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Cite as: AIP Advances 9, 075214 (2019); https://doi.org/10.1063/1.5095842
Submitted: 13 March 2019. Accepted: 24 June 2019. Published Online: 19 July 2019

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NbN superconducting nanowire single-photon detector with an active area of 300 μm-in-diameter

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ABSTRACT
Superconducting nanowire single-photon detectors (SNSPDs) with both an ultra-large-active area and a high count rate (CR) are challenging from the design and fabrication. Here, we develop a NbN SNSPD with a circular active area of 300 μm-in-diameter and use multiple approaches to boost the maximal count rate (MCR). This large-active-area SNSPD is divided into nine pixels (parts). Each pixel consists of serially connected two superconducting nanowire avalanche photodetectors (SC-2SNAP), which yielded a four-fold reduction in the kinetic inductance of a single pixel. To further increase MCR, an optimized series resistance of about 380 Ω is added to each pixel, reducing the full recovery time of each pixel from a few microseconds to approximately 90 ns. All nine pixels show uniform superconducting critical temperatures of ∼7.4 K and switching currents in the range of 15.3–16.7 μA. When the detector coupled to a single-mode fiber and illuminated with 1064-nm photons, the single-pixel exhibits a well-saturated system detection efficiency (SDE) of 67% at a dark CR of 30 Hz, and its CR exceeds 10 MHz with an SDE of 50%. When coupled to a 200-μm multi-mode fiber, the total SDE of nine pixels is approximately 42% and the total MCR exceeds 43 MHz.

I. INTRODUCTION
Superconducting nanowire single-photon detectors (SNSPDs) have recently attracted significant attention owing to their excellent performance, such as their high system detection efficiency (SDE > 90%3,4), low dark count rate (DCR < 1 Hz5), low timing jitter (Tj < 20 ps), and high maximum count rate (MCR > 500 MHz6). These detectors have been successfully applied in various applications, such as long-distance quantum key distribution7 and quantum optics8. However, these SNSPDs are generally single-mode fiber (SMF) coupled, and their active areas are typically less than 20 μm-in-diameter. Recently, there are increasing applications which require multi-mode fiber (MMF) coupled SNSPDs, such as light detection and ranging (LIDAR) and deep space laser communication.9,10 Compared with SMFs, MMFs can provide larger numerical aperture (NA) and core diameter and would significantly increase the signal collection efficiency. For example, LIDAR, as an effective technology for high-resolution aerosol detection,11,12 requires the optical etendue of one stage to be equal to or larger than that of its pre stage to realize the high collection efficiency of the backscattered signals. Therefore, the upper limit of optical etendue of the entire LIDAR system was determined by the SPD active area. MMF coupled SPDs would extend their aperture...
size of the telescopes.\textsuperscript{15,16} The 1064-nm wavelength is one of the most popular wavelengths in the abovementioned applications because 1064-nm commercial lasers have been extensively developed with high power and compact configurations. However, the performance of the widely used InGaAs–APDs at the 1064-nm band is quite poor (low efficiency, low MCR, large DCR, and afterpulsing).\textsuperscript{7} although the active area diameter is up to several hundred microns.

Increasing the active area up to several hundreds microns in diameter is a challenge for SNSPD. Their MCR is limited by the kinetic inductance ($L_k$) of the nanowire,\textsuperscript{1} which is proportional to the nanowire length. If the diameter of the active area increases by a factor of $N$, then the nanowire length and $L_k$ would increase by a factor of $N^2$. Therefore, an increase in the diameter of the active area from tens of microns ($\sim$20) to several hundreds of microns ($\sim$300) would yield significant MCR suppression of the detector ($\sim$225×). Moreover, the probability of defects in the nanowire also increases with the nanowire length, which may suppress the intrinsic detection efficiency of the nanowire. Previously, single-pixel SNSPDs with large active area for various wavelengths have been studied and the largest active area was fabricated to be 100 μm-in-diameter at a wavelength of 332 nm.\textsuperscript{1} While the reported SDE of MMF-coupled SNSPDs (62.5-μm core diameter) was $\sim$20% at the 1064-nm wavelength.\textsuperscript{20} Recently, using multi-pixel scheme to extend the active area has been reported. For example, researchers at the Jet Propulsion Laboratory have developed a 64-pixel array of WSi SNSPD with a 320-μm diameter that operated at 650 mK.\textsuperscript{21} While a 64-pixel array of NbTiN SNSPD, which can operate in a 2-K Gifford–McMahon (G–M) cryocooler, was fabricated with an active area of 100 μm diameter at a wavelength of 532 nm.\textsuperscript{19} The largest active area was fabricated to be 100 μm diameter that operated at 650 mK.\textsuperscript{21} The multi-pixel architecture can reduce the $L_k$ of each pixel; therefore, increasing the total MCR of the SNSPDs. However, either complex semiconducting\textsuperscript{22} or advanced superconducting readout circuits\textsuperscript{23} are required to read out such a large number of pixels, which introduces another challenge for the system integration. It is necessary to make the readout circuits as simple as possible so that they are user friendly for practical applications. A superconducting parallel nanowire structure is another straightforward solution to increase MCR, which has been well studied for both photon and ion detection.\textsuperscript{24–28} Recently, an SMF-coupled detector based on a serially connected two superconducting nanowire avalanche photodetector (SC-2SNAP) configuration has been demonstrated with afterpulse-free operation and faster response speed than standard SNSPDs.\textsuperscript{7}

In this work, we designed and characterized a NbN SNSPD with a 300-μm diameter active area that may potentially improve current 1064-nm wavelength LIDAR applications. Nanowires with good uniformity were obtained via the advanced electron-beam lithography (EBL) technique. The active area was divided into nine pixels and each pixel was designed in a SC-2SNAP configuration to reduce $L_k$. A series resistor was added to each pixel at low temperatures to further increase MCR. All nine pixels exhibited a well-saturated SDE at the 1064-nm wavelength. When the detector was coupled to a 200-μm MMF, the total SDE of nine pixels was measured to be $\sim$42%, and the total MCR exceeded 43 MHz.

II. Design and Fabrication

To reduce the $L_k$, a 7-nm-thick NbN nanowire with a low filling factor ($\sim$0.28) was adopted. The design width and pitch of the nanowire was $\sim$100 and $\sim$360 nm, respectively. Absorptance at the 1064-nm wavelength was simulated using a commercial finite element software (COMSOL Multiphysics). The simulated absorptance for both the parallel and perpendicular polarization photons was $\sim$82% and $\sim$33%, respectively. The active area of the detector was divided into nine pixels, making it compatible with the homemade cryostat. The cryostat was installed with nine semi-rigid coaxial cables as readout channels and cooled by a compact G-M cryocooler (SHI SRDK-101D). Figure 1(a) shows a photograph of the chip-mounting block for the nine-pixel SNSPD array. The block size was halved to approximately 5.2 × 2.6 × 0.8 cm$^3$ by replacing the small A-type (SMA) connectors used in a previous design with small P-type (SMP) connectors.

The NbN thin film was magnetron-sputtering deposited onto a two-inch Si substrate with a distributed Bragg reflector (DBR) acting as an optical cavity.\textsuperscript{29} The DBR comprised multiple SiO$_2$/Ta$_2$O$_5$ bilayers. The NbN thin film was then patterned into a pixel array.
via EBL (ELS-F125G8, Elionix, 125-kV accelerating voltage). The entire 300-μm diameter active area was exposed under a single writing field size of 500 × 500 μm, which guaranteed good uniformity without any stitching error. Using a ZEP520A photoresist and a 1-nA beam current, the total writing time was ∼50 min for 18 devices on a single two-inch Si wafer. The samples were then reactive-ion etched in CF4 plasma. Figure 1(b) shows a low-magnification scanning electron microscopy (SEM) image of the circular active area (300 μm diameter) of the nine-pixel SNSPD array. The nine pixels in Fig. 1(b) are pseudo-colored and numbered 1′ through 9′ from left to right. The nanowire length was nearly the same for all pixels. Figure 1(c) shows a magnified SEM image with the red- and blue-colored nanowires highlighting the SC-2SNAP structure. The inset in Fig. 1(c) is a zoom-in image of a single nanowire with a measured width of 98 nm, which is consistent with the 100-nm design width. Figure 1(d) shows the layout of the SC-2SNAP configuration for a single pixel. In SC-2SNAP, two-parallel nanowires were acted as a basic unit and many of the basic units were connected in series, forming a single pixel. When one nanowire in one unit absorbs a photon, it switches into resistive state. The other serially connected units work as a choke inductor, preventing the current from leaking into the load. Then the current flows into the other parallel nanowire of the unit, thus resulting in an avalanche switch. The $I_{sw}$ of a single pixel was reduced by a factor of four compared from leaking into the load. Then the current flows into the other serially connected nanowires having the same active area. Each pixel was operated individually.

Figure 2 presents a schematic of the setup for conducting the electrical measurements of the SNSPD array, including the bias and readout circuits. All the pixels were biased with a common low-noise voltage source (SIM928, Stanford Research System Inc.) in series with a 20-kΩ resistor to form a quasi-constant-current bias. The photon-response signals were amplified using 50-dB low-noise amplifiers (LNA-650, RF BAY Inc.) at the room temperature. The output signals were then combined using a power combiner (ZCSC-8-13-S+, ZFRSC-42-S+, Mini-Circuits) and counted using a 200-MHz photon counter (SR400, Stanford Research Systems Inc.).

### III. EXPERIMENTAL RESULTS

The superconducting properties of each pixel of the detector were first evaluated. It was found that the superconducting critical temperatures ($T_c$) were in range of 7.41–7.42 K, and the switching currents ($I_{sw}$) defined as the highest bias current of a pixel could sustain before switching to the normal state, were in range of 14.4–15.9 μA (without a series resistance $R_s$ added to the nanowire). The measured $T_c$ and $I_{sw}$ values indicated that the nine pixels possessed good uniformity.

The photon-response pulses of the nine pixels were then individually recorded using an oscilloscope at a bias current of 14 μA. The waveforms were essentially the same since the nanowires of the nine pixels were nearly equal in length. Figure 3(a) shows one of the original waveforms (indicated by a red line with square symbols). Without $R_s$, the response pulse exhibits a non-exponential decay, and a distinguished overshoot was observed in the falling edge. The overshoot, which had a maximum value of 5.3% of the voltage peak value, lasted over 2.5 μs. This overshoot could be attributed to the impedance mismatch occurred in the readout circuit. According to previous studies, an additional $R_s$ was added in series to each pixel to suppress the overshoot and reduce the pulse recovery time. Herein, the $R_s$ resistors were soldered on the printed circuit board and cooled on the 2-K stage.

As shown in Fig. 3(a), the recovery time of the response pulse decreased gradually with increasing $R_s$. The pulse amplitude decreased continuously, which can be attributed to the reduction in distributed current flowing into the load resistance. Increasing $R_s$ beyond 430 Ω (e.g., to 480 Ω) resulted in an overshoot reappeared at ∼50 ns. The impedance of the nanowire after its absorption of photons dramatically increases to several kΩ, while the impedance of the readout circuits is generally 50 Ω. We added a series resistor with resistance of $R_s$ between the SNSPD and readout circuit to improve the impedance match then reduce the signal reflection. The results in Fig. 3(a) indicate that, the optimized $R_s$ is about 380 Ω, at which the measured $I_{sw}$ has a maximum value. On the basis of these results, in series with a 20-kΩ resistor to form a quasi-constant-current bias. The photon-response signals were amplified using 50-dB low-noise amplifiers (LNA-650, RF BAY Inc.) at the room temperature. The output signals were then combined using a power combiner (ZCSC-8-13-S+, ZFRSC-42-S+, Mini-Circuits) and counted using a 200-MHz photon counter (SR400, Stanford Research Systems Inc.).
for each pixel, a 380-Ω $R_s$ was added in the subsequent experiments. With the optimal 380-Ω resistor, an exponential decay was observed in the falling edge of the output pulse. The corresponding waveform is depicted by the blue line with star symbols in Fig. 3(a). The full recovery time, which is defined as the time when the falling edge recovered to 0 V, was reduced to ~90 ns.

Figure 3(b) provides a comparison of $I_{sw}$ with and without the 380-Ω $R_s$ resistor for each pixel. The $I_{sw}$s were $\sim 15.2 \pm 0.7 \mu$A without the $R_s$ resistor, as indicated by the red squares. The 380-Ω $R_s$ resistor increased the $I_{sw}$s by $\sim 0.8 \mu$A to $16 \pm 0.7 \mu$A, as indicated by the blue triangles.

To characterize the performance of a single pixel in the array, the device was coupled to a 1064-nm SMF with a minimum optical spot size diameter of $\sim 7 \mu$m. Figure 4(a) shows the measured SDE and DCR values of pixel 6# as a function of $I_b$. The size of pixel 6# was approximately 26 $\times$ 290 $\mu$m, which was much larger than the spot size. As shown in the figure, the avalanche current ($I_{av}$), defined as the minimum bias current needed to trigger avalanche switching, was $\sim 9 \mu$A ($\sim 0.6I_{sw}$). The device works in avalanche regime when the bias current is higher than $I_{av}$. The SDE increased deeply with increasing $I_b$ and finally reached a saturated plateau. The SDE of pixel 6# was $\sim 67\%$ at a DCR of 30 Hz for the parallel polarization photons. The measured polarization extinction ratio (PER) of the pixel was $\sim 3$, which was slightly larger than the simulated value (2.5).

The SMF was then replaced by an MMF with a 200-μm core diameter. Figure 5(a) shows the SDE of each pixel and the total SDE measured at different $I_b$ values on a logarithmic scale. Each pixel demonstrated a well-saturated SDE plateau. However, the total SDE was limited to 42.3% when the nine pixels operated simultaneously because the polarization in MMFs is difficult to control. Since the 300-μm active-area was coupled with a 200-μm MMF, considering a fiber NA of 0.22 and a working distance about 20 μm, the beam diameter was approximately 210 μm. The SDE histogram of the nine pixels is shown in Fig. 5(b). The highest SDE was observed in the middle of the array (pixel 5#) and the lowest SDEs were measured on the sides (pixels 1# and 9#). This indicates that the photon beam was aligned in the center of the active area. This SDE distribution was caused by the combined effects of the spatial variations in the nine pixels and the illuminated photon intensity. With increasing the incident photon flux, the CR increased gradually. When the CR of pixel 5# reached about 9 MHz, the total CR of the nine pixels operating simultaneously was approximately 43.4 MHz. Further increasing the photon flux caused the latch of the pixel 5# because it received the most input photons among nine pixels.

The timing jitter of the detector was measured using a time-correlated single-photon counting module with a 813-fs resolution (SPC-150 board card, Becker&Hickl GmbH). No fs-pulsed laser at 1064 nm was available in hand. Thus, we used a 1550-nm pulsed laser (FPL-01CAF, Calmar) with a 100-fs pulse width as the photon source. The input photons were strongly attenuated to the single-photon level. When the detector was coupled to the SMF at a bias...
current of 13.5 μA (blue line in Fig. 6), the timing jitter for a single pixel was ~160 ps. The timing jitter was defined as the full width at half maximum of the Gaussian distribution. The detector was then coupled to a 2-m long silica MMF with a 200-μm core diameter and a NA of 0.22, which may cause an estimated time delay about ~110 ps and thereby increase the system timing jitter. The timing jitter of the pixel increased to 207 ps (red curve in Fig. 6) at the same bias when coupled to the 200-μm MMF. This increase in timing jitter under MMF coupling can be attributed to modal dispersion inside the MMFs and geometrical timing jitter.

**IV. DISCUSSION**

Herein, a 300-μm diameter large-active area SNSPD was demonstrated with a SDE over 40% and a MCR of over 43 MHz. Compared with the previous SNSPD with an active area of 100 μm in-diameter, the present active area was increased by nine times and the MCR was improved over four times. Furthermore, the performance (SDE, and MCR) of this detector also met LIDAR system requirements. In future, by replacing the commonly used APDs with our SNSPDs, the detection and dynamic ranges of the LIDAR system would improve the total SDE to 42% due to the unpolarized photons propagating in the MMF. This loss could be reduced by optimizing the optical cavity, which minimizes the polarized sensitivity of the detector. We also note that the MCR of this multi-pixel array was limited by the spatial variations of the nine pixels and the nearly Gaussian distribution of the input photon intensity emitted from the fiber. An interleaved nanowire design can remove the spatial variations of the pixels. An uniform photon illumination by using commercial refractive beam shapers would improve the Gaussian distribution of the incoming light in the fibers. To reduce the timing jitter, several points should be addressed. First, by the low-noise low-temperature amplifier, the single-to-noise ratio of the output pulse is increased, which can effectively reduce the electronic timing jitter. Second, the geometrical timing jitter could be reduced by using a differential cryogenic readout. Besides, the additional jitter caused by modal dispersion inside the MMF could be eliminated if the SNSPD is free-space coupled.

**V. CONCLUSION**

We fabricated and characterized a NbN thin-film SNSPD with an active area of Φ300 μm. To improve the MCR and reduce the complexity of readout circuit, we combined three different approaches (multi-pixel, SC-2-SNAP, and series resistor to the nanowire) in one detector. The full recovery time of each pixel was significantly reduced to ~90 ns. We characterized the detector by coupling it with different types of fibers. With SMF coupling, the SDE of a single pixel was 67% at a DCR of 30 Hz for 1064-nm wavelength. The CR was 10 MHz with an SDE of 50%. Under MMF coupling, the total SDE was ~42%, and the MCR exceeded 43 MHz. The high MCR of the fabricated large-active area SNSPD exhibits promising potential for LIDAR applications.

**ACKNOWLEDGMENTS**

This work was supported by the National Key R&D Program of China (2017YFA0304000), the Science and Technology Commission of Shanghai Municipality under Grant 16JC1400402 and Program of Shanghai Academic/Technology Research Leader under Grant (18XD1404600).

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