Multi-channel system with high-performance fractal superconducting nanowire single-photon detectors

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Abstract: We report on an eight-channel fractal SNSPD system in the wavelength range of 940 nm with minimal polarization sensitivity. The best channel exhibits 96% system detection efficiency and 19 cps dark-count rate.

1. Introduction

Superconducting nanowire single-photon detectors (SNSPDs) are ideal detectors of choice for many classical and quantum photonic applications, due to their superior comprehensive performances [1]. Most commonly used SNSPDs are designed and are made into nanowire-meander structures, which result in polarization dependence of detection efficiency. Fractal SNSPDs were introduced in 2015 [2] to reduce the polarization sensitivity, and afterwards, we demonstrated the devices [3] and systems [4, 5] in the telecommunication wavelength range of 1550 nm, as well as dual-band operation including another wavelength range of 520 nm [6]. Up to now, all these fractal SNSPDs were packaged and configured into single-channel systems, and the multi-channel system with several fractal SNSPDs that all feature low polarization sensitivity remain unexplored. Such a high-performance multi-channel system would be very useful for multi-photon coincidence counting that is often used in experimental quantum photonics to characterize nonclassical light sources [7].

Here, we report on an eight-channel fractal SNSPD system in the wavelength range of 940 nm with minimal polarization sensitivity. This wavelength range overlaps with the emission spectra of a category of single-photon sources based on III-V semiconductor quantum dots [7]. The system includes 6 SNSPDs and 2 cascaded superconducting nanowire avalanche photodetors (SNAPs, a type of specially configured SNSPDs). By comparing their performances, the SNSPDs exceed in low dark-count rates (DCR) whereas the SNAPs exhibit higher operating speed and better timing properties. At a base temperature of 2.2 K, the highest SDE is 96%, with 19 counts per second (cps) DCR, and the average polarization-maximum SDE of eight channels is 85%.

2. Experiment and results

We designed and fabricated the detectors with two different electrical configurations of the nanowires. The first type is the fractal SNSPD composed of a single nanowire, with the photosensitive area of 13.7 μm by 13.7 μm and the width of nanowire of 50 nm. Figure 1 (a) presents the false-colored scanning-electron micrograph (SEM). The other type is the cascaded 2-SNAP, similar to that in Ref. [6], but with an expanded photosensitive area to 15.2 μm by 15.2 μm. This expansion permits more tolerance to the misalignment between the optical fiber mode and the photosensitive region and ensures high coupling efficiency. The width of the nanowire was also 50 nm. Figure 1 (b) presents the false-colored SEM.

We present and compare the measurement results of the fractal SNSPD and 2-SNAP, each with the highest SDE among the same type of devices. All the measurements were performed at the base temperature of 2.2 K in a 0.1-W G-M cryocooler. Figure 1 (c) presents the measured SDE_{max} and SDE_{min} as a function of the normalized bias current at the wavelength of 940 nm, using the method based on time-correlated single-photon counting (TCSPC) [5], and presents the measured DCR of the SNSPD. The SDE-normalized I_b curve becomes saturated when I_b/I_{sw} exceeded 0.74 with the SDE_{max} of 96% and SDE_{min} of 94%, after correcting the overestimated SDE caused by the optical reflectance at the fiber end-facet [5] (The uncorrected numbers are 98% and 96%). The DCR at this bias was measured to be 19 cps. Figure 1 (d) presents the measured SDE_{max}, SDE_{min} and FCR of the SNAP as a function of the normalized bias current at the wavelength of 930 nm, using the same method. The SDE-normalized I_b curve became saturated when I_b/I_{sw} exceeded 0.79 with the corrected SDE_{max} of 89% and SDE_{min} of 86% (The uncorrected numbers are 91% and 89%) and the FCR [5] of 160 cps. Although the SNAP shows higher FCR due to the afterpulses, it has better time-domain performances than the SNSPD. Figure 1 (e)

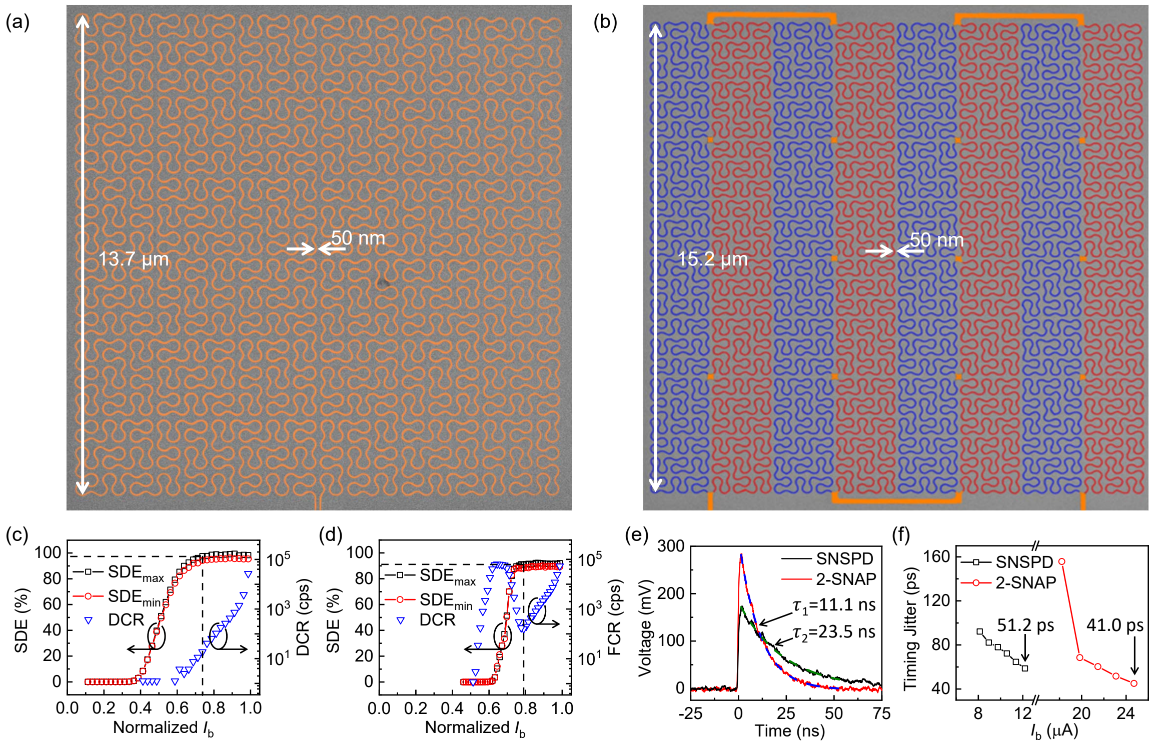

Fig. 1. Fractal superconducting nanowire single-photon detector (SNSPD), cascaded superconducting nanowire avalanche photodetector (SNAP), and their performances. (a) False-colored scanning-electron micrograph of the fabricated SNSPD. The nanowire is designed and made into the arced fractal pattern. The photosensitive area is 13.7 μm by 13.7 μm. (b) False-colored scanning-electron micrograph of the fabricated SNAP. The detector is designed and made into a 16 cascaded 2-SNAP. The photosensitive area is 15.2 μm by 15.2 μm. (c) Measured polarization-maximum system detection efficiency (SDE_{max}), polarization-minimum system detection efficiency (SDE_{min}), and dark-count rate (DCR), as a function of the bias current, I_b, which is normalized to the switching current of this device, I_{sw}. I_{sw} is 13.0 μA for this device. At $I_b/I_{sw} = 0.74$, $SDE_{max} = 98\%$ (without correction, 96% after correction) and DCR = 19 cps. SDE is measured at the wavelength of 940 nm. (d) Measured SDE_{max}, SDE_{min}, and false-count rate (FCR), as a function of the bias current, I_b, which is normalized to I_{sw} of this device. I_{sw} is 24.6 μA for this device. At $I_b/I_{sw} = 0.79$, $SDE_{max} = 91\%$ (without correction, 89% after correction) and FCR = 160 cps. SDE is measured at the wavelength of 930 nm. (e) Output voltage pulses of the SNSPD and the SNAP. The e^{-1} time constants of the falling edges are 23.5 and 11.1 ns, respectively. (f) Measured timing jitter (full width at half maxima of the time-delay histogram), as a function of I_b, for the SNSPD and the SNAP. Note that timing jitter is measured at the wavelength of 1560 nm.

presents the output voltage pulses of the SNSPD and the SNAP. Each pulse was measured with the detector biased at $0.97I_{sw}$. The pulse amplitude of the SNAP is higher than that of the SNSPD due to the higher I_{sw}, and the falling edge is steeper due to the lower kinetic inductance. The e^{-1} time constants of the falling edges for the SNSPD and the SNAP are 23.5 and 11.1 ns, respectively. Figure 1 (f) presents measured timing jitter as a function of I_b at the wavelength of 1560 nm. The lowest timing jitter of the SNAP is 41.0 ps, lower than that of the SNSPD, 51.2 ps.

We characterized the eight-channel fractal SNSPD system after installed all eight channels. Figure 2 (a) presents a photograph of the coldhead with eight detectors installed. Figure 2 (b) presents the measured SDE_{max} as functions of the wavelength, all the detectors were biased at 97% of each I_{sw} and the measured SDE_{max} were peaked between 930 nm to 940 nm. Fig.2 (c) presents measured SDE_{max} as functions of I_b normalized to each I_{sw} at their peak wavelengths. C4 and C7 are SNAPs with shorter saturation platforms. Figure 2 (d) and (e) present the highest SDE_{max} and the corresponding DCR or FCR. The SDE_{max} of all detectors installed in the eight-channel system are above 70%, and the average SDE_{max} of eight channels is 85%. The FCR of SNAPs are slightly higher than the DCR of SNSPDs due to the afterpulses.

3. Conclusion

In conclusion, we have demonstrated an eight-channel system installed with fractal SNSPDs in the wavelength range of 940 nm that all feature low polarization sensitivity. The highest SDE is 96%, with 19 cps DCR. While

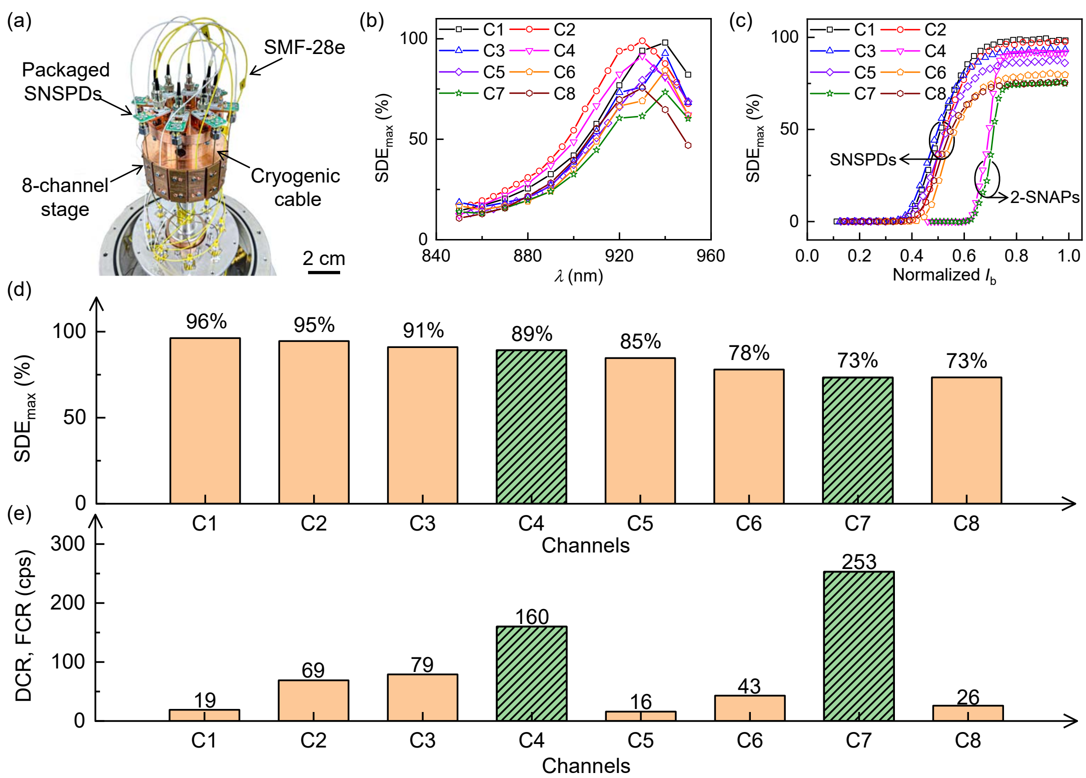

Fig. 2. Eight-channel fractal SNSPD system based on a G-M close-cycled cryocooler. (a) Pthotograph of the cold-head with eight detectors installed. Among them, there are six SNSPDs and two SNAPs. (b) Measured SDE_{max} as functions of the wavelength, λ. Each detector is biased at 97% of its switching current. (c) Measured SDE_{max} as functions of bias current normalized to each switching current. (d) The highest SDE_{max} after correction for each channel. (e) The corresponding DCR or FCR for each channel. Channels C1, C2, C3, C5, C6, and C8 are SNSPDs, and Channels C4 and C7 are SNAPs.

both of the SNSPDs and the SNAPs can achieve high SDE, the comparisons between them illustrate the strengths of each type – the former has lower DCR and therefor, lower noises, and the latter shows better properties in the time domain. Further improvement in the nanofabrication process can further enhance the yield of devices with high SDE and therefore, the comprehensive performances of the system. We believe that such a system would be useful in many quantum photonic applications including multi-photon coincidence measurements.

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