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ABSTRACT

Superconducting detectors have become essential devices for high-performance single-photon counting over a wide wavelength range with excellent time resolution. Detector fabrication typically relies on resist-based lithography processes, which can limit possibilities for device integration, e.g., on unconventional substrates. Here, we demonstrate a resist-free fabrication route for realizing superconducting nanowire single-photon detectors based on focused electron beam-induced deposition. Utilizing direct writing of a Pt–C mask, we achieved nanowire meanders with linewidths below 100 nm, operated them as superconducting devices for the detection of visible and near-infrared photons, and showed detector integration on side-polished optical fibers. Being compatible with device fabrication on curved irregular surfaces, our approach could enable superconducting detector integration in complex configurations.

Superconducting devices are crucial elements for diverse applications ranging from microwave quantum circuits to highly sensitive quantum detectors.[1] The emergence of superconducting nanowire single-photon detectors[2] (SNSPDs) has significantly impacted several research fields in quantum optics and beyond, where the detection of light with a high efficiency and signal-to-noise ratio is central due to weak optical signals. During the last two decades, SNSPDs were developed from research prototypes to commercial products, providing excellent performance metrics including picosecond time resolution, low intrinsic dark count rates (mHz range and below), and near-unity detection efficiency from visible to near-infrared wavelengths.[3,4] Significant advances have also been achieved in up-scaling this technology in terms of active area and number of pixels[5,6] and in integrating these detectors with waveguide technology and photonic integrated circuits.[7]

For the realization of nanoscale superconducting devices applied in modern quantum technologies, resist-based lithography processes are most commonly employed. While these processes are well-suited for conventional planar substrates, they can be linked with limitations for device fabrication on surfaces that are irregular, are curved, or exhibit large three-dimensional topography. Nanofabrication approaches relying on focused charged particle beams can circumvent such limitations, and previous demonstrations have shown that they are suitable for the realization of superconducting devices, including nanowires,[8–10] Josephson junctions,[11,12] resonators,[13] and superconducting quantum interference devices,[12,14] as well as nanowires, nanohelices, and nanotubes via direct focused ion beam-induced deposition of superconducting materials.[15] On the other hand, focused charged particle beams have been successfully employed for the fabrication of nanophotonic structures, e.g., photonic crystal cavities,[16] nanobeam cavities,[17] and direct microstructuring of optical fibers.[18,19] In this Letter, we demonstrate NbTiN nanowire structures fabricated via focused electron beam-induced deposition (FEBID) of a Pt–C mask, followed by reactive ion etching. We achieved superconducting devices on silicon substrates and on side-polished optical fibers, showing single-photon detector operation at visible and near-infrared wavelengths.

We fabricated superconducting single-photon detectors on silicon substrates covered with thermal SiO_2 via the nanofabrication procedure shown in Fig. 1(a). First, NbTiN thin films with a film

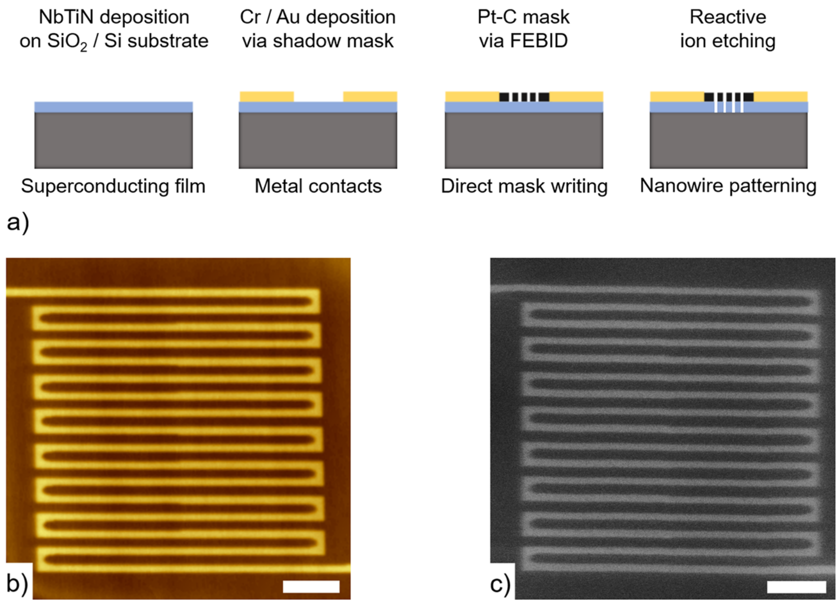

FIG. 1. NbTiN-based superconducting single-photon detectors via focused electron beam-induced deposition (FEBID) and reactive ion etching. (a) Process flow of fabrication steps. (b) Atomic force microscopy characterization after FEBID of the Pt–C mask (scale bar 1 μm; Pt–C height around 9 nm). (c) Scanning electron microscopy image of the superconducting nanowire detector after reactive ion etching (scale bar 1 μm).

thickness of 9 nm were deposited using reactive magnetron co-sputtering parameters described elsewhere.[20] Metal contact pads were deposited with a shadow mask via electron beam evaporation (Cr 5 nm/Au 50 nm). Next, an etch mask for the meandering nanowire was directly written by FEBID of Pt–C using an organometallic precursor (typical writing time of a few minutes). A primary electron energy of 10 keV, a current of 0.54 nA, and dwell times in the range of 1.5–2.0 ms were used. The detector structure was connected to the metal pads using focused ion beam-induced deposition (FIBID; same precursor; 30 keV ion energy) due to the higher deposition rates than FEBID.

The Pt–C mask was characterized by atomic force microscopy (AFM), with a representative example shown in Fig. 1(b) (Pt–C mask height around 9 nm). As a last step in detector fabrication, reactive ion etching with fluorine-based chemistry was employed for nanowire meander pattern transfer of the Pt–C mask to the superconducting NbTiN film. A scanning electron micrograph of a typical device is shown in Fig. 1(c), where the nanowire width was around 100 nm for a meander of 5×5 μm^2. The etch mask deposited by FEBID was found to be compatible with the $CF_4/O_2/Ar$ etching step commonly used for patterning NbTiN nanowires via resist-based approaches. The edge roughness of the resulting nanowire devices appeared comparable to conventional electron beam lithography processes; however, the imaging results were not quantified due to potential ambiguities resulting from the remaining Pt–C mask.

The superconducting nanowire structures were tested in a Gifford–McMahon cryocooler operating at around 2.5 K. The sample chips were mounted on a printed circuit board with RF connectors and characterized during flood illumination using commercial readout electronics relying on a room temperature amplification stage. The count rate curves for the three cases of no illumination, 650 nm illumination, and 850 nm illumination are presented in Fig. 2(a). Note that in the flood illumination case, the remaining Pt–C mask will have an impact on the optical absorption in the SNSPD. Considering the worst-case assumption of a Pt film with 9 nm thickness, we would expect an optical transmittance of around

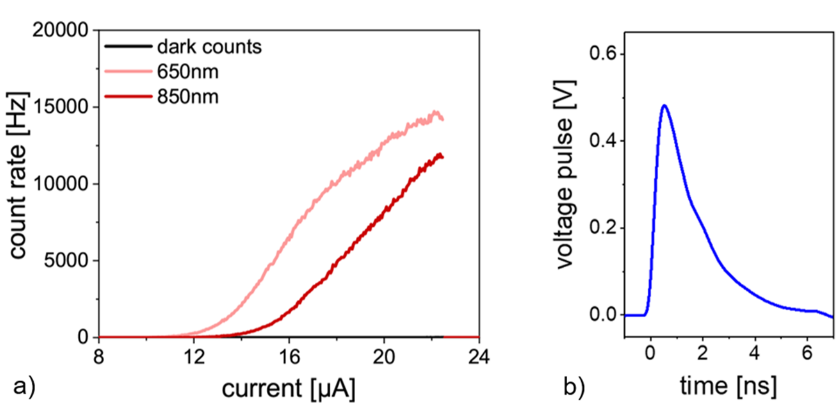

FIG. 2. Characterization of the superconducting nanowire single-photon detector (SNSPD) fabricated via the focused electron beam-induced deposition route. (a) SNSPD count rates for the cases of no illumination (dark counts), 650 nm photons, and 850 nm photons measured under flood illumination. (b) Representative voltage pulse of SNSPD detection counts (averaged over more than 2000 trigger events).

30%.[21] In the presented experimental configuration, the remaining mask had a significant C content, and the thickness was reduced by the $CF_4/O_2/Ar$ etch; hence, we expect optical transmittance significantly exceeding 30%, which would also be acceptable for some applications employing the devices in top illumination. The device shown here had a critical current of 22.5 μA and approached saturating internal quantum efficiency for visible and near-infrared wavelengths. As expected, the onset of photon counts was observed at lower bias current values for photons with higher energy. The critical current value was about 30% lower than that of SNSPDs fabricated by electron beam lithography, which is attributed to current crowding in some relatively narrow turns and/or non-obvious edge roughness of the NbTiN nanowire. The dark count rate of the detector device was relatively low, with values around 10 Hz for bias currents close to the critical current. The voltage pulse signal for single-photon detector operation is shown in Fig. 2(b) (averaged over more than 2000 detection events). When fitting the voltage signal to a single-exponential decay, a time constant of 1.5 ns was found, which is consistent with values expected from kinetic inductance-limited reset time of superconducting detectors.[22] Hence, the detector reset dynamics remained widely unaffected by the remaining Pt–C mask. This behavior can be rationalized by considering it as parallel resistance with high electrical sheet resistivity. Moreover, the temperature dependence of the superconducting properties of the nanowire device was characterized to further assess the impact of the Pt–C mask. The critical currents were measured in a different cryostat in the temperature range from 1.8 to 10 K, showing very similar behavior to a previous report on SNSPDs fabricated via conventional lithography processes.[23] Around 4 K, the critical current dropped significantly, with 50% of the critical current reached at 6 K and 1 μA critical current at 9 K (critical temperature of corresponding NbTiN films ~10–10.5 K[20,24]). These results illustrate that the presented fabrication scheme is suitable for achieving devices comparable to conventional SNSPDs when using relatively thick NbTiN films (9 nm).

In additional experiments, we attempted to improve the infrared sensitivity of the SNSPD devices fabricated via our FEBID approach by using a thinner NbTiN film with a thickness of 6 nm. While we were able to achieve superconducting meander structures, self-resetting detector operation was not possible in this case. Further studies will be needed to identify the underlying reason; one potential explanation would be that NbTiN nanowires with lower thickness are significantly influenced by the presence of the Pt layer via the inverse proximity effect,[25,26] which could be tested by using alternative materials as FEBID masks (e.g., C or superconducting W). While we show here superconducting detectors with relatively narrow linewidths around 100 nm (further patterning tests indicated suitability of the process down to around 50 nm linewidth), it is expected that the presented method is also suited for microwire-based detector geometries,[27] where the requirements on the critical dimensions of the patterning are less demanding. In addition to planar substrates, the proposed FEBID-based approach can be advantageous for integration schemes where detector fabrication needs to be performed on top of complex three-dimensional topographies. Such scenarios could be, for instance, occurring for SNSPD integration with micro-electro-mechanical systems (e.g., miniaturized cryocoolers[28] or reconfigurable photonic integrated circuits[29]) or for detector integration on tips for cryogenic scanning probe microscopy (e.g., scanning near-field optical microscopy). Furthermore, as our approach does not require the use of lithography, it could open up new opportunities for SNSPD integration with materials not compatible with chemicals associated with resist-based processing.

Here, we further explored the direct integration of SNSPDs on side-polished optical fibers via the presented FEBID fabrication route. Detector integration with optical fibers is interesting, e.g., for distributed temperature sensing[30,31] and for time domain reflectometry employed in testing and performance evaluation of fiber networks.[32,33] Superconducting NbTiN thin films with a thickness of 10 nm were directly deposited on side-polished optical fibers, enabled by our robust room temperature magnetron sputtering process compatible with a large variety of photonic material platforms.[24] Nanowire meander structures were fabricated using FEBID deposition of a Pt–C mask followed by reactive ion etching, analogous to above. To facilitate sample handling and contact fabrication, the fiber was placed in trenches on a silicon substrate obtained via deep etching and fixed on the substrate via adhesive tape [Fig. 3(a)]. An Al thin film patterned via photolithography served as a hard mask as well as used for establishing electrical contacts to the nanowire meander on the fiber, which was achieved via conductive silver glue. The Al pads were connected to a printed circuit board via wire bonding. A representative image of a superconducting nanowire meander on the side-polished fiber is shown in Fig. 3(b). Note that the polished fiber surface exhibited a significant amount of defects, but pre-inspection of the sample allowed for placing the meander structure in a suitable area free of extended irregularities. In the described configuration, we were able to achieve a fiber-integrated superconducting nanowire meander with a critical current of 55 μA. The light sensitivity of the device was confirmed at a constant bias current of 30 μA. Detection events were observed under visible-light flood illumination, whereas no counts were registered when turning off the light source. However, we measured voltage pulse signals [Fig. 3(c)] with comparatively low amplitude and the fiber-integrated superconducting nanowire latched,[34] which we attribute to a too large series resistance[35] introduced by the sub-optimum detector contacting scheme. Future experiments will be required to elaborate low-resistance electrical connections from the nanowire detector to the printed circuit board in the cryostat. Promising approaches include conductive adhesives, ribbon bonding, and tape-automated bonding.

The presented scheme for coupling superconducting detectors to optical fibers is different from those reported in the literature. In addition to standard packaging schemes that rely on aligning the fiber end facet with the superconducting detector and bringing it in close proximity,[36] detectors directly fabricated on fiber end facets via focused ion beam milling[37] and lithography combined with reactive ion etching[38] have been shown. SNSPDs have also been coupled to microfibers, relying on the proximity of their evanescent field and interaction distances up to hundreds of micrometers.[39,40] While the coupling efficiency between side-polished structures and nanowire meanders needs to be evaluated in further tests, we anticipate that our approach could be useful for fiber-based experiments in transmission configuration where the evanescent field needs to be probed at high spatial resolution around the fiber circumference. With the possibility of multi-detector and/or multi-pixel integration,

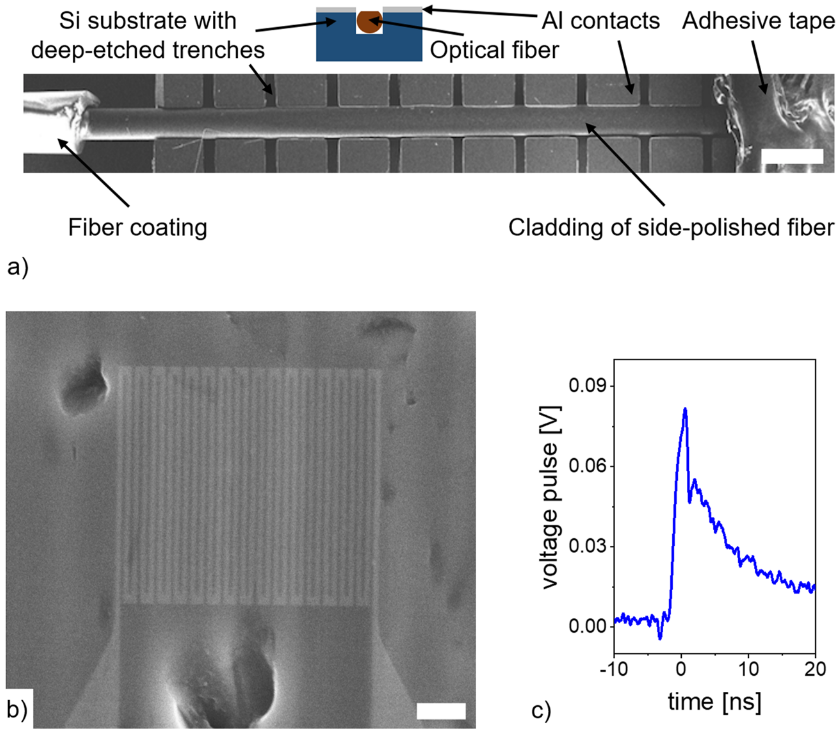

FIG. 3. Superconducting nanowire structures integrated on a side-polished optical fiber. (a) Packaging of optical fiber on a deep-etched silicon substrate and contacting scheme via Al pads (scale bar 250 μm). (b) Scanning electron micrograph of the superconducting nanowire meander (scale bar 1 μm). (c) Voltage pulse of the fiber-integrated nanowire meander during visible-light illumination.

potentially in combination with hybrid approaches,[41] such SNSPDs could, for instance, find applications in fiber-integrated cold atom experiments[42] or for trapped ion qubit readouts[43] in a cryogenic environment.

In summary, we have demonstrated a resist-free fabrication scheme for SNSPDs based on NbTiN thin films. Our approach relies on a focused electron beam for nanofabrication, preventing potential defect generation within the superconducting layer resulting from exposure to ion beams.[44] Moreover, it allows for pre-inspection of the sample before patterning, which is particularly useful for fabrication on non-standard substrates and surfaces with extended defects. Relying on FEBID of a Pt–C mask, we achieved meander structures with a nanowire width of around 100 nm for the detection of visible and near-infrared photons. Our results pave the way for integrating SNSPDs in complex three-dimensional device configurations.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Stephan Steinhauer: Conceptualization (equal); Investigation (equal); Writing – original draft (lead); Writing – review & editing (equal). **Adrian Iovan**: Conceptualization (equal); Investigation (equal); Writing – review & editing (equal). **Samuel Gyger**: Conceptualization (equal); Investigation (equal); Writing – review & editing (equal). **Val Zwiller**: Conceptualization (equal); Funding acquisition (lead); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] R. H. Hadfield and G. Johansson, *Superconducting Devices in Quantum Optics* (Springer International Publishing, 2016).

[2] G. N. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, "Picosecond superconducting single-photon optical detector," Appl. Phys. Lett. **79**, 705–707 (2001).

[3] I. Holzman and Y. Ivry, "Superconducting nanowires for single-photon detection: Progress, challenges, and opportunities," Adv. Quantum Technol. **2**, 1800058 (2019).

[4] I. Esmaeil Zadeh, J. Chang, J. W. N. Los, S. Gyger, A. W. Elshaari, S. Steinhauer, S. N. Dorenbos, and V. Zwiller, "Superconducting nanowire single-photon detectors: A perspective on evolution, state-of-the-art, future developments, and applications," Appl. Phys. Lett. **118**, 190502 (2021).

[5]E. E. Wollman, V. B. Verma, A. E. Lita, W. H. Farr, M. D. Shaw, R. P. Mirin, and S. W. Nam, "Kilopixel array of superconducting nanowire single-photon detectors," Opt. Express **27**, 35279–35289 (2019).
[6]S. Steinhauer, S. Gyger, and V. Zwiller, "Progress on large-scale superconducting nanowire single-photon detectors," Appl. Phys. Lett. **118**, 100501 (2021).
[7]S. Ferrari, C. Schuck, and W. Pernice, "Waveguide-integrated superconducting nanowire single-photon detectors," Nanophotonics **7**, 1725–1758 (2018).
[8]C. Zhang, D. Wang, Z.-H. Liu, Y. Zhang, P. Ma, Q.-R. Feng, Y. Wang, and Z.-Z. Gan, "Fabrication of superconducting nanowires from ultrathin MgB_2 films via focused ion beam milling," AIP Adv. **5**, 027139 (2015).
[9]M. Lyatti, M. A. Wolff, I. Gundareva, M. Kruth, S. Ferrari, R. E. Dunin-Borkowski, and C. Schuck, "Energy-level quantization and single-photon control of phase slips in $YBa_2Cu_3O_{7-x}$ nanowires," Nat. Commun. **11**, 763 (2020).
[10]G. D. Martinez, D. Buckley, I. Charaev, A. Dane, D. E. Dow, and K. K. Berggren, "Superconducting nanowire fabrication on niobium nitride using helium ion irradiation," arXiv:2003.02898 (2020).
[11]E. Y. Cho, Y. W. Zhou, J. Y. Cho, and S. A. Cybart, "Superconducting nano Josephson junctions patterned with a focused helium ion beam," Appl. Phys. Lett. **113**, 022604 (2018).
[12]B. Müller, M. Karrer, F. Limberger, M. Becker, B. Schröppel, C. Burkhardt, R. Kleiner, E. Goldobin, and D. Koelle, "Josephson junctions and squids created by focused helium-ion-beam irradiation of $YBa_2Cu_3O_7$," Phys. Rev. Appl. **11**, 044082 (2019).
[13]O. Kennedy, J. Burnett, J. Fenton, N. Constantino, P. Warburton, J. Morton, and E. Dupont-Ferrier, "Tunable Nb superconducting resonator based on a constriction nano-squid fabricated with a Ne focused ion beam," Phys. Rev. Appl. **11**, 014006 (2019).
[14]E. Y. Cho, H. Li, J. C. LeFebvre, Y. W. Zhou, R. C. Dynes, and S. A. Cybart, "Direct-coupled micro-magnetometer with Y-Ba-Cu-O nano-slit squid fabricated with a focused helium ion beam," Appl. Phys. Lett. **113**, 162602 (2018).
[15]F. I. Allen, "A review of defect engineering, ion implantation, and nanofabrication using the helium ion microscope," Beilstein J. Nanotechnol. **12**, 633–664 (2021).
[16]S. Ahn, S. Kim, and H. Jeon, "Single-defect photonic crystal cavity laser fabricated by a combination of laser holography and focused ion beam lithography," Appl. Phys. Lett. **96**, 131101 (2010).
[17]T. M. Babinec, J. T. Choy, K. J. M. Smith, M. Khan, and M. Lončar, "Design and focused ion beam fabrication of single crystal diamond nanobeam cavities," J. Vac. Sci. Technol. B **29**, 010601 (2011).
[18]K. P. Nayak, F. Le Kien, Y. Kawai, K. Hakuta, K. Nakajima, H. T. Miyazaki, and Y. Sugimoto, "Cavity formation on an optical nanofiber using focused ion beam milling technique," Opt. Express **19**, 14040–14050 (2011).
[19]S. C. Warren-Smith, R. M. André, C. Perrella, J. Dellith, and H. Bartelt, "Direct core structuring of microstructured optical fibers using focused ion beam milling," Opt. Express **24**, 378–387 (2016).
[20]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, "Optimizing the stoichiometry of ultrathin NbTiN films for high-performance superconducting nanowire single-photon detectors," Opt. Express **27**, 26579–26587 (2019).
[21]H. A. Macleod, *Thin-Film Optical Filters* (CRC Press, 2001).
[22]A. J. Kerman, E. A. Dauler, W. E. Keicher, J. K. W. Yang, K. K. Berggren, G. Gol'tsman, and B. Voronov, "Kinetic-inductance-limited reset time of superconducting nanowire photon counters," Appl. Phys. Lett. **88**, 111116 (2006).
[23]R. Gourgues, J. W. N. Los, J. Zichi, J. Chang, N. Kalhor, G. Bulgarini, S. N. Dorenbos, V. Zwiller, and I. E. Zadeh, "Superconducting nanowire single photon detectors operating at temperature from 4 to 7 K," Opt. Express **27**, 24601–24609 (2019).
[24]S. Steinhauer, L. Yang, S. Gyger, T. Lettner, C. Errando-Herranz, K. D. Jöns, M. A. Baghban, K. Gallo, J. Zichi, and V. Zwiller, "NbTiN thin films for superconducting photon detectors on photonic and two-dimensional materials," Appl. Phys. Lett. **116**, 171101 (2020).
[25]D. Katayama, A. Sumiyama, and Y. Oda, "Proximity-induced superconductivity in platinum metals," Phys. Rev. B **68**, 132502 (2003).
[26]C. Ojeda-Aristizabal, M. Ferrier, S. Guéron, and H. Bouchiat, "Tuning the proximity effect in a superconductor-graphene-superconductor junction," Phys. Rev. B **79**, 165436 (2009).
[27]I. Charaev, Y. Morimoto, A. Dane, A. Agarwal, M. Colangelo, and K. K. Berggren, "Large-area microwire MoSi single-photon detectors at 1550 nm wavelength," Appl. Phys. Lett. **116**, 242603 (2020).
[28]H. Cao and H. ter Brake, "Progress in and outlook for cryogenic microcooling," Phys. Rev. Appl. **14**, 044044 (2020).
[29]S. Gyger, J. Zichi, L. Schweickert, A. W. Elshaari, S. Steinhauer, S. F. Covre da Silva, A. Rastelli, V. Zwiller, K. D. Jöns, and C. Errando-Herranz, "Reconfigurable photonics with on-chip single-photon detectors," Nat. Commun. **12**, 1408 (2021).
[30]M. G. Tanner, S. D. Dyer, B. Baek, R. H. Hadfield, and S. Woo Nam, "High-resolution single-mode fiber-optic distributed Raman sensor for absolute temperature measurement using superconducting nanowire single-photon detectors," Appl. Phys. Lett. **99**, 201110 (2011).
[31]S. D. Dyer, M. G. Tanner, B. Baek, R. H. Hadfield, and S. W. Nam, "Analysis of a distributed fiber-optic temperature sensor using single-photon detectors," Opt. Express **20**, 3456–3466 (2012).
[32]C. Schuck, W. H. P. Pernice, X. Ma, and H. X. Tang, "Optical time domain reflectometry with low noise waveguide-coupled superconducting nanowire single-photon detectors," Appl. Phys. Lett. **102**, 191104 (2013).
[33]Q. Zhao, L. Xia, C. Wan, J. Hu, T. Jia, M. Gu, L. Zhang, L. Kang, J. Chen, X. Zhang, and P. Wu, "Long-haul and high-resolution optical time domain reflectometry using superconducting nanowire single-photon detectors," Sci. Rep. **5**, 10441 (2015).
[34]A. J. Annunziata, O. Quaranta, D. F. Santavicca, A. Casaburi, L. Frunzio, M. Ejrnaes, M. J. Rooks, R. Cristiano, S. Pagano, A. Frydman, and D. E. Prober, "Reset dynamics and latching in Niobium superconducting nanowire single-photon detectors," J. Appl. Phys. **108**, 084507 (2010).
[35]J. K. W. Yang, A. J. Kerman, E. A. Dauler, V. Anant, K. M. Rosfjord, and K. K. Berggren, "Modeling the electrical and thermal response of superconducting nanowire single-photon detectors," IEEE Trans. Appl. Supercond. **17**, 581–585 (2007).
[36]E. A. Dauler, M. E. Grein, A. J. Kerman, F. Marsili, S. Miki, S. W. Nam, M. D. Shaw, H. Terai, V. B. Verma, and T. Yamashita, "Review of superconducting nanowire single-photon detector system design options and demonstrated performance," Opt. Eng. **53**, 081907 (2014).
[37]G. Bachar, I. Baskin, O. Shtempluck, and E. Buks, "Superconducting nanowire single photon detectors on-fiber," Appl. Phys. Lett. **101**, 262601 (2012).
[38]Y. Dai, K. Jia, G. Zhu, H. Li, Y. Fei, Y. Guo, H. Yuan, H. Wang, X. Jia, Q. Zhao, L. Kang, J. Chen, S. N. Zhu, P. Wu, Z. Xie, and L. Zhang, "All-fiber device for single-photon detection," PhotoniX **4**, 7 (2023).
[39]L. You, J. Wu, Y. Xu, X. Hou, W. Fang, H. Li, W. Zhang, L. Zhang, X. Liu, L. Tong, Z. Wang, and X. Xie, "Microfiber-coupled superconducting nanowire single-photon detector for near-infrared wavelengths," Opt. Express **25**, 31221–31229 (2017).
[40]X. Hou, N. Yao, L. You, H. Li, Y. Wang, W. Zhang, H. Wang, X. Liu, W. Fang, L. Tong, Z. Wang, and X. Xie, "Ultra-broadband microfiber-coupled superconducting single-photon detector," Opt. Express **27**, 25241–25250 (2019).
[41]F. Najafi, J. Mower, N. C. Harris, F. Bellei, A. Dane, C. Lee, X. Hu, P. Kharel, F. Marsili, S. Assefa, K. K. Berggren, and D. Englund, "On-chip detection of non-classical light by scalable integration of single-photon detectors," Nat. Commun. **6**, 5873 (2015).
[42]Y. Meng, C. Liedl, S. Pucher, A. Rauschenbeutel, and P. Schneeweiss, "Imaging and localizing individual atoms interfaced with a nanophotonic waveguide," Phys. Rev. Lett. **125**, 053603 (2020).
[43]S. L. Todaro, V. B. Verma, K. C. McCormick, D. T. C. Allcock, R. P. Mirin, D. J. Wineland, S. W. Nam, A. C. Wilson, D. Leibfried, and D. H. Slichter, "State readout of a trapped ion qubit using a trap-integrated superconducting photon detector," Phys. Rev. Lett. **126**, 010501 (2021).
[44]W. Zhang, Q. Jia, L. You, X. Ou, H. Huang, L. Zhang, H. Li, Z. Wang, and X. Xie, "Saturating intrinsic detection efficiency of superconducting nanowire single-photon detectors via defect engineering," Phys. Rev. Appl. **12**, 044040 (2019).