

Fractal Superconducting Nanowires Detect Infrared Single Photons with 84% System Detection Efficiency, 1.02 Polarization Sensitivity, and 20.8 ps Timing Resolution

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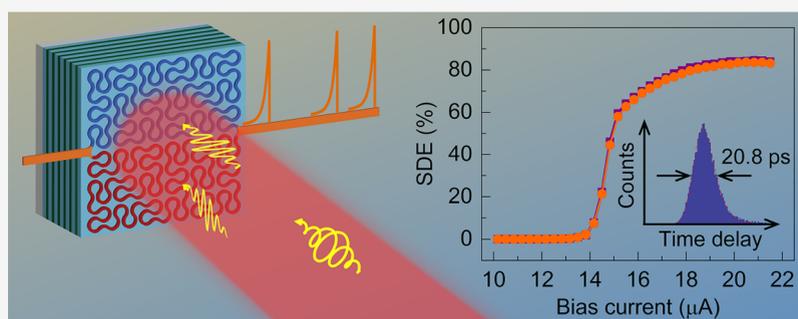
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ABSTRACT: The near-unity system detection efficiency (SDE) and excellent timing resolution of superconducting nanowire single-photon detectors (SNSPDs), combined with their other merits, have enabled many classical and quantum photonic applications. However, the prevalent design based on meandering nanowires makes SDE dependent on the polarization states of the incident photons; for unpolarized light, the major merit of high SDE would get compromised, which could be detrimental to photon-starved applications. Here, we create SNSPDs with an arced fractal geometry that almost completely eliminates this polarization dependence of the SDE, and we experimentally demonstrate $84 \pm 3\%$ SDE, $1.02^{+0.06}_{-0.02}$ polarization sensitivity at the wavelength of 1575 nm, and 20.8 ps timing jitter in a 0.1 W closed-cycle Gifford–McMahon cryocooler, at the base temperature of 2.0 K. This demonstration provides a novel, practical device structure of SNSPDs, allowing for operation in the visible, near-infrared, and mid-infrared spectral ranges, and paves the way for polarization-insensitive single-photon detection with high SDE and high timing resolution.

KEYWORDS: superconducting nanowire single-photon detectors, fractal, timing jitter, current crowding, photon counters, quantum optics

INTRODUCTION

Because of their near-unity system detection efficiency (SDE),^{1–7} low dark-count rate (DCR),⁸ high count rate,^{9–12} excellent timing resolution,^{13,14} and broad working spectral range,^{15–18} superconducting nanowire single-photon detectors (SNSPDs)¹⁹ have been widely used in classical and quantum photonic applications,²⁰ ranging from LiDAR,²¹ detection of luminescence from singlet oxygen,²² and quantum key distribution (QKD)²³ to quantum computing.^{24,25} Indeed, these detectors have become indispensable tools and enabling components in the systems requiring faint-light detection. However, the prevalent design based on meandering nanowires yields polarization-dependent SDE, which could be problematic if information is encoded in polarization states. In particular, when the polarization states of the photons are unknown, time-varying, or random, it may not be possible to rotate the polarization states to maximize the SDE of SNSPDs. Therefore, the major merit of these detectors would get

severely compromised, and this compromise could be detrimental to many photon-starved applications that stringently require high SDE. For photon-number-resolving detection or coincidence photon counting, the fidelity to resolve n photons or the n -fold coincidence count rate scales with SDE^n ,^{26,27} which quickly drops if the SDE decreases. In a QKD system using SNSPDs, the polarization-dependent mismatch of SDE makes the system vulnerable to quantum hacking.²⁸ Furthermore, the subtle trade-offs between the SDE and timing resolution²⁹ make their simultaneous optimization challenging. Recently, 85% SDE at the wavelength of 915 nm

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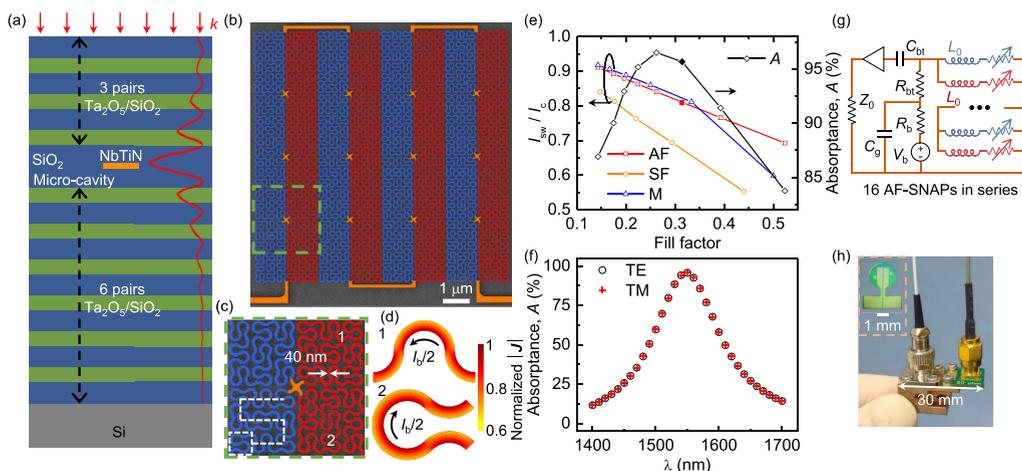


Figure 1. Design, fabrication, and packaging of arced fractal SNAPs (AF-SNAPs). (a) Schematic of the optical structure of an AF-SNAP. The nanowire is sandwiched in an optical microcavity supported by distributed Bragg structures, which are composed of dielectric alternating layers of silicon dioxide (SiO_2) and tantalum pentoxide (Ta_2O_5). The detector is illuminated from top, and the red line presents the simulated distribution of the light intensity, assuming the absence of the nanowire. The nanowire is positioned in the microcavity, where the light intensity is the strongest. (b) False-colored scanning-electron micrograph of an AF-SNAP, in which the photosensitive nanowires are colored in red and blue, and the auxiliary structures are colored in orange. (c) Zoom-in micrograph of the region enclosed in the green-dashed box in (b). The width of the nanowire was measured to be 40 nm. (d) Simulated and normalized distribution of supercurrent density, $|J|$, at the proximity of an L-turn and a U-turn, denoted in (c) as 1 and 2, respectively. (e) Simulated normalized switching currents, I_{sw}/I_c , of the arced fractal (red), standard fractal (orange), and meandering (blue) nanowires, as functions of the fill factor. The simulated optical absorbance (black) of the arced fractal nanowire is also presented as a function of the fill factor. The fill factor used in this work is 0.31. (f) Simulated optical absorbance of the AF-SNAP for two orthogonal linear polarization states, transverse-electric (TE) and transverse-magnetic (TM) states, as functions of the wavelength, λ . (g) Equivalent circuitry of the AF-SNAP, which is composed of 16 cascaded 2-SNAPs. (h) Photograph of the chip package. Inset: a photograph of the keyhole-shaped chip.

with 7.7 ps device timing jitter¹⁴ and 98% SDE at the wavelength of 1425 nm with 26 ps system timing jitter⁶ were demonstrated on meandering SNSPDs, but the SDEs were still polarization-dependent.

To address the issue of polarization dependence of the SDE, several approaches have been proposed and demonstrated, including spiral SNSPDs,^{30,31} two orthogonal side-by-side meanders,³⁰ double-layer orthogonal meanders,³² SNSPDs involving compensating high-index materials,^{33,34} specially designed SNSPDs with a low polarization dependence at a certain wavelength,^{4,35} and fractal SNSPDs.^{29,36,37} These demonstrations all have successfully reduced the polarization sensitivity (PS, the ratio of the polarization-maximum SDE, SDE_{max} and over the polarization-minimum SDE, SDE_{min}) of SNSPDs; however, none of them could simultaneously preserve other major merits, in particular, high SDE and excellent timing resolution. Among these demonstrations, amorphous SNSPDs, made of WSi or MoSi, have exhibited over 80%^{32,35} and even over 90% SDE;⁴ however, their timing jitter ranges from 76 to 465 ps; on the other hand, polycrystalline SNSPDs, made of NbN or NbTiN, have shown a better timing resolution; however, so far, the highest SDE demonstrated on polycrystalline SNSPDs with low-PS designs is 60%,²⁹ still significantly lower than the state-of-the-art SDE_{max} of meandering SNSPDs, which is over 90% demonstrated by several research groups.^{1–7} Therefore, it remains an outstanding challenge how to boost the SDE of SNSPDs with a low PS to the level comparable to the SDE_{max} of their meandering counterparts while simultaneously optimizing the timing resolution.

Although the geometry of the fractal SNSPDs^{29,37} eliminated the global orientation of the nanowire and therefore significantly reduced the PS, it was also this geometry that

brought the major obstacle for further enhancing the SDE and timing resolution. The fractal design contains a plethora of U-turns and L-turns that may limit the switching current, I_{sw} , due to the current-crowding effect,³⁹ which may further affect the SDE and timing resolution. In the past, we demonstrated fractal superconducting nanowire avalanche photodetectors (SNAPs)²⁹ with 60% SDE, 1.05 PS, and 45 ps timing jitter. However, it is still elusive whether this route, using fractal geometry, is a practical one to combine high SDE, low PS, and low timing jitter.

In this paper, we report on our design and demonstration of a fiber-coupled fractal SNAP, fully packaged in a 0.1 W closed-cycle Gifford–McMahon (GM) cryocooler with a base temperature of 2.0 K, achieving $84 \pm 3\%$ SDE, $1.02^{+0.06}_{-0.02}$ PS at a wavelength of 1575 nm, and 20.8 ps timing jitter. An enabling innovation is that we used an arced fractal geometry⁴⁰ for the nanowire to successfully reduce the current-crowding effect and, therefore, increased I_{sw} to a level comparable to that in the meandering structure with the same nanowire width, thickness, and fill factor, achieving saturated, near-unity internal quantum efficiency, P_r . We integrated the arced fractal nanowire with an optical microcavity, supported by dielectric distributed Bragg structures, for enhancing the optical absorbance, A , of the nanowire.^{3,5,7,41}

RESULTS AND DISCUSSION

Figure 1a presents a schematic of the optical structure of an arced fractal SNAP (AF-SNAP). Six pairs of alternating silicon dioxide (SiO_2) and tantalum pentoxide (Ta_2O_5) layers were deposited on a silicon substrate, functioning as the bottom Bragg reflector; three pairs formed the top reflector; in between a SiO_2 defect layer was sandwiched. The thicknesses of a SiO_2 layer and a Ta_2O_5 layer in the Bragg reflectors are

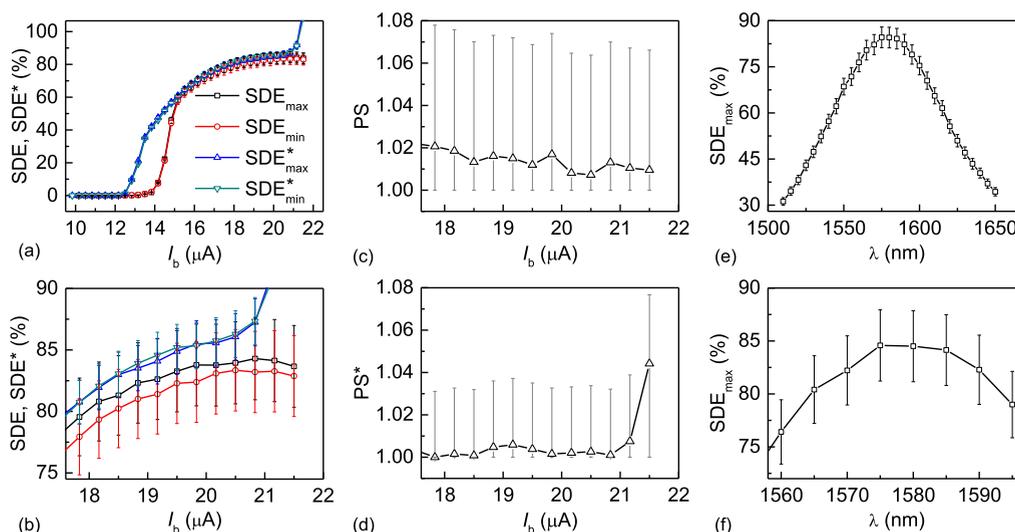


Figure 2. Measured SDE and polarization dependence of an arced fractal SNAP (AF-SNAP). (a) Measured SDE_{\max} , SDE_{\min} , SDE_{\max}^* and SDE_{\min}^* as functions of the bias current, I_b . (b) Zoom-in view of (a) at the high-bias regime with I_b exceeding $17.5 \mu\text{A}$. (c) Polarization sensitivity, PS, calculated from the measured SDE_{\max} and SDE_{\min} . (d) Polarization sensitivity, PS^* , calculated from the measured SDE_{\max}^* and SDE_{\min}^* . (e) Measured spectrum of SDE_{\max} at a bias current of $21.17 \mu\text{A}$. (f) Zoom-in view of the SDE_{\max} spectrum near a central wavelength of 1575 nm .

264 and 180 nm, respectively; and the thickness of the SiO_2 defect layer is 529 nm, targeting for a wavelength of 1550 nm with optimal optical absorptance. The red line in Figure 1a shows the simulated distribution of the light intensity in the dielectric stacks (without the nanowires) at a wavelength of 1550 nm for top illumination; and the NbTiN nanowires were designed to locate in the middle of the defect layer of the optical microcavity, where the light intensity is the strongest. The thickness of the NbTiN film used in this work was 9 nm. Figure 1b presents a false-colored scanning-electron micrograph of a fabricated AF-SNAP, before the top Bragg layers were integrated. The photosensitive region of the detector was $10.2 \mu\text{m}$ by $10.2 \mu\text{m}$, and the width of the nanowire was measured to be 40 nm [Figure 1c]. The photosensitive region of the detector is composed of 64 second-order arced fractal Peano curves⁴⁰ that are electrically connected according to the circuitry in Figure 1g. In comparison to the standard Peano fractal curve,^{29,37} the arced Peano fractal curve⁴⁰ reduced the current-crowding effect at the turns. We simulated the normalized distribution of the supercurrent density, $|J|$, at the proximity of an L-turn and a U-turn [Section S1 of Supporting Information], which are presented in Figure 1d. Figure 1e further presents the simulated I_{sw} , normalized to the critical current of a straight nanowire with the same width and thickness, I_c , of the meandering, standard fractal, arced fractal nanowires as functions of the fill factor. We used a commercial software COMSOL Multiphysics based on the finite-element method for these simulations. At a fill factor of 0.31 used in this work, the simulated optical absorptance for the plane wave at a wavelength of 1550 nm is 96%, and the normalized switching current of the arced fractal nanowire is 0.81. As a comparison, with the same fill factor, 0.31, the normalized switching currents of the meandering nanowire and the standard fractal nanowire are 0.82 and 0.67, respectively, further evidencing that the current-crowding effect in the arced fractal nanowire is significantly reduced, compared with that in the standard fractal one. A detailed comparison of the distribution of the supercurrent density of these three types

of geometry is presented in Section S1 of Supporting Information. Figure 1f presents the simulated optical absorptance, A , of the AF-SNAP for the plane wave as functions of the wavelength for two orthogonal linear polarization states, denoted as transverse-electric (TE) and transverse-magnetic (TM) states. A peaks at 1550 nm and remains above 50% in the wavelength range from 1490 to 1610 nm. The simulation shows that A is completely polarization-independent. To investigate the coupling efficiency, η_c , we simulated the optical modes of the optical microcavity without the nanowires. The simulated mode-field diameter (MFD) at the plane of nanowires coupled with a Corning high-index optical fiber (HIF, HI 1060 FLEX) used in this paper was $6.8 \mu\text{m}$, which ensured a η_c of 99%, assuming perfect alignment. In comparison, the MFD at the plane of nanowires coupled with a Corning SMF-28e+ optical fiber (SMF) was $10.7 \mu\text{m}$ and the corresponding coupling efficiency is 89%. The detector coupled with HIF is more tolerable to the spatial misalignment than the detector coupled with SMF. A detailed simulation regarding optical modes of the cavity is presented in Section S2 of Supporting Information. Electrically, the detector was composed of 16 cascaded 2-SNAPs, as we used previously,²⁹ and Figure 1g presents the equivalent circuit diagram. The chips were etched into the keyhole shape by the Bosch process for self-aligned packaging.⁴² A detailed fabrication process is presented in Section S3 of the Supporting Information. Figure 1h shows a photograph of the resulting chip package and the inset presents a photograph of a keyhole-shaped chip. In this package, the detector was self-aligned and directly coupled with a HIF, with a MFD of $6.3 \pm 0.3 \mu\text{m}$, which was connected to the SMF, with a MFD of $10.4 \pm 0.5 \mu\text{m}$, through an in-line mode-field adapter (Section S4 of Supporting Information).

We used the experimental setup, schematically presented in Section S4 of Supporting Information, to measure SDE and the polarization dependence. The base temperature for these measurements was 2.0 K. At this temperature, $I_{\text{sw}} = 21.67 \mu\text{A}$. A cryogenic, low-noise microwave amplifier was mounted on the 40 K stage and used to amplify the output pulses. We first measured the DCR as a function of the bias current (Section

SS of Supporting Information). Then, we biased the detector at 21.17 μA , tuned the laser wavelength, and found that the SDE peaked at 1575 nm for this particular detector. The wavelength deviation from the designed wavelength with the maximum optical absorptance is presumably due to deviations of the thicknesses of the deposited dielectric layers and the refractive indices. We then fixed the wavelength at 1575 nm and scanned the polarization states of the input light over the Poincaré sphere and found the polarization states corresponding to $\text{SDE}_{\text{max}}^*$ and $\text{SDE}_{\text{min}}^*$; at these two polarization states, we measured $\text{SDE}_{\text{max}}^*$ and $\text{SDE}_{\text{min}}^*$ as the functions of the bias current [Figure 2a]. To accurately measure the SDE*, we calibrated each optical attenuator at each polarization state and each wavelength for these measurements (Section S6 of Supporting Information). In the high-bias regime ($I_b > 20.17 \mu\text{A}$), as shown in Figure 2a,b, the $\text{SDE}^* - I_b$ curves go upward, showing additional false counts other than the dark counts and showing an unrealistic SDE*. Similar observations have previously been reported on meandering SNAPs⁴³ and also SNSPDs.⁴⁴ We re-measured the SDE_{max} and SDE_{min} using the method based on time-correlated photon counting⁴⁴ to exclude the false counts. Note that we use SDE^* to refer to the SDE directly measured with the CW laser [Figure S5a for the experimental setup], excluding the dark counts; and we use SDE to refer to the SDE measured by time-correlated photon counting, excluding all false counts [Figure S5b for the experimental setup]. The values of the SDE and SDE^* in Figure 2a,b,e,f take into account the fiber end-facet reflection that occurred when we used an optical power meter to measure the optical power coming out from the fiber to avoid under-calculating the optical power delivered to the cryogenic AF-SNAP system and, therefore, to avoid over-calculating SDE and SDE^* (Section S7 of Supporting Information). In Figure 2, the associated error bars present the uncertainties with 68% confidence ($k = 1$)⁴⁵ of the measurements (Section S8 in the Supporting Information). At a bias current of 19.83 μA , SDE_{max} was measured to be $84 \pm 3\%$, SDE_{min} was measured to be $82 \pm 3\%$, and the resulting PS ($\text{SDE}_{\text{max}}/\text{SDE}_{\text{min}}$) was $1.02_{-0.02}^{+0.06}$. $\text{SDE}_{\text{max}}^*$ and $\text{SDE}_{\text{min}}^*$ were measured to be both $85 \pm 2\%$, and the resulting PS^* was $1.00_{-0}^{+0.03}$. At this bias current, DCR and false-count rate (FCR) were measured to be 2.1×10^3 and 2.2×10^3 cps, respectively (Section S5 of Supporting Information). At a bias current of 17.83 μA , SDE_{max} and SDE_{min} decreased to 80 ± 3 and $78 \pm 3\%$, respectively; $\text{SDE}_{\text{max}}^*$ and $\text{SDE}_{\text{min}}^*$ decreased to both $81 \pm 2\%$ [Figure 2b]; and the measured FCR and DCR at this bias current were 3.7×10^2 and 3.0×10^2 cps, respectively. In the low-bias regime, $I_b < 15.83 \mu\text{A}$, the detector was unstable,⁴⁶ generating multiple false pulses with low amplitudes after detecting one photon [Section S9 of Supporting Information], and resulting in the pronounced deviation of SDE^* from the SDE. PS and PS^* , as functions of the bias current, were calculated and presented in Figure 2c,d. Figure 2e presents SDE_{max} as a function of the wavelength, λ , at a bias current of 21.17 μA . The full width at half maxima (fwhm) of the spectrum of SDE_{max} is 110 nm, which is slightly smaller than the fwhm, 120 nm, of the designed spectrum of the optical absorptance [Figure 1f]. Figure 2f presents a zoom-in view of the SDE_{max} for the wavelengths ranging from 1560 to 1595 nm, in which $\text{SDE}_{\text{max}} > 75\%$. We note that here, the measurements of the SDE and SDE^* were performed at relatively low average input-photon rates going into the cryogenic AF-SNAP system, 1.79×10^5 and $1.82 \times 10^5 \text{ s}^{-1}$, respectively.

As the flux of the input photons increases, the SDE would decrease. To characterize the SDE of the AF-SNAP at various input-photon rates, we measured the SDE_{max} as a function of the average input-photon rate (Section S10 of Supporting Information). Note that we used the oscilloscope to measure the SDE_{max} in Figure 3a with a sampling rate of 2.5 GS/s and a

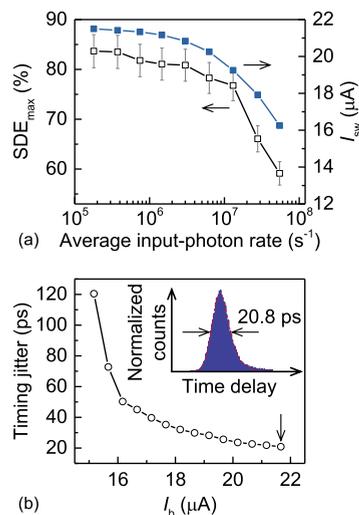


Figure 3. Timing properties of an arced fractal SNAP. (a) Measured SDE_{max} and the switching current, I_{sw} , as functions of the average input-photon rate. (b) Measured timing jitter as a function of the bias current, I_b . Inset: measured time-delay histogram at a bias current of 21.67 μA and the EMG fitting, showing a full width at half maxima of a EMG fitting of 20.8 ps.

time span per frame of 1 ms because the maximum count rate of the input channel of the TAC is 12.5 Mcps, smaller than the photon-count rate we needed in this measurement. As the flux of the incident photon increases, the switching current decreases. Each value of SDE_{max} in Figure 3a is measured at a bias current of $0.99I_{\text{sw}}$. The results show that when the average input-photon rate increases to $5.47 \times 10^7 \text{ s}^{-1}$, SDE_{max} drops to 59%, and the corresponding photon-count rate with the FCR excluded was 26 Mcps.

Figure 3b presents the measured timing jitter of the AF-SNAP by using a mode-locked fiber laser with a central wavelength of 1560 nm, a fast photodetector with 3 dB bandwidth of 40 GHz, and a real-time oscilloscope with a bandwidth of 4 GHz. The experimental setup is schematically presented in Section S11 of Supporting Information. Each data point in Figure 3b is the fwhm of the exponentially modified Gaussian (EMG) fitting⁴⁷ to the time-delay histograms [Figure S12b]. The lowest value of timing jitter was 20.8 ps at 21.67 μA . The time-delay histogram and the EMG fitting is shown in the inset of Figure 3b. Timing jitter monotonically increased with decreasing the bias current in the avalanche regime, for example, at $I_b = 19.67 \mu\text{A}$, timing jitter increased to 25.6 ps. As for the other temporal properties, in the avalanche regime, the exponential fitting to the recovery edge of the output pulse shows a $1/e$ time constant of 8.68 ns [Section S9 of Supporting Information].

We estimated the highest possible SDE for the current configuration of our system. The total transmittance of the two types of optical fibers connected through the mode-field adapter was measured to be 98% at ambient temperature; the coupling efficiency, η_c , between the high-index optical fiber and

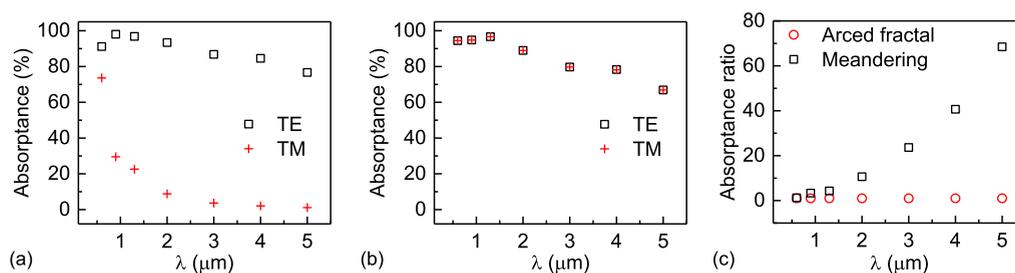


Figure 4. Simulated visible, near-infrared, and mid-infrared spectra of optical absorptance and the polarization dependence for the meandering and arced fractal SNSPDs. (a) Simulated optical absorptance of meandering SNSPDs for TE- and TM-polarization states. (b) Simulated optical absorptance of arced fractal SNSPDs for TE- and TM-polarization states. (c) Calculated absorptance ratios of TE- and TM-polarization states for meandering and arced fractal SNSPDs.

the photosensitive area was calculated to be 99%, assuming a perfect alignment; the optical absorptance, A , was simulated to be 96% at a wavelength of 1550 nm; and the internal quantum efficiency, P_r , was assumed to be 100%. The product of these numbers gives an estimation of the highest possible SDE to be 93%. The measured SDE, 84%, is less than this estimation of the highest possible SDE presumably because (1) certain misalignment between the optical mode and the photosensitive area existed in the package and (2) P_r was less than 100%.

The geometry of arced fractal nanowires can be applied to SNSPDs/SNAPs targeted for other interesting wavelengths by similarly re-designing the optical structures of the devices. In particular, the polarization dependence of SDE becomes more severe at longer wavelengths for meandering SNSPDs, and we think that the geometry presented in this work would be useful for creating SNSPDs working in the mid-infrared with low PS. We simulated and optimized the optical absorptance of meandering [Figure 4a] and arced fractal SNSPDs [Figure 4b] at some additional wavelengths, 0.6, 0.9, 1.3, 2, 3, 4, and 5 μm, for TE and TM polarization states. The optical structures are similar to that in Figure 1a except for that two, rather than three, pairs of alternating top layers maximize the optical absorptance of a meandering SNSPD for TE polarization and except for the modified thicknesses of the dielectric layers for different wavelengths. The simulation took into account the wavelength dependence of the refractive indices of the materials,^{48–50} which are listed in Section S12 of Supporting Information. The calculated absorptance ratios of these two polarizations are presented in Figure 4c. At the longer wavelengths, the absorptance ratio for the meandering SNSPD increases, whereas the absorptance ratio for the arced fractal SNSPD remains constantly 1. As the polarization-dependent optical absorptance is the dominant contributor to the PS, and as this work demonstrates that the AF-SNAPs can reach a high SDE and high timing resolution at the near infrared, we think that arced fractal SNSPDs/SNAPs should be good device structures for polarization-insensitive single-photon detection in the mid-infrared, as well as the visible, spectral ranges.

CONCLUSIONS

In conclusion, we demonstrated a fiber-coupled AF-SNAP with $84 \pm 3\%$ SDE, $1.02_{-0.02}^{+0.06}$ residual PS at a wavelength of 1575 nm, and 20.8 ps timing jitter. The SDE was boosted to the level comparable to the amorphous SNSPDs/SNAPs with low PS,^{4,32,35} but the timing resolution of the NbTiN AF-SNAP exceeded (see Section S13 of Supporting Information for comparison; we also note that at their reported SDEs,

amorphous SNSPDs/SNAPs listed in Section S13 of Supporting Information exhibited lower DCR than the FCR and DCR of the NbTiN AF-SNAP that we report in this paper, but amorphous SNSPDs/SNAPs require lower temperatures). These combined properties have not been achieved with any single-photon detectors reported previously and are enabled by our comprehensive device design. In particular, the arced fractal geometry of the nanowires is the key enabling innovation that reduces the current-crowding effect and increases the switching current to the level comparable to that in the meandering SNSPDs and, therefore, enhances both SDE and timing resolution. Since the introduction of fractal SNSPDs in 2015,³⁶ although we kept enhancing their performances,^{29,37} it had been elusive whether the fractal designs of the nanowires could be practical device structures; it is this work that gives a positive and unambiguous answer by showing that fractal SNSPDs are practical devices with excellent comprehensive performances, comparable to meandering SNSPDs, on top of which low PS is added. The arced fractal geometry is equally applicable to designing SNSPDs working in other spectral ranges, in particular, mid infrared. This demonstration is a detector coupled with a single-mode optical fiber, but the same geometry can be used for detectors coupled with few- or multi-mode optical fibers and for detecting single photons coming from the free space. Additionally, the negligibly small PS of the arced fractal SNSPDs/SNAPs would eliminate the security loophole, due to the polarization-dependent mismatch of the SDE, in the QKD systems.²⁸ We believe that this work paves the way for polarization-insensitive single-photon detection with high SDE and high timing resolution.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsp Photonics.1c00730>.

Distributions of supercurrent density in the meandering, standard fractal, and arced fractal SNSPDs; optical modes of the microcavity; nanofabrication process for making the detectors; measurements of the SDE and its polarization dependence; DCR and false-count rate; calibration of the optical attenuators; measurements of fiber end-facet reflectance; uncertainty analysis on the measured SDE and polarization sensitivity; output pulses in the avalanche and unstable regimes; measurements of the SDE at various input-photon rates; measurements of the timing jitter; refractive indices used in optical

simulation; and comparison of performances of SNSPDs with low polarization sensitivity (PDF)

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Author Contributions

Y.M., K.Z., and N.H. contributed equally to this work. X.H., Y.M., and K.Z. conceived the project. Y.M., K.Z., N.H., and X.H. designed the devices and performed numerical simulation. S.S., S.G., and V.Z. sputtered NbTiN films. K.Z., N.H., and X.L. fabricated the devices. Y.M. and L.X. performed the measurements. X.H., Y.M., K.Z., and N.H. analyzed the data and wrote the paper. All authors commented and revised the paper. X.H. supervised the project.

Notes

The authors declare no competing financial interest.

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