Advanced Devices & Instrumentation
A SCIENCE PARTNER JOURNAL

RESEARCH ARTICLE

An On-Chip Photon-Counting Reconstructive Spectrometer with Tailored Cascaded Detector Array

Jingyuan Zheng[1†], You Xiao[2†], Mingzhong Hu[1], Hao Li[2], Lixing You[2], Xue Feng[1,3], Fang Liu[1,3], Kaiyu Cui[1,3], Yidong Huang[1,3,4], and Wei Zhang[1,3,4*]

[1]Beijing National Research Center for Information Science and Technology (BNRist), Department of Electronic Engineering, Tsinghua University, Beijing 100084, China. [2]State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China. [3]Frontier Science Center for Quantum Information, Beijing 100084, China. [4]Beijing Academy of Quantum Information Sciences, Beijing 100193, China.

*Address correspondence to: zwei@tsinghua.edu.cn
†These authors contributed equally to this work.

Citation: Zheng J, Xiao Y, Hu M, Li H, You L, Feng X, Liu F, Cui K, Huang Y, Zhang W. An On-Chip Photon-Counting Reconstructive Spectrometer with Tailored Cascaded Detector Array. *Adv. Devices Instrum.* 2023;4:Article 0021. https://doi.org/10.34133/adi.0021

Submitted 8 March 2023
Accepted 3 August 2023
Published 6 September 2023

The hybrid integration of superconducting nanowire single-photon detectors (SNSPDs) on various substrates and photonic structures has great potential on developing complicated photonic devices based on single-photon detections, such as photon-counting reconstructive spectrometers for the spectral sensing of single-photon level faint light. In this paper, we introduce the cascaded absorption effect of SNSPDs to develop a photon-counting reconstructive spectrometer. The device includes a Rowland grating as the spatial dispersion element and a tailored cascaded SNSPD array in the focusing region of the grating. The spectral responses of the SNSPDs could be flexibly modulated by their coiled patterns and the cascaded absorption in the array, which are used as the bases for spectral reconstruction. A prototype device was designed and fabricated to demonstrate the principle of the scheme. The experiment results showed the feasibility of the spectral response modulations by the coiled pattern design and the cascaded absorption effect of the SNSPD array. It supports the spectral measurement and reconstruction in the wavelength range of 1,495 to 1,515 nm, with a spectral resolution of 0.4 nm. The proposed scheme achieves the bases for spectral reconstruction only by the design of SNSPDs and without the spectral modulation effects of additional photonic structures. It provides an interesting and promising way to develop devices with high photon utilization.

Introduction

Superconducting nanowire single-photon detectors (SNSPDs) have many attractive properties, such as high detection efficiency, low dark count, low timing jitter, high photon count rate, and so on [1]. They have been widely used in various applications requiring single-photon detection. Since SNSPDs are thin films of serval nanometers in thickness, they are convenient to be fabricated on various substrates, combining with other photonic structures. This characteristic provides an interesting and important way to realize complicated single-photon detection applications via the hybrid integration of SNSPDs and photonic structures.

Usually, SNSPDs are fabricated on the flat surface of a substrate. They absorb and detect photons that incident along the vertical direction to the surface. The SNSPDs in this form are commercialized and have been widely used in researches of quantum optics and quantum information [2] and many other fields of single-photon detections [3,4]. To extend the scale and functions of photonic quantum information systems, quantum photonic circuits (QPCs) developed rapidly in recent years. In many applications of QPCs, photons in waveguides are detected, and their coincidences are recorded. The waveguide-integrated SNSPDs are proposed to avoid the chip-to-fiber coupling before these photons are detected. At present, SNSPDs have been integrated on waveguides of various materials and structures [5], such as gallium arsenide (GaAs) waveguide [6], silicon strip [7] and shallow ridge [8] waveguide, silicon nitride (SiN) waveguide [9], lithium niobate (LN) waveguide [10,11], and so on. They also have been applied in several applications of QPCs, such as on-chip quantum interference [9], the central node in measurement-device-independent quantum key distribution [12], and so on. Moreover, several resonator structures have been introduced to improve the performances of the waveguide-integrated SNSPDs, such as asymmetric nanobeam cavities [13] and photonic crystal cavities [14,15]. Recently, the cascaded absorption effect of superconducting nanowire was introduced in the development of waveguide-integrated

SNSPDs. In this work, multiple superconducting nanowire sections were fabricated along the waveguide on its surface, each of them had limited absorption. When a multiphoton light pulse passed through the waveguide, the photons in the pulse would be absorbed one by one at different sections and discriminated according to their detection times in these sections. Hence, it realized a function of photon-number-resolving detection with over 100 pixels [16].

The development of waveguide-integrated SNSPDs largely extends the functions of QPCs. It also shows that different photonic applications would inspire new ways of hybrid integration of SNSPDs and on-chip photonic structures. An interesting example is the photon-counting spectrometer, which measures the spectra of single-photon-level faint lights [17]. Traditionally, it is realized by a monochromator and a single-photon detector. The spectrum is obtained by scanning the filter center wavelength of the monochromator and recording the photon counts at each wavelength. This function could be realized on a chip integrating a Rowland grating and a SNSPD along the focusing line of the grating. The photons with different wavelengths would be diffracted by the grating to the different location of the SNSPD and discriminated by the times of the single-photon events when the photon was absorbed [18]. Another way is the photon-counting reconstructive spectrometer, in which an SNSPD array is integrated with photonic structures on the same chip. The spectral response of each SNSPD in the array is modulated with a specific pattern by the photonic structures. The correlation between the spectral responses of different SNSPDs is low; hence, these spectral responses could be used as a set of bases to reconstruct the spectrum of the incident faint light. Several photonic structures have been introduced to realize different spectral response modulations of the SNSPDs, including an in-plane tailored disorder [19], a metasurface array [20], and 3-dimensional printed photonic crystals [21]. In these works, the scatter losses would be introduced by the photonic structures, and only a part of photons could be collected and detected by the SNSPDs, limiting the photon utilization of these devices. It is an attractive topic that how to realize a SNSPD-based integrated photon-counting reconstructive spectrometer avoiding the scattering loss of the photonic structures. It requires a new way to modulate the spectral response of the SNSPDs.

In this paper, we introduce the cascaded absorption effect to develop the SNSPD-based integrated photon-counting reconstructive spectrometer. In the proposed scheme, the photons with different wavelengths are diffracted by a Rowland grating to different directions in the focusing region on the chip. A series of SNSPDs with different shapes is fabricated at the focusing region. The photons would pass through these SNSPDs one by one and eventually be absorbed and detected by one of them. The spectral responses of these SNSPDs are determined by their shapes and the cascaded absorption effect, which could be designed with low correlation. The spectra of the incident faint light on the chip could be reconstructed by the photon counts of these SNSPDs and their spectral responses. A prototype device was fabricated and tested in this work, showing that flexible spectral response modulations of the SNSPDs could be achieved by the proper design of superconducting nanowire shapes, considering the cascaded absorption effect.

Methods

The principle

The proposed spectrometer is integrated on a silicon photonic chip. It has 2 parts on the chip, as shown by Fig. 1A. One is a Rowland grating. The Rowland grating can be regard as a combination of a flat grating and a concave reflector. The photons with different wavelengths are diffracted to different directions by the Rowland grating and then focused at different positions in its focus region. The other is a tailored cascaded SNSPD array. The principle of the scheme is shown in Fig. 1B. Because of the diffraction effect, the spatial distribution of photons in the focus region of the Rowland grating [denoted by $p(x)$] is determined by the spectrum of the input photons [denoted by $f(\lambda)$]. Considering that an SNSPD locates across the focus region. If the superconducting nanowire is a straight line, the SNSPD would have near-zero response since its width is too small to achieve obvious absorption. To improve its absorption, the superconducting nanowire should be coiled, such as the zigzag pattern commonly used in SNSPDs. Large absorption could be expected if the pattern of the coiled nanowire has a high filling ratio. If the superconducting nanowire locates across the focus region with a nonuniform coiled pattern, it can be expected that it would have larger absorption at the position that its pattern has a higher filling ratio, and vice versa. Hence, the spectral response of the SNSPD would be modulated by the filling ratio of its coiled pattern. In the proposed spectrometer, an array with many SNSPDs locates across the focus region side by side, as shown in Fig. 1A and B. It can be expected that the diffracted photons would be absorbed by a specific SNSPD eventually, after they pass through the SNSPDs before this one. Hence, almost all the photons would be absorbed by the SNSPD array, without the scatter loss introduced by photonic structures in previous works. Moreover, the SNSPDs in the array have different coiled patterns. The spectral response of a specific SNSPD is determined not only by its coiled pattern but also by the spectral responses of the SNSPDs before it. By proper design the coiled patterns of all these SNSPDs, the spectral responses with low correlations [denoted by $r_i(\lambda)$, $i = 1, 2, \ldots$] could be achieved. They can be used as the bases of the spectral reconstruction. It is worth noting that this scheme also could be realized using other on-chip dispersion components, such as array waveguide gratings [22], photonic crystals [23], and so on.

When the input faint light is measured by the proposed spectrometer, the photon counts of these SNSPDs can be expressed as

$$c_i = \int f(\lambda) r_i(\lambda) d\lambda \delta T \quad (1)$$

where c_i is the photon counts of the ith SNSPD, $f(\lambda)$ is the spectrum of the input light, $r_i(\lambda)$ is the spectral response of the ith SNSPD, and δT is the measurement time of photon counting. The spectral reconstruction can be operated according to these photon counts if the spectral responses of all the SNSPDs are calibrated and some prior information of the $f(\lambda)$ is known [24].

The prototype device

We designed and fabricated a prototype device to demonstrate the spectral response modulation of the tailored cascaded SNSPD arrays by proper pattern design of SNSPDs and the cascaded absorption effect. In this device, the single-photon level faint light injects into an on-chip waveguide vertically by a fiber-to-chip coupling grating and then illuminates the Rowland grating as shown in Fig. 1A. Bragg distributed reflectors (DBRs) are designed at the grating facets to improve the diffraction efficiency [25]. The details of the Rowland grating are described in Section S1. The SNSPD array has 16 SNSPDs side by side across the focus region of the Rowland grating,

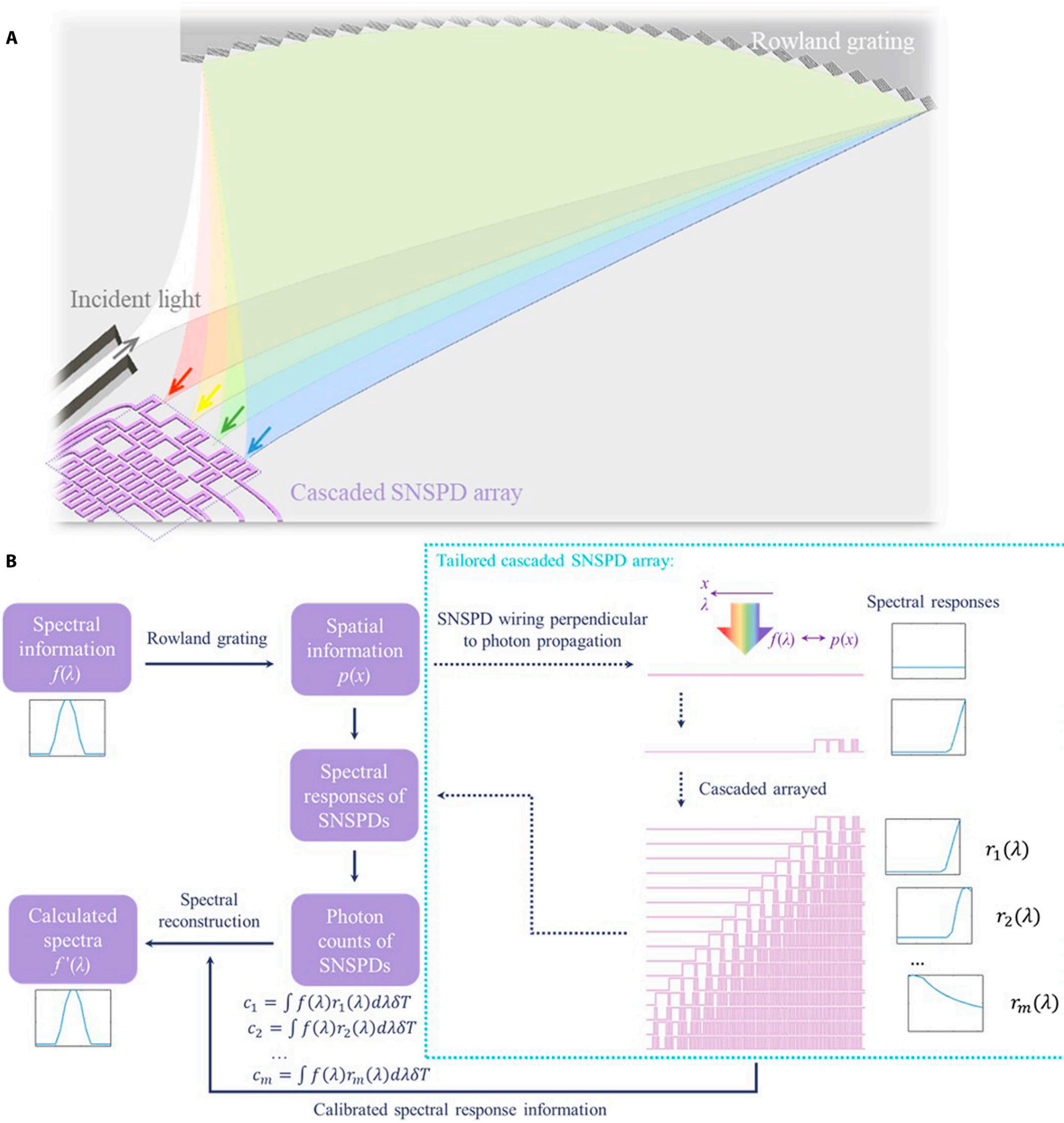

Fig. 1. (A) Sketch and (B) principle of the proposed photon-counting reconstructive spectrometer with tailored cascaded SNSPD array and a Rowland grating.

which is shown in Fig. 2A. They have very different spectral responses by designing its zigzag pattern, considering the cascaded absorption effect. The length of photon detection region of each SNSPD is around 16 μm. Eight pattern units with different filling ratios are used to design the coiled patterns of the SNSPDs, which are shown in Section S2.

The prototype device was fabricated on a silicon-on-insulator substrate with a 220-nm silicon layer. A ~30-nm SiO_2 film was deposited as a buffer layer on the silicon-on-insulator substrate. A ~6-nm NbN film was sputtered on the buffer layer as the material for the SNSPDs. Then, the cascaded SNSPD array and their electrodes were defined and etched. After that, the SiO_2 buffer layer was removed by dry-etching in the region for the Rowland grating, the coupling grating, and the input waveguide. Then, the coupling grating and the input waveguide were achieved by a dry-etching process with a 70-nm etching depth, and the Rowland grating was etched by a dry-etching process with a 220-nm etching depth on the silicon layer in this region. Figure 2B shows schematic diagram of the fabricated device, and Fig. 2C to E shows the scanning electron microscope

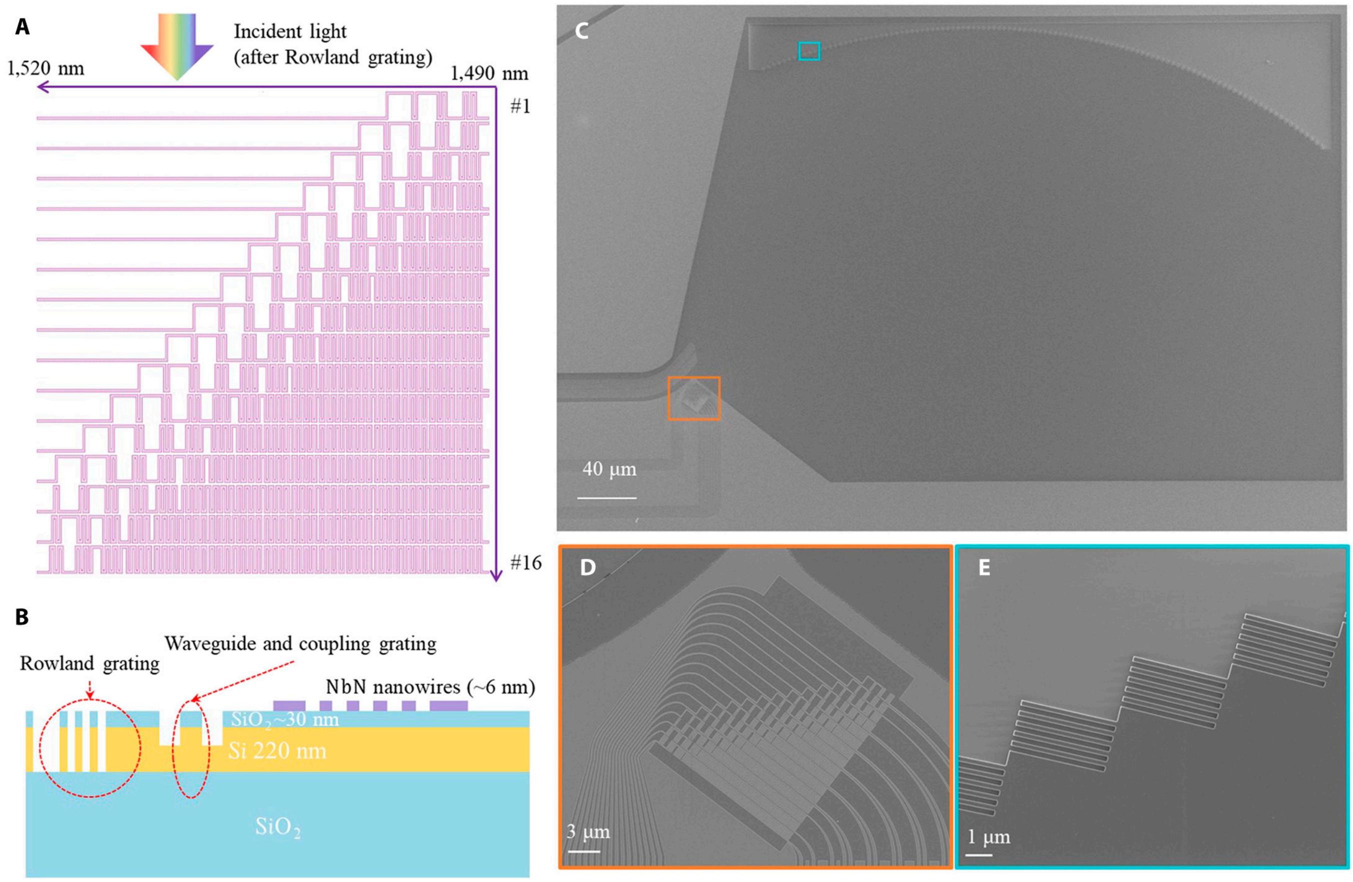

Fig. 2. The prototype device. (A) The coiled pattern design of the SNSPDs on the device. (B) The cross-sectional schematic diagram of the device. (C) The scanning electron microscope picture of the whole device. The details of the tailored cascaded SNSPD array and the Rowland grating with DBR, which indicated by the red and blue squares in the picture, are shown in (D) and (E), respectively.

pictures on the details of the device. The device was packaged in a cryostat at a temperature of around 2.32 K. The light under measurement was delivered into the cryostat and aligned to the coupling grating of the device by a piece of optical fiber.

Results

Spectral responses

We measured the spectral responses of all the SNSPDs in the fabricated device, which are $r_i(\lambda)$ in Eq. 1. A monochromatic light was generated by a tunable laser (Santec TSL-770). It was attenuated to single-photon level and its wavelength swept from 1,490 to 1,523 nm with a wavelength sampling interval of 0.3 nm. The details of the experimental setup and the calibration method are shown in Section S3. The measured spectral responses of all the 16 SNSPDs are shown in Fig. 3. It is shown that 13 SNSPDs in the array have the modulated spectral responses of single-photon detection. In the wavelength range of 1,495 to 1,515 nm, there is a main peak in the spectral response of each SNSPD. The wavelength of the main peak rises with the increasing serial number of the SNSPDs. According to the coiled pattern design of the SNSPD array, it shows that for a specific SNSPD, the response reduction at the wavelength longer than the peak wavelength is due to the low filling ratio of its coiled pattern. On the other hand, the response reduction at the wavelength shorter than the peak wavelength is due to the cascaded photon absorption by the SNSPDs before

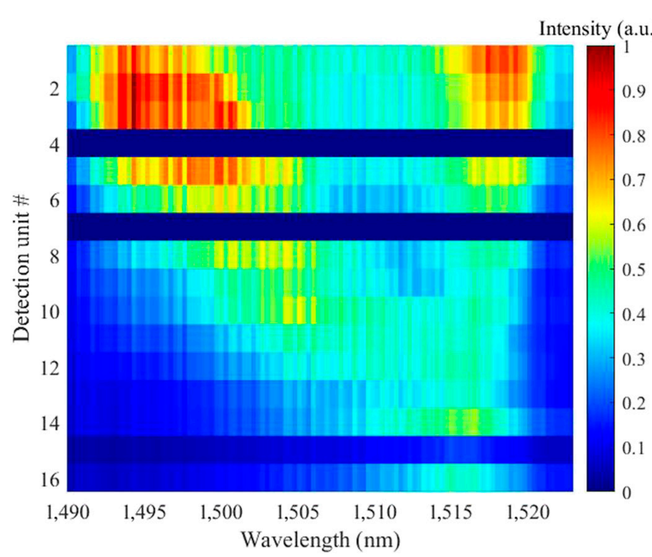

Fig. 3. The measured spectral responses of the 16 SNSPDs. The *x* axis indicates the wavelength, the *y* axis indicates the serial numbers of the SNSPDs, and the color in the figure indicates the normalized intensity of the responses. a.u., arbitrary units.

it. Hence, the total spectral response of a SNSPD is determined by these 2 effects, demonstrating the principle of the proposed spectrometer. It is also worth noting that all the SNSPDs have another response peak at 1,515 to 1,523 nm. It is due to the photon absorption of the curved nanowires connecting the coiled patterns and the electrodes, which are shown in Fig. 2E. The intensity and wavelength of this response peak also vary with the increasing serial number of the SNSPDs, showing the effect of cascaded absorption.

It is worth noting that the superconducting performance of the 4th and 7th detection units do not support single-photon detection due to the fabrication defects. They were not used in the following experiment of spectral reconstruction

Spectral reconstruction

We measured different types of single-photon level faint light and took the spectral reconstruction by the prototype device. First, the attenuated monochromatic light generated by a tunable laser was measured and reconstructed. The typical results are shown in Fig. 4A, and the wavelength of the monochromatic light can be reconstructed successfully by this device during the wavelength range of 1,495 to 1,515 nm, using the spectral responses determined by the coiled patterns and cascaded absorption effect of the SNSPD array. To demonstrate the spectral resolution of the prototype device, 2 monochromatic lights with different wavelengths were measured and reconstructed. The typical reconstruction results of 2 monochromatic lights near 1,505 nm are shown in Fig. 4B, with different wavelength intervals. The 2 monochromatic lights can be discriminated in all the cases, showing that the device supports a wavelength resolution of 0.4 nm at this wavelength. Then, we measured and reconstructed 2 monochromatic lights in the range of 1,495 to 1,515nm, with a wavelength interval of 0.4 and 0.6 nm. The results are shown in Fig. 4C and D, respectively. It shows that the device can support a wavelength resolution of 0.4 and 0.6 nm over this wavelength range of 20 nm, with comparable quality of spectral reconstruction. We also demonstrated the spectral reconstruction of a broadband light by this prototype device, which was generated by a supercontinuum source and filtered by a coarse wavelength division multiplexer. It shows that the reconstructed spectrum agrees well with the reference spectrum, which was measured by a commercial optical spectrum analyzer before the light was attenuated.

Discussion

In this paper, the cascaded absorption effect of multiple SNSPDs was introduced to realize an integrated photon-counting reconstructive spectrometer. In this scheme, an on-chip dispersion component, such as a Rowland grating, is used to diffract the

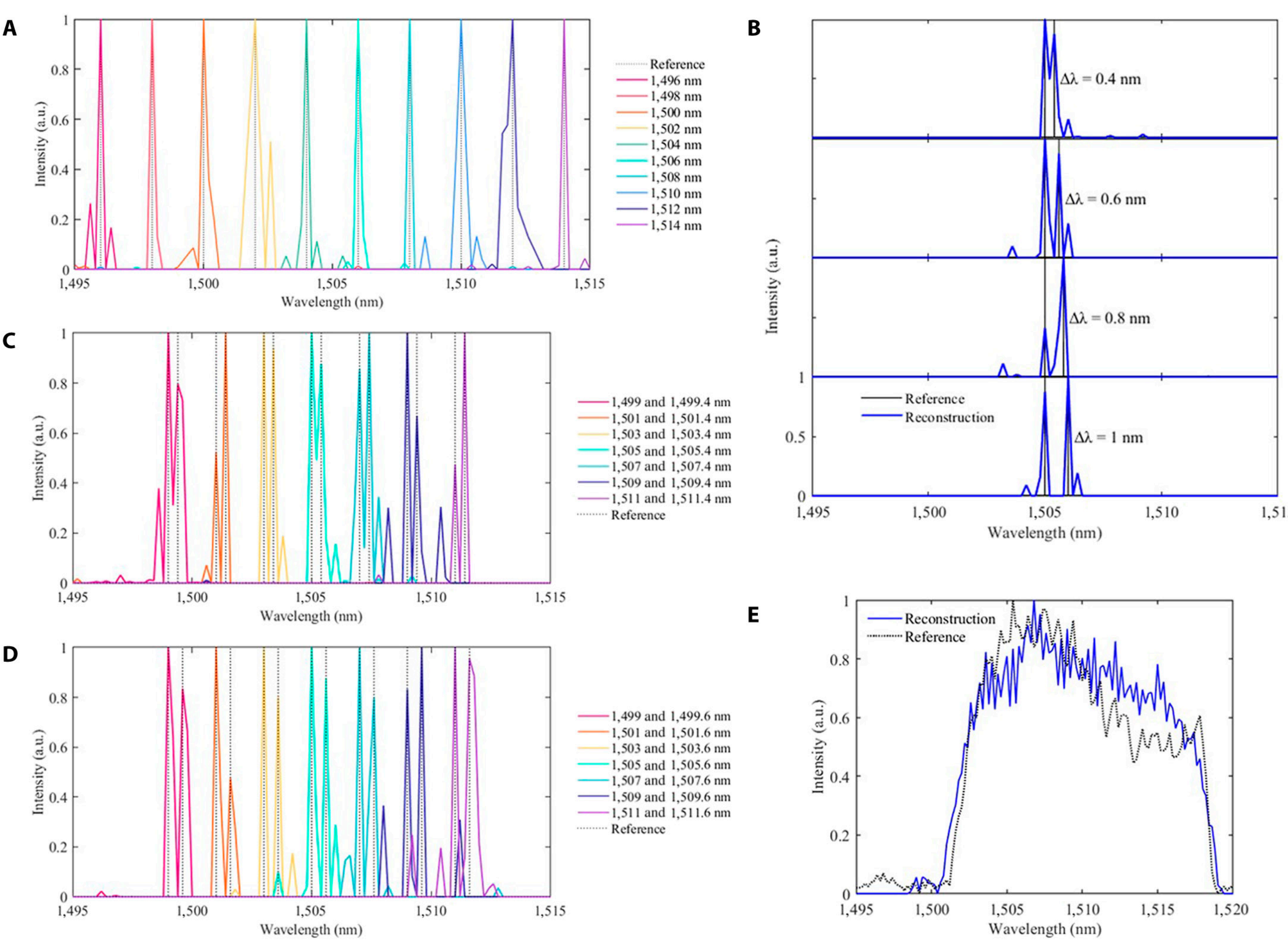

Fig. 4. The experimental results of spectral reconstruction of the prototype device. (A) Reconstruction results of the monochromatic lights at different wavelengths. (B) Reconstruction results of 2 monochromatic lights near 1,505 nm with a wavelength interval of 0.4, 0.6, 0.8, and 1.0 nm. (C and D) Reconstruction results of 2 monochromatic lights at different wavelengths with a wavelength interval of 0.4 and 0.6 nm, respectively. (E) Reconstruction result of a broadband faint light.

photons with different wavelengths to different positions in the focus region. A tailored cascaded SNSPD array locates in the focus region. Each SNSPD in the array has a specific coiled pattern in the region. The spectral response of the SNSPD can be modulated by the coiled pattern design and the cascaded absorption effect. Since the photons would be eventually absorbed by a specific SNSPD after pass through the SNSPDs before it, almost all the diffracted photons are utilized in this scheme. We designed and fabricated a prototype device to demonstrate the principle of the scheme. The experiment results show the feasibility of spectral response modulations by the coiled pattern design and the cascaded absorption effects of the SNSPD array. Using the measured spectral responses as the reconstructive bases, the prototype device supports the spectral measurement and reconstruction in the wavelength range of 1,495 to 1,515 nm. A spectral resolution of 0.4 nm was achieved in this wavelength range.

According to the measured spectral responses in Fig. 3, it is clear that if several SNSPDs have high responses at a specific wavelength, the responses of the SNSPDs behind them at this wavelength are quite low. In addition, the last SNSPD has very low response at most wavelengths. It shows that most photons are absorbed by the SNSPD array and a high on-chip detection efficiency would be expected for the prototype device. On the other side, the measured system detection efficiency is quite low (0.03% to 0.05% in the wavelength range of 1,495 to 1,515 nm). It is mainly due to the drift of the alignment between optical fiber and on-chip coupling grating when the device was cooled in the cryostat. Besides, the detection band of the SNSPD array is determined by the location of these SNSPDs in the focus region of the Rowland grating. Since both the coupling grating and the DBR structure at the Rowland grating have limited bandwidths to achieve their best performances, the deviations in the fabrication process leaded to the mismatching between the best operation bands of the coupling grating/Rowland grating and the detection band. It would also lead to large detection efficiency reduction. Hence, to fully play out the advantage of the proposed scheme, high-performance fiber-to-chip coupling technique in a cryostat under low temperature is required. Edge coupling is desired to extend the operation bandwidth of the device. In addition, the fabrication process should be improved to provide better matching between the operation band of Rowland grating and the detection band of the SNSPD array. It is worth noting that the performance of the device was measured when each detection unit operated under a dark count rate of about 8 Hz. We could estimate the minimum light intensity that the device can detect by a criterion of signal-to-noise ratio of 1, under which the total recorded photon counts of the device is equal to its dark counts. It is about −110 dBm, with a fluctuation of several decibels due to the variation of the detection efficiency at different wavelengths. Obviously, it also can be highly improved since the efficiency of the device has large space to be promoted.

Moreover, since the prototype device was designed to demonstrate the spectral response modulation of the SNSPDs in an array with the cascaded absorption effect, it used quite simple coiled pattern designs on all the SNSPDs as shown in Fig. 2A. It can be expected that better performance of the spectral reconstruction over a broad bandwidth could be achieved if the SNSPDs are designed with more complicated patterns, according to the prior information of the faint light under measurement. It provides an interesting way to achieve the bases for spectral reconstruction only by the design of SNSPDs and without the modulation effect of additional photonic structures.

Acknowledgments

We thank Photec for help with the cryostat assembly and testing. **Funding:** The National Key R&D Program of China (2018YFB2200400), Natural Science Foundation of Beijing (Z180012), National Natural Science Foundation of China (61875101 and 91750206), and Tsinghua Initiative Scientific Research Program. **Author contributions:** W.Z. and J.Z. proposed the scheme. J.Z. and Y.X. designed and fabricated the device. J.Z. and M.H. performed device measurement and analyzed data. J.Z. and W.Z. wrote the manuscript. Y.H. revised the manuscript and supervised the project. H.L., L.Y., X.F., F.L., and K.C. contributed to discussion of this study and the revision of the manuscript. All authors read and approved the final manuscript. **Competing interests:** The authors declare that they have no competing interests

Data Availability

Data underlying the results presented in this paper could be obtained from the authors upon reasonable request.

Supplementary Materials

Sections S1 to S4
Figs. S1 to S3
Table S1
Reference [26]

References

1. Holzman I, Ivry Y. Superconducting nanowires for single-photon detection: Progress, challenges, and opportunities. *Adv Quant Technol*. 2019;2(3-4):1800058.
2. You L. Superconducting nanowire single-photon detectors for quantum information. *Nano*. 2020;9(9):2673–2692.
3. Polakovic T, Armstrong W, Karapetrov G, Meziani Z-E, Novosad V. Unconventional applications of superconducting nanowire single photon detectors. *Nanomater Inter*. 2020;10(6):1198.
4. Guan Y, Li H, Xue L, Yin R, Zhang L, Wang H, Zhu G, Kang L, Chen J, Wu P. Lidar with superconducting nanowire single-photon detectors: Recent advances and developments. *Opt Lasers Eng*. 2022;156:107102.
5. Ferrari S, Schuck C, Pernice W. Waveguide-integrated superconducting nanowire single-photon detectors. *Nano*. 2018;7(11):1725–1758.
6. Sprengers JP, Gaggero A, Sahin D, Jahanmirinejad S, Frucci G, Mattioli F, Leoni R, Beetz J, Lermer M, Kamp M, et al. Waveguide superconducting single-photon detectors for integrated quantum photonic circuits. *Appl Phys Lett*. 2011;99(18):181110.
7. Pernice WHP, Schuck C, Minaeva O, Li M, Goltsman GN, Sergienko AV, Tang HX. High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits. *Nat Commun*. 2012;3(1):1325.
8. Lingjie Yu HW, Li H, Wang Z, Huang Y, You L, Zhang W. A silicon shallow-ridge waveguide integrated superconducting

nanowire single photon detector towards quantum photonic circuits. *Chin Phys Lett*. 2019;(8):084202.
9. Schuck C, Guo X, Fan L, Ma X, Poot M, Tang HX. Quantum interference in heterogeneous superconducting-photonic circuits on a silicon chip. *Nat Commun*. 2016;7(1):10352.
10. Sayem AA, Cheng R, Wang S, Tang HX. Lithium-niobate-on-insulator waveguide-integrated superconducting nanowire single-photon detectors. *Appl Phys Lett*. 2020;116(15):151102.
11. Lomonte E, Wolff MA, Beutel F, Ferrari S, Schuck C, Pernice WHP, Lenzini F. Single-photon detection and cryogenic reconfigurability in lithium niobate nanophotonic circuits. *Nat Commun*. 2021;12(1):6847.
12. Xiaodong Z, Peiyu Z, Renyou G, Liangliang L, Guanglong H, Qi C, Qu F, Zhang L, Cai X, Lu Y, et al. Heterogeneously integrated, superconducting silicon-photonic platform for measurement-device-independent quantum key distribution. *Adv Photon*. 2021;3(5):055002.
13. Akhlaghi MK, Schelew E, Young JF. Waveguide integrated superconducting single-photon detectors implemented as near-perfect absorbers of coherent radiation. *Nat Commun*. 2015;6(1):8233.
14. Vetter A, Ferrari S, Rath P, Alaee R, Kahl O, Kovalyuk V, Diewald S, Goltsman GN, Korneev A, Rockstuhl C, et al. Cavity-enhanced and ultrafast superconducting single-photon detectors. *Nano Lett*. 2016;16(11):7085–7092.
15. Münzberg J, Vetter A, Beutel F, Hartmann W, Ferrari S, Pernice WHP, Rockstuhl C. Superconducting nanowire single-photon detector implemented in a 2D photonic crystal cavity. *Optica*. 2018;5(5):658–665.
16. Cheng R, Zhou Y, Wang S, Shen M, Taher T, Tang HX. A 100-pixel photon-number-resolving detector unveiling photon statistics. *Nat Photonics*. 2023;17(1):112–119.
17. Yang Z, Albrow-Owen T, Cai W, Hasan T. Miniaturization of optical spectrometers. *Science*. 2021;371(6528): eabe0722.
18. Cheng RS, Zou CL, Guo X, Wang SH, Han X, Tang HX. Broadband on-chip single-photon spectrometer. *Nat Commun*. 2019;10.
19. Hartmann W, Varytis P, Gehring H, Walter N, Beutel F, Busch K, Pernice W. Broadband spectrometer with single-photon sensitivity exploiting tailored disorder. *Nano Lett*. 2020;20(4):2625–2631.
20. Zheng J, Xiao Y, Hu M, Zhao Y, Li H, You L, Feng X, Liu F, Cui K, Huang Y, et al. Photon counting reconstructive spectrometer combining metasurfaces and superconducting nanowire single-photon detectors. *Photon Res*. 2023;11(2):234–244.
21. Xiao Y, Wei S, Xu J, Ma R, Liu X, Zhang X, Tao TH, Li H, Wang Z, You L, et al. Superconducting single-photon spectrometer with 3D-printed photonic-crystal filters. *ACS Photonics*. 2022;9(10):3450–3456.
22. Cheben P, Schmid JH, Delâge A, Densmore A, Janz S, Lamontagne B, Lapointe J, Post E, Waldron P, Xu DX. A high-resolution silicon-on-insulator arrayed waveguide grating microspectrometer with sub-micrometer aperture waveguides. *Opt Express*. 2007;15(5):2299–2306.
23. Momeni B, Hosseini ES, Adibi A. Planar photonic crystal microspectrometers in silicon-nitride for the visible range. *Opt Express*. 2009;17(19):17060–17069.
24. Gao L, Qu Y, Wang L, Yu Z. Computational spectrometers enabled by nanophotonics and deep learning. *Nano*. 2022;11(11):2507–2529.
25. Brouckaert J, Bogaerts W, Selvaraja SK, Dumon P, Baets R, Thourhout D. Planar concave grating demultiplexer with high reflective Bragg reflector facets. *IEEE Photon Technol Lett*. 2008;20:309–311.
26. Hu P, Li H, You L, Wang H, Xiao Y, Huang J, Yang X, Zhang W, Wang Z, Xie X. Detecting single infrared photons toward optimal system detection efficiency. *Opt Express*. 2020;28(24):36884–36891.