photon detectors, as they provide high system detection efficiency (SDE) [2-4], low dark count rate (DCR) [5], low timing jitter (TJ) [6, 7], high count rate (CR) [8], and broadband sensitivity [9, 10]. To date, SNSPDs have been used in many applications, such as quantum key distribution [11, 12], photonic Boson sampling [13], dark matter detection [14, 15], and satellite laser ranging and detection (LIDAR) [16].

Generally, to achieve a saturated internal detection efficiency (IDE), the width of the superconducting strip is usually fabricated to ~100 nm, which is the same magnitude as the formed size of the hotspot after photon absorption [17]. However, a theory proposed by Vodolazov [18] in 2017 predicts that a micron-wide dirty superconducting strip is able to detect a single-photon when it is biased by a current close to the depairing current (I_{dep}). In 2018, Korneeva et al. have experimentally shown that the micrometer-wide NbN short bridge can detect a single-photon in a wavelength range of 408-1550 nm [19]. Since then, studies of the superconducting microstrip single-photon detector (SMSPD) have emerged. In 2019, Manova at al. developed NbN SMSPD with an IDE of ~30% at 1330 nm wavelength at 1.7-K operating temperature [20]. In 2020, Chiles et al [21] and Charaev et al [22] reported very large active area of SMSPDs with saturated IDE at 1550 nm at sub-1K operating temperature through very thin amorphous materials (2-3 nm WSi$_3$ or ~3 nm MoSi$_2$). Unfortunately, the SDEs of the reported SMSPDs at the telecom wavelength of 1550 nm are still at a low value (<6%), either due to a low IDE [19, 20] or a low optical absorbance (owing to the use of a very thin film, a low filling factor, or a lack of optical cavity [21, 22]). Furthermore, the IDE of the reported NbN SMSPDs at 1550 nm are still far from saturation [19, 23]. How to realize
a high-performance SMSPD that can be operated in a closed-cycle cryocooler is still an opening question. In response, more elaborated works have to be done and more insights to the detection mechanism of SMSPD are required. Numerical simulations based on SMSPDs embedded in an optical cavity are necessary. A proper geometrical configuration to reduce the current crowding effect on sharp turns is needed to bias the microstrip close to its $I_{\text{dep}}$, while maintaining a high optical absorptance.

This study reports a He ion pre-irradiated NbN SMSPD that can obtain a saturated IDE at 0.84 K operating temperature, with a 7-nm-thick, 1-μm-wide, double spiral strip configuration and an active area of 50 μm in diameter. Combined with a distributed Bragg reflector (DBR)-based cavity design and a high filling factor ($f$) of 0.8, results demonstrate a simulated absorption efficiency of the microstrip up to ~100% and an experimental SDE of 92.2% at 1550 nm through single mode fiber (SMF) coupling. The detector also exhibits a low polarization extinction ratio (PER) of ~1.03, a low DCR of ~200 cps, and a low system TJ of ~48 ps. Operated in a 2.1-K closed-cycle cryocooler, the detector shows a maximum SDE of over 70% at 1550 nm. In addition, the SMSPD is further coupled with a multimode fiber (MMF), where the detector shows a maximum SDE of over 60% and a TJ of ~50 ps.

2. Design and fabrication of SMSPDs

Numerical simulations are performed using a commercial software (COMSOL Multiphysics). Figure 1(a) shows the schematics of the optical stack of SMSPDs, where the microstrips were stacked on top of the DBR substrate [4]. The DBR structure is comprised of 13 periodic SiO$_2$/Ta$_2$O$_5$ bilayers in quarter of the central wavelength of 1550 nm, stacked on the top of the Si substrate. Owing to formation of an optical cavity, the absorptance of the microstrips is greatly enhanced. Figure 1(b) shows the simulated optical absorptance as a function of the microstrip thickness, with a fixed strip width of 1 μm and varied $f$ (0.4-0.8). A weak influence on absorptance is observed when the strip thickness is greater than 7 nm. A 1-μm-wide microstrip with $f = 0.8$ demonstrates high absorptance of ~97%. Moreover, for a 7-nm (10-nm)-thick strip, with $f$=0.92 (0.84), the absorptance could reach to ~100%. Figure 1(c) shows the wavelength dependence of the simulated absorptance, where small dips in absorptance occur in the resonant band (1400-1750 nm, determined at 3 dB cutoff). This behavior is much different with the simulations for the nanowires on the DBR substrate [4], where no dips of absorptance appeared in the resonant band. This may be contributed to some destructive interferences appear in some specific wavelengths because of the narrow spacing between the microstrips (i.e., grating interference effect when the wavelength is larger than the spacing of the grating). In addition, the absorptance of microstrips in the transverse-electric (TE, solid lines) and transverse-magnetic (TM, dashed lines) polarization showed small differences at high $f$, resulting in a low polarization sensitivity. For example, for $f = 0.8$ at 1550 nm, the simulated polarization sensitivity (PER = TE/TM) is found to be 97.2%/95.9%/1.01, which was much smaller than the PER (~3-4) of the regular nanowires with $f$~0.6 [4].

According to the simulation, the SMSPDs are designed with a fixed 1-μm width and a varied $f$ of 0.4-0.8. To reduce the current crowding effect, the detectors are patterned with a double spiral strip configuration based on previous studies [24, 25]. As a comparison, different geometrical configurations [see Figure 2(a)-(d)] are also designed with the same width on one wafer, including a short micro bridge (called Bridge), a modified double spiral strip (called Spiral-1), a regular double spiral strip (called Spiral-2), and a conventional meandered strip (called Meander). The $f$ of the microstrips mentioned is ~0.8 with an active area of 50 μm in diameter or a side length of 50 μm. One limitation of the double spiral strip configuration is that a photon insensitive zone appears in the center of the pattern, owing to the use of a wider strip to optimize corner curvature. To maximize the coupling efficiency, the detector can be coupled using a lens fiber (small laser beam waist) with an eccentric alignment. Other method on optimizing the current crowding effect will be shown in a separate study.
Fig. 1. (a) Cross-section schematic diagram of the NbN SMSPD. From top to bottom, optical stacks correspond to a NbN microstrip, a 13-layer SiO$_2$/Ta$_2$O$_5$ distributed Bragg reflector, and an Si substrate, respectively. (b) Simulated microstrip thickness dependence of optical absorptance at different $f$ (0.4, 0.6, and 0.8), with a fixed strip width of 1 $\mu$m. (c) Simulated wavelength dependence of optical absorptance for microstrips with varied $f$ in a wavelength range of 1300 nm-1900 nm at two different polarizations of light: TE (solid lines) and TM (dashed lines).

Fig. 2. Layouts (top panels, a-d) and magnified SEM images (bottom panels, e-h) of four different SMSPDs. (a) & (e), the short micrometer bridge; (b) & (f), the modified double spiral strip; (c) & (g), the regular double spiral strip; (d) & (h), the conventional meandered strip. The $f$ of the microstrips (b-d, f-h) is 0.8. The blue arrows mark the directions of the current flow.

For fabricating SMSPDs, a 7-nm-thick NbN film is deposited on a 2-inch DBR wafer, using reactive DC magnetron sputtering in a mixture of Ar and N$_2$ gases. To improve the IDE of NbN microstrips, He ion irradiation is conducted to the NbN-covered wafer in a 300-mm medium-current ion implanter through a He ion energy of 20 keV at room temperature [26]. The ion irradiation fluence was ~5x10$^{16}$ ion/cm$^2$ empirically. Then, the irradiated NbN film was processed to form the designed patterns using electron beam lithography and reactive ion etching (RIE). Figure 2(e)-(h) show the magnified scanning electron microscope (SEM) images of the four different patterns. The coplanar waveguide electrodes were finally fabricated using ultraviolet lithography and RIE.

3. Measurements and results
The SMSPDs are characterized at two different bath temperatures: (1) 0.84 K in an adsorption refrigerator and (2) 2.1 K in a compact closed-cycle G-M cryocooler. To prevent the SMSPDs from latching (detector latched at the normal state) [27, 28], a shunted resistor is connected in parallel to the SMSPD chip through wire-bonding. We chose a shunt resistor of ~6.8 Ω (measured at room temperature), which showed optimal performance in IDE and output voltage magnitude. The detector was then biased and read out through a cryogenic coaxial cable, connecting to the room temperature circuits (i.e., a bias-tee, a low noise amplifier, and a photon counter). Figure 3(a) shows the sweeping current-voltage (I-V) curves for the chip connected with (blue line) or without (red line) a shunt resistor. It can be observed that with a shunt resistor, the nominal switching current \( I_{\text{sw}} \) is increased from 66 μA to 80 μA. In the low voltage region (-0.4 to 0.4 mV), the I-V curve demonstrated a slope, which corresponded to a ~5 Ω contact resistance. Because the nominal \( I_{\text{sw}} \) is influenced by the shunt resistor, we first screened the devices without the shunt resistor. Figure 3(b) shows the \( I_{\text{sw}} \) comparison of the four different SMSPD configurations on the same wafer with a fabricated width of ~1 μm, measured at 2.1 K. For the \( I_{\text{sw}} \), at least five samples are tested for each pattern. The average \( I_{\text{sw}} \)s of the Bridge, Spiral-1, and Spiral-2, are 65.4 ± 0.8 μA, 65.2 ± 0.7 μA, and 64.4 ± 1.0 μA, respectively, while that of the Meander is only 43.5 ± 0.9 μA (~0.67 of those of the Spiral-1). This result confirmed that the sample with a double spiral structure can effectively reduce the current crowding effect, thus guaranteeing a higher \( I_{\text{sw}} \) (IDE). Therefore, in the following experiment, a modified double spiral strip (Spiral-1) configuration is characterized due to the higher \( I_{\text{sw}} \).

![Fig. 3.](image)

The optical-electrical performance of the SMSPDs are further characterized based on the reported setup and methods [4]. The uncertainty of SDE is less than 2% using a PTB traceable power meter. Figure 4 shows the comparison of the SDEs versus bias current \( I_b \) for the SMSPDs fabricated with irradiated (called chip MS-1) and un-irradiated (called chip MS-2) NbN thin films. Both chips have the same film thickness (~7 nm, deposited on the same batch) and the same geometrical configuration (1-μm wide, \( f = 0.8 \), and a diameter of 50 μm). The chips were cooled in the 2.1 K G-M cryocooler and were both connected with a shunt resistor and coupled with a lens SMF (a beam waist of ~6 μm). The input photon flux was \( 1 \times 10^5 \) photon/s at the wavelength of 1550 nm. Owing to the mentioned photon insensitive zone in the center (~10 μm in diameter), the SMF was eccentrically aligned to maximize the coupling efficiency. Notably, the maximum SDEs of the SMSPDs fabricated with irradiated and un-irradiated NbN thin films are ~70% and ~3%, respectively. \( I_{\text{sw}} \) with the shunt resistor was reduced to ~0.65 of the un-irradiated value, mainly due to the reduction of electron
density of states in Femi level \( (N_0) \) [29]. To explain the significant enhanced IDE of the irradiated SMSPD, the physical parameters of the SMSPDs fabricated with un-irradiated and irradiated NbN thin films were characterized, as shown in Table 1. It can be found that, the square resistance \( (R_{sq}) \) was increased and the critical temperature \( (T_c) \) was suppressed in the irradiated samples, both of which would result in a larger hotspot formation in the microstrip [18]. A larger hotspot size would help reduce the detection current of the SMSPD. Similar phenomenon was also observed for the irradiated nanowires [26]. Meanwhile, a ratio of \( I_{sw}/I_{dep} \approx 0.63 \) at 2.1 K for the un-irradiated microstrip was deduced by using the approximate expression of \( I_{dep}(T) = 0.74 \frac{w(\Delta(0))^{3/2}}{eR_{sq}D} \left[ 1 - \left( \frac{T}{T_c} \right)^2 \right]^{3/2} \) [30]. Here \( T \) is the operating temperature, \( w \) is the strip width, \( \Delta(0) = 1.76k_BT_c \) is the superconducting gap at 0 K, \( e \) is the electron charge, and \( D \) is the diffusion coefficient. This ratio of \( I_{sw}/I_{dep} \) for irradiated samples slightly raised to \( \approx 0.66 \) at the same \( T = 2.1 \) K. Thus, it is speculated that a combined mechanism may play a role that involves the larger hotspot formation and higher \( I_{sw} \) close to the \( I_{dep} \) due to ion irradiation effect. Additionally, the results of irradiated samples show that the NbN film currently used in our laboratory is not suitable to achieve high-performance SMSPD. Deeper analysis of the changes in the physical properties of the film via irradiation will provide us with guidance for preparing films suitable for SMSPD. Both issues will be further explored in another study.

![Graph](image)

**Fig. 4.** Comparison of SDE (solid scatters) and DCR (open scatters) of the SMSPDs fabricated with irradiated and un-irradiated NbN thin films as a function of bias current \( (I_b) \) at 2.1 K.

**Table 1.** Parameters of the SMSPDs fabricated with un-irradiated and irradiated NbN thin films. \( R_{sq}(20\,\text{K}) \) is the square resistance at 20 K. \( D \) is the diffusion coefficient. \( I_{dep}(0\,\text{K}) \) and \( I_{dep}(2.1\,\text{K}) \) are the calculated depairing current at 0 K and 2.1 K. The \( I_{sw} \) at 2.1 K is measured without a shunt resistor.

| Samples      | \( R_{sq}(20\,\text{K}) \) (\( \Omega/\text{sq} \)) | \( T_c \) (K) | \( D \) (\( \text{cm}^2/\text{s} \)) | \( I_{dep}(0\,\text{K}) \) (\( \mu\text{A} \)) | \( I_{dep}(2.1\,\text{K}) \) (\( \mu\text{A} \)) | \( I_{sw}(2.1\,\text{K}) \) (\( \mu\text{A} \)) | \( I_{sw}/I_{dep}(2.1\,\text{K}) \) |
|--------------|-----------------------------------------------|----------------|---------------------------------|----------------------------------|---------------------------------|---------------------------------|---------------------------------|
| un-irradiated| 839                                           | 7.14           | 0.44                           | 185                              | 161.5                           | 101.1                           | 0.63                            |
| irradiated   | 1036                                          | 6.40           | 0.50                           | 119                              | 100.5                           | 66.0                            | 0.66                            |

Empirically, lowering the operating temperature would help improve the IDE of SMSPD. Figure 5(a) shows the temperature dependence of our best SMSPD (chip MS-1) coupling with the lens SMF. The SDE (solid scatters) and DCR (open scatters) of the chip MS-1 as a function of \( I_b \) are recorded at 2.1 K and 0.84 K, respectively. At 0.84 K, a weak saturated SDE plateau appears at the high current region, implying near-unity IDE. A maximum SDE of 92.2% at a DCR of 200 cps are obtained at 1550 nm wavelength. The measured SDE data are fitted at 0.84 K with the sigmoid function (dashed line), showing the saturation trend of
the SDE with the current increase. The polarization controller is also adjusted to study the polarization sensitivity of detector, as shown in Figure 5(b). The PER (ratio between the maximum and minimum SDEs) of the chip MS-1 shows a value of less than 1.03, consistent with the simulation (≈1.01) at 1550 nm. Low polarization sensitivity is preferred in many applications, e.g., providing a high SDE for the MMF-coupled systems.

**Fig. 5.** (a) Bias current dependences of SDE and DCR of the SMSPD (chip MS-1), measured at two different temperatures, with 1550 nm light illumination. (b) Maximum (solid sphere) and minimum (solid square) SDEs measured at two different polarization of light at 0.84 K. Inset shows a microscope image of the SMSPD with an active area of 50 μm in diameter. Dashed lines are sigmoid function fits in both figures.

Low TJ is a significant advantage of SNSPDs over the other counterpart detectors. It is interesting to determine whether the SMSPD can maintain a low TJ as well as the SNSPD. Previously, TJ in SMSPD showed a strong current dependence and a minimum jitter of ~46 ps was obtained at the current where IDE saturates, measured using a 1064 nm ps laser [20]. Here, we show the system TJ of the chip MS-1 using the TCSPC module and a 1550-nm fs laser [31]. Figure 6 (a) and (b) show the histogram of the time delay between the laser synchronization signal and output pulse of the SMSPD, recorded at high and low currents at 0.84 K, respectively. TJ was defined as the full width of half maximum (FWHM) of the normalized counts. As shown in Figure 6(a), the count histogram at high $I_b$ of ~95 μA ($0.98 I_{sw}$) was fitted well by the Gaussian distribution, which produced a TJ of 47.5 ps. However, in Figure 6(b), at the lower $I_b$ of ~76 μA ($0.79 I_{sw}$), the TJ increased to 142.4 ps, where count
histogram shows non-Gaussian shape with a “shoulder”. The “shoulder” can be regarded as the superposition of the main and secondary peaks, as shown by the fit curves [green and orange lines in the Figure 6(b)]. Recent theoretical model has reproduced the non-Gaussian shape by using a modified time-dependent Ginzburg-Landau equation [32]. The mechanism was associated with the position dependent vortex dynamics and the existence of fast and slow absorption sites across the superconducting strip. At the low current, the vortices, and antivortices move slower, leading to increased delay time, thus increasing TJ. Figure 6(c) presents the current dependence of the TJ. Generally, the TJ decreases with the increase of the current. However, at the currents where the IDE changes rapidly (e.g., 72-84 μA, light orange region in the figure), an inflection point of TJ appears in this current region, which may be caused by the effects of the non-Gaussian shape. The arrows in the figure mark two specific currents, at which Figure 6(a) and (b) are reordered.

**Figure 7** shows more details of the chip MS-1. Figure 7(a) shows the photon-response pulse of the SMSPD, with a fitted decay time (1/e criterion) of ~36 ns for the falling edge of the pulse. Although shunted with a resistor, a high pulse magnitude of ~190 mV was observed, guaranteeing a good signal-to-noise ratio of the output pulse. Figure 7(b) shows the CR dependence of the SDE measured at 0.84 K. A CR of ~5.7 MHz at 3 dB point. (c) Wavelength dependencies of the absorbance and SDE at TE polarization and 0.84 K for simulated absorbance (red dashed line) and the measured values with error bars (red stars). (d) The SDE and DCR versus $I_b$ with an MMF coupling at 0.84 K. The illustration shows the TJ is 50 ps at $I_b = 95$ μA.

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inductance [33]. Figure 7(c) shows the wavelength dependence of the SDE at TE polarization at $I_b = 93 \mu A$ at 0.84 K. At the wavelength range of 1520 nm to 1630 nm, the SDE shows a value greater than 88%. Because the difference between the peak and dip values of the simulated absorbance in this wavelength range is ~2.6%, which is close to the measurement error of the SDE, it is difficult to observe a clear dip (around 1570 nm) in the SDE. When the wavelength is longer than 1590 nm, the SDE demonstrates a slight decrease with the increase of the wavelength because of the non-saturation of the SDEs at the longer wavelength.

Furthermore, Figure 7(d) demonstrates the performance of our device coupled with a lens MMF with a core diameter of 50 $\mu$m and a beam waist of ~28 $\mu$m. The MMF-coupled SDE was ~61%, recorded at a photon flux of $1 \times 10^9$ photon/s. The low SDE may contributed to the low optical coupling caused by coupling misalignment. Another reason could be due to the blocking loss at high count rate, which is related to the detector’s dead time. However, according to our knowledge, this SDE is still the highest value reported for the MMF-coupled detectors at 1550 nm. Meanwhile, owing to the broadband background radiation transmitted by the MMF coupling, a significantly raised DCR was observed, which can be suppressed using cold narrowband filters, e.g., a MMF-coupled filter bench [34]. Through Gaussian fitting, TJ of ~50 ps at $I_b = 95 \mu A$ is obtained, which is slightly different compared to that of the SMF coupling due to the fiber-associated dispersion in optical signal transmission in MMF [35].

Finally, the SMSPD performances are compared with the state-of-the-art of the large active area SNSPDs at 1550 nm wavelength listed in Table 2, showing the potential of the SMSPD. The SMSPD with an active area of 50 $\mu$m and operated at 1550 nm usually demonstrates a very large kinetic induction (i.e., a long decay time over 1 $\mu$s without a series resistor), large TJ, and a very low yield. In contrast, the SMSPD with the same size exhibits an improved decay time, TJ, and yield (~68% (14/21) in one wafer), making it attractive for applications requiring a large active area, high timing performance, and efficient detection.

**Table 2. Comparison of the key merits of the SNSPDs and SMSPDs operated at 1550 nm wavelength**

| Detectors | Material | Area ($\mu$m) | SMF Coupling | MMF Coupling | Decay time (ns) |
|-----------|----------|--------------|--------------|--------------|----------------|
| SNSPD     | MoSi$_3$ [2] | $\Phi 50$  | 98.0 | $-10^4$ | 550 | 1.23 | N/A | N/A | N/A | ~400 |
|           | NbTiN$_3$ [3] | $\Phi 50$  | 75 | $-10^2$ | 18.7 $\mu$A | 3.75 | 50 | $-10^3$ | N/A | N/A |
| SMSPD     | MoSi$_3$ [21] | 400x400 | <6 | $-10^2$ | N/A | N/A | N/A | N/A | N/A | 75$^*$ |
|           | NbN [39] | $\Phi 20$ | 35 $\mu$m | $-10^2$ | 45 | N/A | N/A | N/A | 2.5$^*$ |
|           | NbN (this paper) | $\Phi 50$ | 92.2 | $-10^3$ | 47.5 | 1.03 | 61.0 | $-10^3$ | 50.0 | 36$^*$ |

$^1$Use of a low temperature amplifier.
$^2$Not identical to the rest time, due to the influence of the shunt resistor.

4. Conclusions

In conclusion, this paper simulated, fabricated, and characterized a NbN microstrip on a DBR substrate with various filling factors (0.4-0.8) and various strip configurations (bridge, double spiral, and meander). Simulation shows that a high filling factor is necessary to achieve high SDE in the SMSPD. A double spiral strip configuration is helpful in reducing the current crowding effect. Owing to the use of the NbN film pre-irradiated by He ions, the IDE of the NbN SMPSD is significantly improved, providing more physical insights to the detection mechanism of the SMPSD. Based on the abovementioned methods, this study successfully demonstrated the NbN SMSPD with a strip wide of 1 $\mu$m, a filling factor of ~0.8, and an active area of 50 $\mu$m in diameter, showing a maximum SDE of 92.2% at 1550 nm, a DCR of...
200 cps, a TJ of 48 ps, and a PER of 1.03 at 0.84 K. Operated in a 2.1 K closed-cycle cryocooler, the detector shows a maximum SDE of over 70% at 1550 nm. In addition, the SMSPD was further coupled with a multimode fiber, where the detector shows a maximum SDE of over 60% and a TJ of ~50 ps. Results of this study shed light on the development SMSPDs for efficient single-photon detection, which would show the potential applications prospects in quantum optics and photon-starved LIDAR.

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Disclosures
The authors declare that they have no conflicts of interest.

References
1. G. N. 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, 705-707 (2001).
2. P. Hu, H. Li, L. You, H. Wang, Y. Xiao, J. Huang, X. Yang, W. Zhang, Z. Wang, and X. Xie, "Detecting single infrared photons toward optimal system detection efficiency," Opt. Express 28, 36884-36891 (2020).
3. D. V. Reddy, R. R. Nerem, S. W. Nam, R. P. Mirin, and V. B. Verma, "Superconducting nanowire single-photon detectors with 98% system detection efficiency at 1550 nm," Optica 7, 1649-1653 (2020).
4. W. Zhang, L. You, H. Li, J. Huang, C. Lv, L. Zhang, X. Liu, J. Wu, Z. Wang, and X. Xie, "NbN superconducting nanowire single photon detector with efficiency over 90% at 1550 nm wavelength operational at compact cryocooler temperature," Sci. China Phys. Mech. Astron. 60, 120314 (2017).
5. H. Shibata, K. Shimizu, H. Takesue, and Y. Tokura, "Ultimate low system dark-count rate for superconducting nanowire single-photon detector," Opt. Lett. 40, 3428-3431 (2015).
6. B. Korzh, Q.-Y. Zhao, J. P. Allmaras, S. Frasca, T. M. Autry, E. A. Bersin, A. D. Beyer, R. M. Briggs, B. Bumble, M. Colangelo, G. M. Crouch, A. E. Dane, T. Gerrits, A. E. Lita, F. Marsili, G. Moody, C. Peña, E. Ramirez, J. D. Rezac, N. Sinclair, M. J. Stevens, A. E. Velasco, V. B. Verma, E. E. Wollman, S. Xie, D. Zhu, P. D. Hale, M. Spiropulu, K. L. Silverman, R. P. Mirin, S. W. Nam, A. G. Kozorezov, M. D. Shaw, and K. K. Berggren, "Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector," Nat. Photonics 14, 250-255 (2020).
7. D. Y. Vodolazov, "Minimal Timing Jitter in Superconducting Nanowire Single-Photon Detectors," Phys. Rev. Appl. 11, 014016 (2019).
8. W. Zhang, J. Huang, C. Zhang, L. You, C. Lv, L. Zhang, H. Li, Z. Wang, and X. Xie, "A 16-Pixel Interleaved Superconducting Nanowire Single-Photon Detector Array With A Maximum Count Rate Exceeding 1.5 GHz," IEEE Trans. Appl. Supercond. 29, 1-4 (2019).
9. H. Li, Y. Wang, L. You, H. Wang, H. Zhou, P. Hu, W. Zhang, X. Liu, X. Yang, L. Zhang, Z. Wang, and X. Xie, "Supercontinuum single-photon detector using multilayer superconducting nanowires," Photonics Res. 7, 1425-1431 (2019).
10. F. Marsili, F. Bellei, F. Najafi, A. E. Dane, E. A. Dauler, R. J. Molnar, and K. K. Berggren, "Efficient single photon detection from 500 nm to 5 um wavelength." Nano. Lett. 12, 4799-4804 (2012).
11. K. J. Wei, W. Li, H. Tan, Y. Li, H. Min, W. J. Zhang, H. Li, L. X. You, Z. Wang, X. Jiang, T. Y. Chen, S. K. Liao, C. Z. Peng, F. H. Xu, and J. W. Pan, "High-Speed Measurement-Device-Independent Quantum Key Distribution with Integrated Silicon Photonics," Phys. Rev. X 10, 031030 (2020).
12. Y. Liu, Z. W. Yu, W. Zhang, J. Y. Guan, J. P. Chen, C. Zhang, X. L. Hu, H. Li, C. Jiang, J. Lin, T. Y. Chen, L. You, Z. Wang, X. B. Wang, Q. Zhang, and J. W. Pan, "Experimental Twin-Field Quantum Key Distribution through Sending or Not Sending," Phys. Rev. Lett. 123, 100505 (2019).
13. H.-S. Zhong, H. Wang, Y.-H. Deng, M.-C. Chen, L.-C. Peng, Y.-H. Luo, J. Qin, D. Wu, X. Ding, Y. Hu, P. Hu, X.-Y. Yang, W.-J. Zhang, H. Li, Y. Li, X. Jiang, L. Gan, G. Yang, L. You, Z. Wang, L. Li, N.-L. Liu, C.-Y. Lu, and J.-W. Pan, “Quantum computational advantage using photons,” Science 10, 8770 (2020).

14. T. Polakovic, W. Armstrong, G. Karapetrov, Z. E. Meziani, and V. Novosad, "Unconventional Applications of Superconducting Nanowire Single Photon Detectors," Nanomaterials (Basel) 10, 1198 (2020).

15. Y. Hochberg, I. Charaev, S. W. Nam, V. Verma, M. Colangelo, and K. K. Berggren, "Detecting Sub-GeV Dark Matter with Superconducting Nanowires," Phys. Rev. Lett. 123, 151802 (2019).

16. L. Xue, Z. Li, L. Zhang, D. Zhai, Y. Li, S. Zhang, M. Li, L. Kang, J. Chen, P. Wu, and Y. Xiong, "Satellite laser ranging using superconducting nanowire single-photon detectors at 1064 nm wavelength," Opt. Lett. 41, 3848-3851 (2016).

17. C. M. Naturajan, M. G. Tanner, and R. H. Hadfield, "Superconducting nanowire single-photon detectors: physics and applications," Supercond. Sci. Tech. 25, 063001 (2012).

18. D. Y. Vodolazov, "Single-Photon Detection by a Dirty Current-Carrying Superconducting Strip Based on the Kinetic-Equation Approach," Phys. Rev. Appl. 7, 034014 (2017).

19. Y. P. Korneeva, D. Y. Vodolazov, A. V. Semenov, I. N. Florya, N. Simonov, E. Baeva, A. A. Korneev, G. N. Goltsman, and T. M. Klapwijk, "Optical Single-Photon Detection in Micrometer-Scale NbN Bridges," Phys. Rev. Appl. 9, 064057 (2018).

20. N. N Manova, E. O Smirnov, Yu P Korneeva, A A Korneev, and G. N. Goltsman, "Superconducting photon counter for nanophotonics applications," J. Physics: Confer. Series 1410, 012147 (2019).

21. I. Charaev, Y. Morimoto, A. Dane, A. Agarwal, M. Colangelo, and K. K. Berggren, "Large-area microwire MoSi single-photon detectors at 1550 nm wavelength," Appl. Phys. Lett. 116, 242503 (2020).

22. J. Chiles, S. M. Buckley, A. Lita, V. B. Verma, J. Allmaras, B. Korzh, M. D. Shaw, J. M. Shainline, R. P. Mirin, and S. W. Nam, "Superconducting microwave detectors based on WSi with single-photon sensitivity in the near-infrared," Appl. Phys. Lett. 116, 242602 (2020).

23. A. V. Naumov, Y. Korneeva, D. Vodolazov, I. Florya, N. Manova, E. Smirnov, A. Korneev, M. Mikhailov, G. Goltsman, T. M. Klapwijk, M. G. Gladush, and K. R. Karimullin, "Single photon detection in micron scale NbN and α-MoSi superconducting strips," EPJ Web Confer. 190, 04010 (2018).

24. J. Huang, W. J. Zhang, L. X. You, X. Y. Liu, Q. Guo, Y. Wang, L. Zhang, X. Y. Yang, H. Li, Z. Wang, and X. M. Xie, "Spiral superconducting nanowire single-photon detector with efficiency over 50% at 1550 nm wavelength," Supercond. Sci. Tech. 30, 074004 (2017).

25. I. Charaev, A. Semenov, S. Doernier, G. Gomard, K. Ilin, and M. Siegel, "Current dependence of the hot-spot reponse spectrum of superconducting single-photon detectors with different layouts," Supercond. Sci. Tech. 30, 025016 (2017).

26. W. Zhang, Q. Jia, L. You, X. Ou, H. Huang, L. Zhang, H. Li, Z. Wang, and X. Xie, "Saturating Intrinsic Detection Efficiency of Superconducting Nanowire Single-Photon Detectors via Defect Engineering," Phys. Rev. Appl. 12, 044040 (2019).

27. M. W. Brenner, D. Roy, N. Shah, and A. Bezyadin, "Dynamics of superconducting nanowires shunted with an external resistor," Phys. Rev. B 85, 224507 (2012).

28. E. Toomey, Q.-Y. Zhao, A. N. McCaughan, and K. K. Berggren, "Frequency Pulling and Mixing of Relaxation Oscillations in Superconducting Nanowires," Phys. Rev. Appl. 9, 064021 (2018).

29. J. Y. Juang, D. A. Rudman, J. Talvacchio, and R. B. van Dover, "Effects of ion irradiation on the normal state and superconducting properties of NbN thin films," Phys. Rev. B Condens. Matter 38, 2354-2361 (1988).

30. J. R. Clem, and V. G. Kogan, "Kinetic impedance and depairing in thin and narrow superconducting films," Phys. Rev. B 86, 174521 (2012).

31. L. X. You, X. Y. Yang, Y. H. He, W. X. Zhang, D. K. Liu, W. J. Zhang, L. Zhang, L. Zhang, X. Y. Liu, S. J. Chen, Z. Wang, and X. M. Xie, "Jitter analysis of a superconducting nanowire single-photon detector," AIP Adv. 3, 072135 (2013).

32. D. Y. Vodolazov, N. N. Manova, Y. P. Korneeva, and A. A. Korneev, "Timing Jitter in NbN Superconducting Microstrip Single-Photon Detector," Phys. Rev. Appl. 14, 044041 (2020).

33. C. Zhang, W. Zhang, J. Huang, L. You, H. Li, C. Lv, T. Sugihara, M. Watanebe, H. Zhou, Z. Wang, and X. Xie, "NbN superconducting nanowire single-photon detector with an active area of 300 μm-in-diameter," AIP Adv. 9 (2019).

34. C. Zhang, W. Zhang, L. You, J. Huang, H. Li, X. Sun, H. Wang, C. Lv, H. Zhou, X. Liu, Z. Wang, and X. Xie, "Suppressing Dark Counts of Multimode-Fiber-Coupled Superconducting Nanowire Single-Photon Detector," IEEE Photon. J. 11, 1-8 (2019).

35. J. Chang, I. E. Zadeh, J. W. N. Los, J. Zichi, A. Fognini, M. Geyers, S. Dorenbos, S. F. Pereira, P. Urbach, and V. Zwiller, "Multimode-fiber-coupled superconducting nanowire single-photon detectors with high detection efficiency and time resolution," Appl. Opt. 58, 9803-9807 (2019).