Fractal superconducting nanowires detect infrared single photons with 91% polarization-independent system efficiency and 19 ps timing resolution

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The near-unity detection efficiency 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 the detection efficiency dependent on the polarization states of the incident photons; for unpolarized light, the major merit of high detection efficiency would get compromised, which could be detrimental for photon-starved applications. In quantum-key distribution systems, the polarization dependence of detection efficiency of the SNSPDs could also be a vulnerable security loophole. Here, we create SNSPDs with an arced fractal topology that almost completely eliminates this polarization dependence of the detection efficiency while preserving other major merits of the SNSPDs. We experimentally demonstrated $91\pm2\%$ system detection efficiency at the wavelength of 1590 nm for photons in any polarization state and 19 ps timing jitter. The detector was fiber-coupled and fully packaged in a 0.1-W close-cycled Gifford-McMahon cryocooler. This demonstration provides a novel, practical device structure of SNSPDs, allowing for operation in the visible, near- and mid-infrared spectral ranges, and paves the way for polarization-insensitive single-photon detection with high detection efficiency and high timing resolution.

Because of their near-unity system detection efficiency (SDE) [1–7], low dark-count rate (DCR) [8], high count rates [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], quantum-key distribution [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 is 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 for many photonstarved applications that stringently require high detection efficiency. For photon-number-resolving detection or coincidence photon counting, the fidelity to resolve nphotons or the n-fold coincidence count rate scales with SDE^{n} [26, 27], which quickly drops if SDE decreases. In a quantum-key distribution system using SNSPDs, the polarization-dependence mismatch of the detection efficiency makes the system vulnerable for quantum hacking [28]. Furthermore, the subtle trade-offs between SDE

and timing resolution [29] make their simultaneous optimization challenging. Recently, 85% SDE at the wavelength of 915 nm and 7.7 ps device timing jitter [14], and 98% SDE at the wavelength of 1425 nm and 26 ps system timing jitter [6], were demonstrated on meandering SNSPDs, but the SDEs were still polarization-dependent.

To address the issue of polarization dependence of 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 highindex materials [33, 34], specially designed SNSPDs with 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 polarizationmaximum SDE, SDE_{max}, over the polarization-minimum SDE, SDE_{min} [38]) of SNSPDs; however, none of them could simultaenously preserve other major merits, in particular, high detection efficiency and excellent tim-Among these demonstrations, amoring resolution. phous SNSPDs, made of WSi or MoSi, have exhibited over 80% [32, 35] and even over 90% SDE [4], however, their timing jitter ranges from 99 ps to 465 ps; on the other hand, polycrystalline SNSPDs, made of NbN or NbTiN, have shown 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 low PS to the level comparable to the SDE_{max} of

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Fig. 1. Design, fabrication, and packaging of arced fractal superconducting nanowire avalanche photodetectors (AF-SNAPs). (a) 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 oxide (SiO₂) and tantalum oxide (Ta₂O₅). 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 was positioned in the micro-cavity where the light intensity is the strongest. (b) A 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) A 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 AF-SNAP (red), a standard fractal SNAP (orange), and a meandering SNAP (blue), as functions of the fill factor. The simulated optical absorptance (black) of the AF-SNAP is also presented as a function of the fill factor. The fill factor used in this work is 0.31. (f) Simulated optical absorptance of the AF-SNAP for two orthogonal linear polarization states, transverse-electric (TE) and transverse-magnetic (TM) states, as functions of wavelength, λ . (g) Equivalent circuitry of the AF-SNAP, which is composed of 16 cascaded 2-SNAPs. (h) A photograph of the chip package. Inset: a photograph of the keyhole-shaped chip.

their meandering counterparts while simultaneously optimizing the timing resolution.

Although the topology of the fractal SNSPDs [29, 37] eliminated the global orientation of the nanowire, and therefore, significantly reduced PS, it was also this topology that brought the major obstacle for further enhancing SDE and timing resolution. The fractal design contains a plethora of U-turns and L-turns that may limit the switching current, due to the current-crowding effect [39], which may further affect 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 topology, is practical to combine high SDE, low PS, and low timing jitter.

In this Letter, we report on our design and demonstration of a fiber-coupled fractal SNAP, fully packaged in a 0.1-W close-cycled Gifford-McMahon (GM) cryocooler, achieving $91\pm2\%$ polarization-independent SDE at the wavelength of 1590 nm and 19 ps timing jitter. An enabling innovation is that we used an arced fractal topology [40] for the nanowire to successfully reduce the current-crowding effect and therefore, increased the switching current 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, $P_{\rm r}$. We integrated the arced fractal nanowire with an optical micro-cavity, supported by dielectric distributed Bragg structures, for enhancing the optical absorptance, A, of the nanowire.

Figure 1 (a) presents a schematic of the optical structure of an arced fractal SNAP (AF-SNAP). Six pairs of alternating silicon oxide (SiO₂) and tantalum oxide (Ta₂O₅) layers were deposited on a silicon substrate, functioning as the bottom Bragg reflector; three pairs formed the top reflector; in between was sandwiched a SiO₂ defect layer, functioning as the optical microcavity. The thicknesses of a SiO₂ and a Ta₂O₅ in the Bragg reflectors are 264 nm and 180 nm, respectively; and the thickness of the SiO₂ defect layer is 529 nm, targeting for the wavelength of 1550 nm with optimal



Fig. 2. Measured system detection efficiency (SDE) and polarization dependence of an arced-fractal superconducting nanowire avalanche photodetector (AF-SNAP). (a) Measured polarization-maximum SDE, SDE_{max}, and polarization-minimum SDE, SDE_{max}, as functions of the bias current, $I_{\rm b}$. The regions in gray in (a), (b), (c), and (d) show the high-bias regime with significant number of false counts and unrealistic SDE. (b) Zoom-in view of SDE_{min} and SDE_{max} at the high-bias regime with $I_{\rm b}$ exceeding 17 µA. (c) The second-order derivatives of SDE_{max}($I_{\rm b}$) and SDE_{min}($I_{\rm b}$), which are denoted as SDE⁽²⁾_{max} and SDE⁽²⁾_{min}, respectively. (d) Polarization sensitivity, PS, calculated from the measured SDE_{max} and SDE_{min}. (e) Measured spectrum of SDE_{max}, at the bias current of 19.33 µA. (f) Zoom-in view of the SDE_{max} spectrum near the central wavelength of 1590 nm.

optical absorptance. The red line shows the simulated distribution of the light intensity in the dielectric stacks (without the nanowires) at the wavelength of 1550 nm for top illumination; and the NbTiN nanowires were designed to locate in the middle of the micro-cavity where the light intensity is the strongest. The thickness of the NbTiN used in this work was 9 nm. Fig. 1 (b) presents a false-colored scanning-electron micrograph of a fabricated AF-SNAP, before the top Bragg layers were integrated. The photosensitive area of the detector was $10.2 \ \mu m$ by $10.2 \ \mu m$, and the width of the nanowire was measured to be 40 nm [Fig. 1 (c)]. Rather than using the standard Peano fractal curve [29], we used an arced Peano fractal curve [40] for the topology, which 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 [Sec. I of Supplementary Information (SI), which are presented in Fig. 1 (d). Fig. 1 (e) further presents the simulated switching currents, I_{sw} , normalized to the critical current of a straight nanowire with the same width and thickness, $I_{\rm c}$, of the meandering, standard fractal, arced fractal SNSPD, and the optical absorptance of the arced fractal SNSPD, as functions of the fill factor. At the fill factor of 0.31 used in this work, the simulated optical absorptance at the wavelength of 1550 nm is 96%, and the normalized switching current of the AF-SNAP is 0.81. As a comparison, 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. Detailed comparison of the distribution of the supercurrent density of these three types of topology is presented in Sec. I of SI. Fig. 1 (f) presents the simulated optical absorptance of the AF-SNAP as functions of wavelength for two orthogonal linear polarizations 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 nm to 1610 nm. The simulation shows that Ais completely polarization-independent. Electrically, the detector was composed of sixteen cascaded 2-SNAPs, as we used previously [29], and Fig. 1 (g) presents the equivalent circuit diagram. The chips were etched into the keyhole shape by Bosch process for self-aligned packaging [41]. Detailed fabrication process is presented in Sec. II of SI. Fig. 1 (h) 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 Corning high-index optical fiber (HI 1060 FLEX), with mode-field diameter

(MFD) of $6.3\pm0.3 \,\mu\text{m}$, which was connected with Corning SMF-28e+ optical fiber, with MFD of $10.4\pm0.5 \,\mu\text{m}$, through an in-line mode-field adapter (Sec. III of SI).



Fig. 3. Timing properties of an arced fractal superconducting nanowire avalanche photodetector. (a) Measured timing jitter as functions of the bias current, $I_{\rm b}$. Inset: measured time-delay histogram at the bias current of 21.25 µA, showing a full width at half maxima of 19 ps. (b) Measured SDE_{max} and the switching current, $I_{\rm sw}$, as a function of the count rate. The dashed lines show the count rate, corresponding to the SDE_{max} that drops by 3 dB, to 45.5%.

We used the experimental setup, schematically presented in Sec. III of SI, to measure SDE and the polarization dependence. The base temperature for these measurements was 2.05 K. A low-noise, cryogenic 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 (Sec. IV of SI). Then, we biased the detector at 19.33 μ A, tuned the laser wavelength and found that the SDE peaked at 1590 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 1590 nm and scanned the polarization states of the input light over the Poincaré sphere, and found the polarization states corresponding to SDE_{max} and SDE_{min} ; at these two polarization states, we measured SDE_{max} and SDE_{min} as the functions of the bias current [Fig. 2 (a)]. To accurately measure the SDE, we calibrated each optical attenuator at each polarization and each wavelength for these measurements. As shown in Fig. 2 (a),

the measured SDE_{max} and SDE_{min} were almost identical. In the high-bias regime, as shown in the grayed region in Fig. 2 (a) and (b), the SDE- $I_{\rm b}$ curves go upward, showing additional false counts other than the dark counts and showing unrealistic SDE. Similar observations have previously been reported on meandering SNAPs [42] and also SNSPDs [43]. We calculated the second-order derivatives of SDE_{max} ($I_{\rm b}$) and SDE_{min} ($I_{\rm b}$), which went positive from negative values when $I_{\rm b} > 19.33$ µA, the inflection point. We used the SDEs at this inflection point as the highest SDEs that we report in this paper, which is $91\pm2\%$ for both SDE_{max} and SDE_{min} . The value of each SDE in Fig. 2 (a), (b), (e), and (f) is the average of five independent measurements and the associated error bar is the standard deviation. DCR at the bias current of 19.33 μ A was measured to be 7.8×10^3 cps (Sec. IV of SI). At the bias current of 16.67 μ A, SDE_{max} drops to 80% [Fig. 2 (a)], and the measured DCR at this bias current was 3.6×10^2 cps. In the low-bias regime, $I_{\rm b} < 14.67$ µA, the detector was unstable [44], generating multiple false pulses with low amplitudes after detecting one photon [Sec. V in SI]. We also measured the autocorrelation functions of the output pulses in these three regimes [Sec. VI in SI], consistent with measurements reported by other researchers [42]. PS, as a function of the bias current, was calculated and presented in Fig. 2 (d). At the bias current of 19.33 µA, PS was calculated to be 1.00, showing polarization independent SDE. Fig. 2 (e) presents SDE_{max} as a function of the wavelength, λ , at the bias current of 19.33 µA. The full width at halfmaxima (FWHM) of the spectrum of SDE_{max} is 105 nm, which is slightly smaller than the FWHM, 120 nm, of the designed spectrum of the optical absorptance [Fig. 1 (f)]. Fig. 2 (f) presents a zoom-in view of the SDE_{max} for the wavelengths ranging from 1570 nm to 1610 nm, in which $SDE_{max} > 80\%$. Note that we used a CW tunable semiconductor laser as the light source for the measurement of SDE_{max} from 1500 nm to 1625 nm [Fig. S3 (a) in Sec. III of SI], and used a pulsed supercontinuum light source, filtered by a monochromator, for the measurement from 1630 nm to 1680 nm [Fig. S3 (b) in Sec. III of SI].

Figure 3 presents the characterization of the timing properties of the AF-SNAP. We measured timing jitter by using a mode-locked fiber laser with the central wavelength of 1560 nm, a fast photodetector with 3-dB bandwidth of 40 GHz, and a real-time oscilloscope with bandwidth of 4 GHz. The experimental setup is schematically presented in Sec. VII of SI. Each data point in Fig. 3 (a) is the FWHM of the Gaussian fitting to the time-delay histograms [Fig. S6 (c)]. The lowest value of timing jitter was 19 ps at 21.25 μ A. The time-delay histogram is shown in the inset of Fig. 3 (a).

To characterize the maximum count rate of the AF-SNAP, we measured the SDE_{max} as a function of the count rate. As the flux of the incident photon increases, the switching current and therefore, the SDE, of the detector, decreases. Fig. 3 (b) presents the results, showing that when the SDE_{max} drops by 3 dB, to 45.5%, the



Fig. 4. Simulated visible, near- 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.

corresponding count rate was 6 Mcps. In the avalanche regime, the exponential fitting to the recovery edge of the output pulse shows a 1/e time constant of 8.6 ns [Sec. V in SI].

We estimated the SDE budget in 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 the photosensitive area was calculated to be 99%, assuming perfect alignment; the optical absorptance was simulated to be 96% at the wavelength of 1550 nm; and the internal quantum efficiency was assumed to be 1. The product of these numbers gives an estimation of SDE to be 93%.

The topology 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 topology presented in this work would be useful for creating polarization-insensitive SNSPDs working in the midinfrared. We simulated and optimized the optical absorptance of meandering [Fig. 4 (a)] and arced fractal SNSPDs [Fig. 4 (b)] at some additional wavelengths, 0.6 µm, 0.9 µm, 1.3 µm, 2 µm, 3 µm, 4 µm, and 5 µm, for TE and TM polarization states. The optical structures are similar to that in Fig. 1 (a) 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 calculated absorptance ratios of these two polarizations are presented in Fig. 4 (c). At the longer wavelength, the absorptance ratio for the meandering SNSPD increases whereas the absorptance ratio for the arced fractal SNSPD remains constantly 1. As the polarizationdependent optical absorptance is the dominant contributor to the PS, and as this work demonstrated that the AF-SNAPs can reach 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.

In conclusion, we demonstrated a fiber-coupled AF-SNAP with $91\pm2\%$ polarization-independent SDE at the wavelength of 1590 nm and 19-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 AF-SNAP exceeded (Sec. VIII. of SI for the comparison). 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 topology of the nanowire 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 fractal SNSPDs were introduced 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 the performances of the meandering SNSPDs, on top of which low polarization sensitivity is added. The arced fractal toplogy 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 topology can be used for detectors coupled with few- or multimode optical fibers and for detecting single photons coming from free space. Additionally, the negligibly small PS of the arced fractal SNSPDs/SNAPs would eliminate the security loophole, due to polarization-dependent mismatch of the detection efficiency, in the quantum-key distribution systems [28]. We believe that this work paves the way for polarization-insensitive single-photon detection with high detection efficiency and high timing resolution.

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AUTHOR CONTRIBUTIONS

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.

COMPETING INTERESTS

The authors declare no conflicts of interest.

- F. Marsili, V. B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vayshenker, B. Baek, M. D. Shaw, R. P. Mirin, and S. W. Nam, Nat. Photonics 7, 210 (2013).
- [2] I. E. Zadeh, J. W. N. Los, R. B. M. Gourgues, V. Steinmetz, G. Bulgarini, S. M. Dobrovolskiy, V. Zwiller, and S. N. Dorenbos, APL Photonics 2, 111301 (2017).
- [3] W. Zhang, L. You, H. Li, J. Huang, C. Lv, L. Zhang, X. Liu, J. Wu, Z. Wang, and X. Xie, Sci. China: Phys., Mech. Astron. 60, 120314 (2017).
- [4] D. V. Reddy, R. R. Nerem, A. E. Lita, S. W. Nam, R. P. Mirin, and V. B. Verma, *CLEO: QELS_Fundamental Sci*ence (Optical Society of America, 2019), paper FF1A-3.
- [5] D. V. Reddy, R. R. Nerem, S. W. Nam, R. P. Mirin, and V. B. Verma, Optica 7, 1649 (2020).
- [6] J. Chang, J. W. N. Los, J. O. Tenorio-Pearl, N. Noordzij, R. Gourgues, A. Guardiani, J. R. Zichi, S. F. Pereira, H. P. Urbach, V. Zwiller, S. N. Dorenbos, and I. E. Zadeh, arXiv: 2011.08941 (2020).
- [7] P. Hu, H. Li, L. You, H. Wang, Y. Xiao, J. Huang, X. Yang, W. Zhang, Z. Wang, and X. Xie, Opt. Express 28, 36884 (2020).
- [8] Y. Hochberg, I. Charaev, S.-W. Nam, V. Verma, M. Colangelo, and K. K. Berggren, Phys. Rev. Lett. 123, 151802 (2019).
- [9] Q. Zhao, T. Jia, M. Gu, C. Wan, L. Zhang, W. Xu, L. Kang, J. Chen, and P. Wu, Opt. Lett. **39**, 1869 (2014).
- [10] J. Münzberg, A. Vetter, F. Beutel, W. Hartmann, S. Ferrari, W. H. Pernice, and C. Rockstuhl, Optica 5, 658 (2018).
- [11] X. Tao, S. Chen, Y. Chen, L. Wang, X. Li, X. Tu, X. Jia, Q. Zhao, L. Zhang, L. Kang, and P. Wu, Supercond. Sci. Technol. **32**, 064002 (2019).
- [12] W. Zhang, J. Huang, C. Zhang, L. You, C. Lv, L. Zhang, H. Li, Z. Wang, and X. Xie, IEEE Trans. Appl. Supercond. 29, 1 (2019).
- [13] 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, Nat. Photonics **14**, 250 (2020).

- [14] I. Esmaeil Zadeh, J. W. N. Los, R. B. M. Gourgues, J. Chang, A. W. Elshaari, J. R. Zichi, Y. J. van Staaden, J. P. E. Swens, N. Kalhor, A. Guardiani, Y. Meng, K. Zou, S. Dobrovolskiy, A. W. Fognini, D. R. Schaart, D. Dalacu, P. J. Poole, M. E. Reimer, X. Hu, S. F. Pereira, V. Zwiller, and S. N. Dorenbos, ACS Photonics 7, 1780 (2020).
- [15] F. Marsili, F. Bellei, F. Najafi, A. E. Dane, E. A. Dauler, R. J. Molnar, and K. K. Berggren, Nano Lett. **12**, 4799 (2012).
- [16] V. B. Verma, A. E. Lita, B. A. Korzh, E. Wollman, M. Shaw, R. P. Mirin, and S.-W. Nam, *Advanced Pho*ton Counting Techniques XIII (International Society for Optics and Photonics 2019), paper 109780N.
- [17] Q. Chen, R. Ge, L. Zhang, F. Li, B. Zhang, Y. Dai, Y. Fei, X. Wang, X. Jia, Q. Zhao, X. Tu, L. Kang, J. Chen, and P. Wu, Mid-infrared single photon detector with superconductor Mo_{0.8}Si_{0.2} nanowire, arXiv:2011.06699 (2020).
- [18] X. Zhang, Q. Wang, and A. Schilling, AIP Adv. 6, 115104 (2016).
- [19] G. N. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, Appl. Phys. Lett. **79**, 705 (2001).
- [20] R. H. Hadfield, Nat. Photonics **3**, 696 (2009).
- [21] G. G. Taylor, D. Morozov, N. R. Gemmell, K. Erotokritou, S. Miki, H. Terai, and R. H. Hadfield, Opt. Express 27, 38147 (2019).
- [22] N. R. Gemmell, A. McCarthy, B. Liu, M. G. Tanner, S. D. Dorenbos, V. Zwiller, M. S. Patterson, G. S. Buller, B. C. Wilson, and R. H. Hadfield, Opt. Express **21**, 5005 (2013).
- [23] H.-L. Yin, T.-Y. Chen, Z.-W. Yu, H. Liu, L.-X. You, Y.-H. Zhou, S.-J. Chen, Y. Mao, M.-Q. Huang, W.-J. Zhang, H. Chen, M.-J. Li, D. Nolan, F. Zhou, X. Jiang, Z. Wang, Q. Zhang, X.-B. Wang, and J.-W. Pan, Phys.

Rev. Lett. 117, 190501 (2016).

- [24] H. Wang, J. Qin, X. Ding, M.-C. Chen, S. Chen, X. You, Y.-M. He, X. Jiang, L. You, Z. Wang, C. Schneider, J. J. Renema, S. Höfling, C.-Y. Lu, and J.-W. Pan, Phys. Rev. Lett. **123**, 250503 (2019).
- [25] 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, Science (2020), (in press).
- [26] K. Zou, Y. Meng, Z. Wang, and X. Hu, Photonics Res. 8, 601 (2020).
- [27] K. Zou, Y. Meng, L. Xu, N. Hu, Z. Wang, and X. Hu, Phys. Rev. Appl. 14, 044029 (2020).
- [28] K. Wei, W. Zhang, Y.-L. Tang, L. You, and F. Xu, Phys. Rev. A 100, 022325 (2019).
- [29] Y. Meng, K. Zou, N. Hu, X. Lan, L. Xu, J. Zichi, S. Steinhauer, V. Zwiller, and X. Hu, Opt. Lett. 45, 471 (2020).
- [30] S. N. Dorenbos, E. M. Reiger, N. Akopian, U. Perinetti, V. Zwiller, T. Zijlstra, and T. M. Klapwijk, Appl. Phys. Lett. 93, 161102 (2008).
- [31] 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, Supercond. Sci. Tech. **30**, 074004 (2017).
- [32] V. B. Verma, F. Marsili, S. Harrington, A. E. Lita, R. P. Mirin, and S. W. Nam, Appl. Phys. Lett. **101**, 251114 (2012).
- [33] R. Xu, F. Zheng, D. Qin, X. Yan, G. Zhu, L. Kang, L. Zhang, X. Jia, X. Tu, B. Jin, W. Xu, J. Chen, and P. Wu, J. Light . Technol. **35**, 4707 (2017).
- [34] A. Mukhtarova, L. Redaelli, D. Hazra, H. Machhadani, S. Lequien, M. Hofheinz, J.-L. Thomassin, F. Gustavo,

J. Zichi, V. Zwiller, E. Monroy, and J.-M. Gérard, Opt. Express **26**, 17697 (2018).

- [35] V. B. Verma, B. Korzh, F. Bussières, R. D. Horansky, S. D. Dyer, A. E. Lita, F. Marsili, M. D. Shaw, H. Zbinden, R. P. Mirin, and S. W. Nam, Opt. Express 23, 33792 (2015).
- [36] C. Gu, Y. Cheng, X. Zhu, and X. Hu, Fractal-inspired, polarization-insensitive superconducting nanowire singlephoton detectors, *Novel Optical Materials and Applications* (Optical Society of America, 2015), paper JM3A.10.
- [37] X. Chi, K. Zou, C. Gu, J. Zichi, Y. Cheng, N. Hu, X. Lan, S. Chen, Z. Lin, V. Zwiller, and X. Hu, Opt. Lett. 43, 5017 (2018).
- [38] We note that some researchers define PS as $(SDE_{max} SDE_{min})/(SDE_{max} + SDE_{min})$, for example, in Refs. 30 and 34, which can be equivalently used for characterizing the polarization dependence of the detection efficiency.
- [39] J. R. Clem and K. K. Berggren, Phys. Rev. B 84, 174510 (2011).
- [40] H. T. Su, Y. Wang, F. Huang, and M. J. Lancaster, J. Supercond. Nov. Magn. 21, 7 (2008).
- [41] A. J. Miller, A. E. Lita, B. Calkins, I. Vayshenker, S. M. Gruber, and S. W. Nam, Opt. Express 19, 9102 (2011).
- [42] S. Miki, M. Yabuno, T. Yamashita, and H. Terai, Opt. Express 25, 6796 (2017).
- [43] S. Chen, L. You, W. Zhang, X. Yang, H. Li, L. Zhang, Z. Wang, and X. Xie, Opt. Express 23, 10786 (2015).
- [44] F. Marsili, F. Najafi, E. Dauler, R. J. Molnar, and K. K. Berggren, Appl. Phys. Lett. 100, 112601 (2012).

Supplementary Information: Fractal superconducting nanowires detect infrared single photons with 91% polarization-independent system efficiency and 19 ps timing resolution

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I. DISTRIBUTION OF SUPERCURRENT DENSITY IN THE MEANDERING, STANDARD FRACTAL, AND ARCED FRACTAL SNSPDS

Figure S1 presents the schematic drawings and the simulated distribution of the supercurrent density of meandering, standard fractal, and arced fractal SNSPDs, with fill factors of 0.3, 0.29, and 0.31, respectively. The fill factor of the meandering SNSPD is defined as the ratio of the width of the nanowire over the pitch; the fill factor of the fractal SNSPDs is defined as the ratio of the area covered by the nanowire over the total photosensitive area of each SNSPD. In Fig. S1 (a), (b), and (c), the dashed boxes show the photosensitive areas. The width of the nanowire is 40 nm.

The supercurrent density, J, satisfies the current-continuity equation, $\nabla \cdot J = 0$, and London equation, $\nabla \times J = 0$, in which the effect of the magnetic field is neglected [1]. The potential field, u, defined as $J = \nabla u$, satisfies Laplace equation, $\nabla \cdot \nabla u = 0$. As shown in Fig. S1 (d), (e), (f), (g), and (h), we define boundaries A-B as the inflow boundaries, where u satisfies the boundary condition, $\nabla u = J_{\rm b}$, where $J_{\rm b}$ is the density of the bias current at A-B boundaries, and define boundaries C-D as the outflow boundaries, where u satisfies the boundary condition, u = 0. For other boundaries, u satisfies the boundary condition, $\nabla u = 0$, where there is no inward or outward current flow. We solve uand J by using the commercial software Comsol Multiphysics. The simulated distribution of the supercurrent density at the proximity of the turns are presented in Fig. 1S (d), (e), (f), (g), and (h). We note that the supercurrent density in (d) is normalized to its maximum, which appears at location indicated by the arrows; the supercurrent density in (e) and (f) is normalized to their maximum, which appears at location indicated by the arrows; and the supercurrent density in (g) and (h) is normalized to their maximum, which appears at location indicated by the arrows; and the supercurrent density in (g) and (h) is normalized to their maximum, which appears at location indicated by the arrows; and the supercurrent density in (g) and (h) is normalized to their maximum, which appears at location indicated by the arrows; and the supercurrent density in (g) and (h) is normalized to their maximum, which appears at location indicated by the arrows; and the supercurrent density in (g) and (h) is normalized to their maximum, which appears at location indicated by the arrows.

Figure S1 (i), (j), and (k) present the supercurrent density across the nanowires at the locations 1, 2, 3, 4, 5, and 6. In the photosensitive region of the meandering SNSPD, the normalized supercurrent density across the nanowire is constantly 0.81, as shown in Fig. S1 (i). In the fractal SNSPDs, the photosensitive regions include a plethora of turns, where the distribution of the supercurrent density across the nanowire is nonuniform. In Fig. S1 (j), 2 and 4 are the representative locations where the distributions are the most nonuniform, whereas 3 is the representative location where the distributions at 2 and 4 differs sightly. Similarly, in Fig. S1 (k), 5 is the representative location where the distribution is the most uniform, whereas 6 is the representative location where the distributions are the most nonuniform; for other locations in the arced fractal SNSPD, the distributions are in between. Compared with the standard fractal SNSPD, the topology of the arced fractal SNSPD enhances the supercurrent density, which can be seen by comparing Fig. S1 (j) and (k).



Fig. S1. Schematic drawings and simulated distributions of the supercurrent densities of meandering, standard fractal, and arced fractal superconducting nanowire single-photon detectors (SNSPDs). (a), (b), and (c) present the layouts of the meandering, standard fractal, and arced fractal SNSPDs, respectively. Their fill factors are 0.3, 0.29, and 0.31. (d), (e), (f), (g), and (h) present the simulated distributions of the supercurrent densities in proximity of the turns. (i), (j), and (k) present the distribution of supercurrent density across the nanowires at the locations 1, 2, 3, 4, 5, and 6.

II. NANOFABRICATION PROCESS FOR MAKING THE DETECTORS

Figure S2 presents the schematic drawing of the nanofabrication process for making the detectors presented in this paper. On a 4-inch, 300-µm-thick, double-polished silicon wafer [Fig. S2 (a)], we deposited 6 pairs of SiO_2/Ta_2O_5 alternating layers and a half of SiO_2 micro-cavity by ion-beam deposition (IBD, Optofab 3000) [Fig. S2 (b)]. The targeted thicknesses for the SiO_2 , Ta_2O_5 , and the half micro-cavity were 264 nm, 180 nm, and 260 nm, respectively. Then, we sputtered a 9-nm thick NbTiN film by a reactive co-sputtering process at room temperature [2] [Fig. S2 (c)]. Magnetron sources with titanium (Ti) and niobium (Nb) 3-inch targets were operated in an Ar/N_2 plasma, under the radio frequency (RF) power of 240 W for the Ti target and 120 W for the Nb target. The thickness of the deposited film was *in-situ* monitored by a quartz crystal monitor. We diced the wafer into dies with a dimension of 2 cm by 2 cm; and the following processes were performed on one die, or, more, if needed.

We made the metallic contact pads by a lift-off process [Fig. S2 (d)]. We patterned the contact pads by using a negative-tone photoresist, NR9-3000PY, and optical lithography. A 10-nm thick titanium and 100-nm thick gold were subsequently sputtered. Then, we lifted off the unwanted metal by immersing the chip in hot N-Methyl pyrrolidone (NMP) at 95 °C for 30 minutes.

We patterned the nanowires by scanning-electron-beam lithography and reactive-ion etching [Fig. S2 (e)]. Highresolution, negative-tone electron-beam resist, hydrogen silsesquioxane (HSQ), was used. We spun a layer of 55-nmthick HSQ on top of the chip and exposed the HSQ resist using Vistec scanning-electron-beam-lithography facility with an accelerating voltage of 100 kV and 0.25 nA beam current. We developed the chip in 25% Tetramethylammonium Hydroxide (TMAH) at ambient temperature for 4 minutes, followed by rinsing the chip in de-ionized (DI) water. We transferred the pattern from the HSQ layer to the underneath NbTiN layer by CF_4 (15 sccm) reactive-ion etching for 40 second, at the condition of 100 W RF power and 2.7 Pa chamber pressure.

The top half of the micro-cavity and distributed Bragg reflector were made by another lift-off process. First, we patterned the top reflector by using NR9-3000PY photoresist [Fig. S2 (f)]. Using IBD, we deposited another half SiO₂ micro-cavity, targeted at 269 nm, to sandwich the NbTiN nanowires and 3 pairs of Ta₂O₅/SiO₂ bi-layers, with the targeted thicknesses of 180 nm/264 nm, respectively [Fig. S2 (g)]. Then, we did lift-off by immersing the chip in hot NMP at 95 °C for 30 minutes [Fig. S2 (h)].

After fabricating the whole stack, we etched the chip into the keyhole shape for self-aligned packaging [3]. We used a positive-tone photoresist, AZ 4620, and spun it at 1500 rpm for 60 second to obtain a 10-µm thick layer. We baked the chip on a hot plate at 110 °C for 3 min, then exposed the chip by a mask aligner (Suss MJB4) for 40 second, and developed it in diluted AZ400K developer (AZ400K : DI water=1:4) for 3 min. We used inductively-coupled plasma etching (SENTECH instruments S500) to transfer the pattern to the stack. The etching gases were CHF₃ and argon, the RF power at the sample substrate was 40 W, and the RF power of the inductive coil was 400 W. To etch the silicon substrate, we used Bosch process (Oxford Plasmalab System 100). The passivation gas was C_4F_8 , and the etching gas was SF_6 . The gas flow was 100 sccm and the RF power at the sample substrate was 0, and the RF power of the inductive coil was 700 W. After etching the silicon substrate, we removed the residual photoresist by immersing the chip in hot NMP at 95 °C for 5 minutes. The resulting chip was as shown in the inset of Fig. 1 (h) as well as schematically in Fig. S1 (i).



Fig. S2. Schematic presentation of the nanofabrication process of the keyhole-shaped chips containing the arced fractal superconducting nanowire avalanche photodetectors. (a) The process starts from a 4-inch silicon wafer. (b) The bottom distributed Bragg layers are deposited by ion-beam deposition. (c) A layer of 9-nm-thick NbTiN film is deposited by reactive magnetic sputtering. (d) The titanium-gold electrical contact pads are made by optical lithography, sputtering, and liftoff processes. (e) Nanowires are patterned by scanning-electron-beam lithography using negative-tone resist, hydrogen silsesquioxane (HSQ), followed by reactive-ion etching. (f) The top distributed Bragg structure is patterned by aligned optical lithography. (g) The top distributed Bragg layers is deposited by ion-beam deposition. (h) The top distributed Bragg structure is made of the liftoff process. (i) The keyhole-shaped structure is made by Bosch process to etch through the silicon substrate and the deposited distributed Bragg layers.

III. MEASUREMENT OF SYSTEM DETECTION EFFICIENCY AND ITS POLARIZATION DEPENDENCE

Figure S3 presents the schematic drawing of the experimental setup for measuring the system detection efficiency (SDE) and its polarization dependence of the AF-SNAP. Fig. S3 (a) presents experimental setup for measuring SDE from 1500 nm to 1625 nm; Fig. S3 (b) presents experimental setup for measuring SDE from 1630 nm to 1680 nm.



Fig. S3. Schematic drawing of the experimental setup for measuring the system detection efficiency (SDE) and its polarization dependence of the AF-SNAP. (a) Experimental setup for measuring SDE from 1500 nm to 1625 nm. (b) Experimental setup for measuring SDE from 1630 nm to 1680 nm. CW: continuous-wave; GM: Gifford-McMahon; SMF: single-mode fiber; HIF: high-index fiber; MFA: mode-field adapter.

IV. DARK-COUNT RATE

Figure S4 present the measured dark-count rate (DCR). Fig. S4 (a) plots DCR as a function of the bias current; and Fig. S4 (b) plots SDE vs. DCR. Similar to those in Fig. 2, the grayed region in Fig. S4 (b) indicates that the detector outputs false counts, in addition to the dark count, and therefore, the measured SDE in the grayed region is not realistic.



Fig. S4. Measured dark-count rate (DCR). (a) DCR as a function of the bias current. (b) SDE vs. DCR.

V. OUTPUT PULSES IN THE AVALANCHE AND UNSTABLE REGIMES

Figure S5 presents the temporal traces of the output pulses in the avalanche (a) and unstable (b and c) regimes, measured by a real-time oscilloscope with the bandwidth of 4 GHz and the sampling rate of 20 Gs/s. The electrical pulses were amplified by a cryogenic amplifier with the bandwidth of 1.5 GHz mounted at the 40 K stage of the cryocooler. Fig. S5 (a) shows the output pulse at the bias current of 18.75 μ A, where the detector was operated in the avalanche regime [4]. The exponential fitting to the recovery edge shows a 1/e time constant of 8.6 ns. Fig. S5 (b) presents the output traces at the bias current of 11.67 μ A, where the detector was operated in the unstable regime. Fig. S5 (c) shows a zoom-in view of the pulses in the dashed box in (b). In the unstable regime, a portion of the bias current leaked into the load impedance [4].



Fig. S5. Temporal traces of the output pulses of the arced fractal superconducting nanowire avalanche photodetector. (a) Temporal trace of an output pulse at the bias current of 18.75 μ A, where the device is operated in the avalanche regime. An exponential fit (red line) to the recovery edge shows a 1/e time constant of 8.6 ns. (b) Temporal trace of the output pulses at the bias current of 11.67 μ A, where the device is operated in unstable regime. (c) A zoom-in view of the temporal trace showing in the dashed box in (b).

VI. MEASUREMENT OF THE AUTO-CORRELATION FUNCTIONS OF THE OUTPUTS

At the high bias regime, $I_{\rm b} > 19.33 \ \mu$ A, the AF-SNAP outputs additional false counts other than dark counts. The similar observations have been reported on the meandering SNAPs [5] and also SNSPDs [6]. To characterize the statistics of the outputs, we measured their auto-correlation functions [5], $G(\tau_{\rm e}) = \langle CR_1(t) \cdot CR_2(t+\tau_{\rm e}) \rangle / \langle CR_1(t) \rangle$. $\langle CR_2(t+\tau_e) \rangle$, where CR_1 is the count rate of the Start channel, CR_2 is the count rate of the Stop channel, and τ_e is the electrical time delay between the Start and Stop channels. The experimental setup is schematically presented in Fig. S6 (a). An continuous-wave (CW) laser diode, after attenuated, was used to illuminate the AF-SNAP. The output was split into two channels with a microwave power divider. In one channel, the pulses were delayed electrically by τ_e . The pulse pairs in the dashed box shown in Fig. S6 (a) were counted by the TAC. Fig. S6 (b), (c), (d), and (e) present the measured $G(\tau_e)$ at the bias currents of 21.17 μ A, 20 μ A, 16.25 μ A, and 15 μ A, respectively. $G(\tau_e)$ shows an abrupt increase at $\tau_e = 83$ ns, consistent with the measurement of the SDE as a function of the count rate shown in Fig. 3 (b). In the high-bias regime, as shown in Fig. S6 (b), $G(83 \text{ ns} < \tau_{e} < 3200 \text{ ns})$ is larger than 1; when the bias current decreases, at the bias current of 20 μ A, as shown in Fig. S6 (c), $G(\tau_e > 172 \text{ ns})$ approaches 1 except for the overshoot at 83 ns $< \tau_{\rm e} < 172$ ns; in the avalanche regime, as shown in Fig. S6 (d), $G(\tau_{\rm e})$ is almost constantly 1 for $\tau_e > 86$ ns; but when the bias current further decreases, close to the unstable regime, the overshoot at 75 ns $< \tau_{\rm e} < 152$ ns appears again. Finally, a zoom-in view of the $G(\tau_{\rm e})$ for the electrical time delay, $\tau_{\rm e}$, ranging from -2.5 ns to 30 ns, illustrating the recovery time of the detector.



Fig. S6. Measured auto-correlation functions, $G(\tau_e)$, of the outputs from the arced fractal superconducting nanowire avalanche photodetector. (a) Experimental setup. (b), (c), (d), and (e) present the measured $G(\tau_e)$ at the bias current of 21.17 µA, 20 µA, 16.25 µA, and 15 µA, respectively. (f) present a zoom-in view of $G(\tau_e)$, at the bias current of 21.17 µA and with τ_e ranging from -2.5 ns to 30 ns. CW: continuous-wave; TAC: time-to-amplitude converter.

VII. MEASUREMENT OF TIMING JITTER

We measured timing jitter of the AF-SNAP at the central wavelength of 1560 nm. Fig. S7 (a) shows the experimental setup. A mode-locked, femtosecond fiber laser was used as the light source. The pulse width was 67 fs, and the repetition rate was 82 MHz. A 50:50 fiber coupler split the light into two channels, with one, after attenuation, going to a fast photodetector with a 3-dB bandwidth of 40 GHz, and another, after attenuation, to the AF-SNAP working at 2.05 K. We measured the histogram of the time delays between the outputs from the photodetector and the AF-SNAP, at different bias currents, using the oscilloscope, and fitted each histogram with a Gaussian function. The full width at half-maxima (FWHM) of each Gaussian fitting is defined as timing jitter. Fig. S7 (b) presents the time-delay histograms and fittings of the AF-SNAP at various bias currents. The lowest timing jitter was measured to be 19 ps.



Fig. S7. **Experimental setup for measuring timing jitter and the results.** (a) Experimental setup for measuring timing jitter. (b) Measured histograms of the time delays at various bias currents and the Gaussian fittings. PD: photodetector; GM: Gifford-McMahon; SMF: single-mode fiber; HIF: high-index fiber; MFA: mode-field adapter.

VIII. COMPARISON OF PERFORMANCES OF SNSPDS WITH LOW POLARIZATION SENSITIVITY

Table S1 presents the comparison of performances of the AF-SNAP presented in this paper and the SNSPDs/SNAPs with low polarization sensitivity reported in literature.

Reference	System	Polarization	Timing jitter	Material	Working temperature
	detection	sensitivity			
	efficiency				
This work	91%	1.00	19 ps	Polycrystalline NbTiN	$2.05~\mathrm{K}$
Meng et al., 2020 [7]	60%	1.05	45 ps	Polycrystalline NbTiN	$2.7~\mathrm{K}$
Chi et al., 2018 [8]	67%(DE)	1.1		Polycrystalline NbTiN	2.6 K
Dorenbos et al., 2008 [9]	0.6%	1.04		Polycrystalline NbTiN	4.2 K
Mukhtarova <i>et al.</i> , 2018 [10]	28%	1.2		Polycrystalline NbN	$0.77~\mathrm{K}$
Huang et al., 2017 [11]	52.5%	1.04		Polycrystalline NbN	$2.3~\mathrm{K}$
Xu et al., 2017 [12]	61%(DE)	1.09		Polycrystalline NbN	$2.1~\mathrm{K}$
Reddy et al., 2019 [13]	96%	1.02		Amorphous MoSi	$0.7~{ m K}$
Verma <i>et al.</i> , 2015 [14]	87.1%	1.03	76 ps	Amorphous MoSi	0.7 K
Verma <i>et al.</i> , 2012 [15]	87.7%	1.02	$465 \mathrm{ps}$	Amorphous WSi	$0.15~\mathrm{K}$

TABLE S1. Comparison of Performances of SNSPDs with Low Polarization Sensitivity

DE: detection efficiency, excluding the coupling efficiency, $\eta_{\rm c}$

- [1] J. R. Clem and K. K. Berggren, Phys. Rev. B 84, 174510 (2011).
- [2] J. Zichi, J. Chang, S. Steinhauer, K. von Fieandt, J. W. N. Los, G. Visser, N. Kalhor, T. Lettner, A. W. Elshaari, I. E. Zadeh, and V. Zwiller, Opt. Express 27, 26579 (2019).
- [3] A. J. Miller, A. E. Lita, B. Calkins, I. Vayshenker, S. M. Gruber, and S. W. Nam, Opt. Express 19, 9102 (2011).
- [4] F. Marsili, F. Najafi, E. Dauler, R. J. Molnar, and K. K. Berggren, Appl. Phys. Lett. 100, 112601 (2012).
- [5] S. Miki, M. Yabuno, T. Yamashita, and H. Terai, Opt. Express 25, 6796 (2017).
- [6] S. Chen, L. You, W. Zhang, X. Yang, H. Li, L. Zhang, Z. Wang, and X. Xie, Opt. Express 23, 10786 (2015).
- [7] Y. Meng, K. Zou, N. Hu, X. Lan, L. Xu, J. Zichi, S. Steinhauer, V. Zwiller, and X. Hu, Opt. Lett. 45, 471 (2020).
- [8] X. Chi, K. Zou, C. Gu, J. Zichi, Y. Cheng, N. Hu, X. Lan, S. Chen, Z. Lin, V. Zwiller, and X. Hu, Opt. Lett. 43, 5017 (2018).
- [9] S. N. Dorenbos, E. M. Reiger, N. Akopian, U. Perinetti, V. Zwiller, T. Zijlstra, and T. M. Klapwijk, Appl. Phys. Lett. 93, 161102 (2008).
- [10] A. Mukhtarova, L. Redaelli, D. Hazra, H. Machhadani, S. Lequien, M. Hofheinz, J.-L. Thomassin, F. Gustavo, J. Zichi, V. Zwiller, E. Monroy, and J.-M. Gérard, Opt. Express 26, 17697 (2018).
- [11] 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, Supercond. Sci. Tech. 30, 074004 (2017).
- [12] R. Xu, F. Zheng, D. Qin, X. Yan, G. Zhu, L. Kang, L. Zhang, X. Jia, X. Tu, B. Jin, W. Xu, J. Chen, and P. Wu, J. Light. Technol. 35, 4707 (2017).
- [13] D. V. Reddy, R. R. Nerem, A. E. Lita, S. W. Nam, R. P. Mirin, and V. B. Verma, CLEO: QELS_Fundamental Science (Optical Society of America, 2019), paper FF1A-3.
- [14] V. B. Verma, B. Korzh, F. Bussières, R. D. Horansky, S. D. Dyer, A. E. Lita, F. Marsili, M. D. Shaw, H. Zbinden, R. P. Mirin, and S. W. Nam, Opt. Express 23, 33792 (2015).
- [15] V. B. Verma, F. Marsili, S. Harrington, A. E. Lita, R. P. Mirin, and S. W. Nam, Appl. Phys. Lett. 101, 251114 (2012).