

Superconducting nanowire single-photon detectors

A perspective on evolution, state-of-the-art, future developments, and applications

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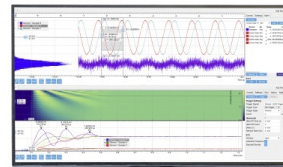
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ABSTRACT

Two decades after their demonstration, superconducting nanowire single-photon detectors (SNSPDs) have become indispensable tools for quantum photonics as well as for many other photon-starved applications. This invention has not only led to a burgeoning academic field with a wide range of applications but also triggered industrial efforts. Current state-of-the-art SNSPDs combine near-unity detection efficiency over a wide spectral range, low dark counts, short dead times, and picosecond time resolution. The present perspective discusses important milestones and progress of SNSPDs research, emerging applications, and future challenges and gives an outlook on technological developments required to bring SNSPDs to the next level: a photon-counting, fast time-tagging imaging, and multi-pixel technology that is also compatible with quantum photonic integrated circuits.

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I. INTRODUCTION

A. Single-photon detection and the emergence of SNSPDs

Technologies operating at the single-photon level, the quantum of the electromagnetic field,¹ are crucial for communication, sensing, and computation.^{2,3} Photons can encode information using different degrees of freedom including polarization, momentum, number state, energy, and time. For instance, quantum key distribution (QKD) was demonstrated over a distance exceeding 4600 km,⁴ potentially forming the backbone of a quantum internet.⁵ As crucial as the single-photon carriers, are the high-performance single-photon detectors to perform measurements on the quantum bits. They were instrumental in recent demonstration of large-scale Boson sampling,⁶ showing a

computational advantage over conventional supercomputers. Furthermore, in a number of other fields including bio-imaging, light detection and ranging (LiDAR),^{7–9} optical time domain reflectometry (OTDR),^{10,11} single-molecule detection,¹² semiconductor circuits inspection,¹³ star light correlation spectroscopy,¹⁴ diffuse optical tomography,¹⁵ positron emission tomography (PET),¹⁶ mass spectroscopy, and quantum metrology measurements,¹⁷ single-photon/particle detectors are essential. For these applications, tremendous efforts have been made to produce single-photon detectors combining near unity system detection efficiencies (SDEs), low dark count rates (DCRs), short timing jitters, high maximum count rates, photon number resolution capabilities, and large active areas.

Single-photon avalanche diode (SPAD)^{18,19} and photomultiplier tubes (PMTs)^{20,21} were first used to detect single photons. However,

combining high detection efficiency with high time-resolution and low noise in SPADs and PMTs remains a challenge. In addition, a limited spectral response (limited at 1100 nm for silicon) and afterpulsing further limit their use for quantum technologies. With two decades of development since their inception,²² superconducting nanowire single-photon detectors (SNSPDs) offer unrivaled detection metrics with an unprecedented combination of performance, for a comparison of SPADs and PMTs with SNSPDs, see Ref. 23.

B. A brief history of SNSPDs development

Before the inception and maturity of SNSPDs, other superconducting devices such as Josephson-junctions,²⁴ superconducting quantum interference devices (SQUIDs),²⁵ hot electron bolometers,^{26,27} and transition edge sensors (TESs)^{28–30} already achieved high performances. The first demonstration of single-photon detection with current-biased superconducting microbridges was reported in 2001 at a wavelength of 0.81 μm .²² The field of SNSPDs then underwent fast development and was driven by applications' requirements. In 2002, meandering nanowires were introduced to increase the active area.³¹ In 2003, the first commercial use of SNSPD, for integrated circuit fault testing, was reported.³² A key driver pushing SNSPD early development was quantum key distribution (QKD) that made commercialization viable. The first SNSPD based QKD was reported in 2006³³ and was followed by a world record 200 km QKD experiment³⁴ doubling the previous distance achieved with InGaAs SPADs and matched the loss threshold for space to ground QKD of 40 dB. Soon after these pioneering works, fiber-coupled SNSPDs reached a detection efficiency of 24% at 1550 nm (Ref. 35) and were further improved to 47% with antenna structures.³⁶ Optical cavities were integrated with SNSPDs to boost the detection efficiency to 57% at 1550 nm.³⁷ In 2012, by stacking two WSi SNSPDs and connecting them in parallel, the system detection efficiency (SDE) was improved to over 87%.³⁸ Another important development in 2011 and 2012 was the integration of SNSPDs with photonic waveguides,^{39,40} which made high on-chip detection efficiency possible and delivered a key element to the toolbox of integrated quantum photonics (see Sec. III A). In 2013, WSi SNSPDs in an integrated cavity reached an SDE of 93% at 1550 nm,⁴¹ 92%–93% SDE was subsequently demonstrated with other material platforms.^{42,43} In 2020, three independent groups reported > 98% SDE based on three different material systems: MoSi with distributed Bragg reflectors,⁴⁴ dual-layer NbN meanders,⁴⁵ and NbTiN with a membrane cavity.⁴⁶

Aside from a high detection efficiency, detectors with low dark count rates, i.e., undesired detection events generated without illumination or due to black-body radiation, are vital in many photon-starved applications. Early works⁴⁷ showed intrinsic dark counts to originate from vortices crossing the nanowire cross section, which may be triggered by thermal fluctuations or current-assisted unbinding of vortex-antivortex pairs.⁴⁸ Additionally, black-body radiation can be a major source of dark counts, especially for large area SNSPDs and particularly at longer wavelengths.⁴⁹ To suppress black-body induced dark counts, cold filters⁵⁰ or fibers with end-face coatings can be used.⁵¹ It has also been shown that the dark count rate increases under illumination due to the suppression of switching current by incident light.⁵² As of 2021, a dark count rate as low as 10^{-4} per second has been demonstrated,^{50,53} further studies are required to determine the origin of the remaining dark counts.

High time resolution is one of the distinctive advantages of SNSPDs. Time jitter represents the time interval statistics between photons impinging the detector and the generation of the electrical detection signal. Early experimental works^{54,55} showed that in addition to time jitter of the detector itself (briefly discussed in Sec. I C), several other experimental parameters such as electrical noise, fiber dispersion, and the accuracy of laser synchronization signals all contribute to the overall system time jitter. Experimentally, in 2006 a sub-30 ps time jitter was demonstrated by making SNSPDs from a 4 nm-thick NbN film.⁵⁶ In 2016, a timing jitter of 17.8 ps was achieved using an ultrafast time-correlated single-photon counting setup.⁵⁷ In 2017, by employing a cryogenic amplifier, a 14.8 ps jitter was demonstrated⁴² with NbTiN SNSPDs. In the same year, by optimizing the experimental measurement setup, a 12 ps timing jitter was demonstrated with NbN SNSPDs.⁵⁸ Recently, the fiber-coupled SNSPD's timing jitter was pushed down to 7.7 ps.⁵⁹ As of April 2021, the best reported time jitter belongs to short straight nanowires and is < 3 ps for NbN⁶⁰ and 4.8 ps for WSi.⁶¹

C. Understanding SNSPDs' performance optimization and trade-offs

To date, the theoretical understanding of the exact detection mechanism in SNSPDs is still under development. We discuss some of the leading models in Sec. II A. Here, we briefly hint at some basic observations to discuss the operation limits of SNSPDs.

Generally speaking, the detection efficiency of a SNSPD is influenced by two parameters: its optical absorption, i.e., what fraction of photons incident on the SNSPD is absorbed in the detector and the internal efficiency, the probability that an absorbed photon generates a measurable detection event. Small constrictions along the nanowires (due to nano-fabrication and/or variation in the superconducting film) were shown to be one limiting factor for the critical current as well as for the internal detection efficiency.^{62,63} It was also demonstrated that bends in a meandering nanowire can lead to a noticeable reduction of the critical current as shown in Refs. 64–66; this current crowding issue can be addressed by optimizing the bend geometry⁶⁷ or with spiral SNSPDs.⁶⁸ As for the absorption efficiency, the optical absorption of typical superconductors used for SNSPD fabrication has been studied,⁶⁹ and the polarization dependence of SDE and nanowire designs (fill factor, linewidth, and device size) are well-understood and comprehensively discussed in Refs. 70 and 71. To minimize polarization dependence, three-dimensional architecture,³⁸ near-field optics,⁷² dielectric capping layers,⁷³ or fractal-shape nanowires^{74,75} were demonstrated.

The operation temperature dependence of SNSPDs is, at least experimentally, well understood: If the internal detection efficiency at a specific temperature and for a specific photon energy is unsaturated (no plateau in the detection rate vs bias current curve), the detection efficiency reduces as the temperature increases. Additionally, both intrinsic and blackbody induced dark counts are temperature dependent.⁷⁶ The former, independent of the applicable model or exact origin of DCR, is due to the fact that potential barriers (for example, for vortex crossing or vortex-antivortex depairing) or electron/photon interaction time constants are all temperature dependent. The intrinsic darkcount, for a fixed bias to switching current ratio, often increases with higher temperature. Extrinsic darkcount may decrease with temperature as the detection efficiency for photons (for example, long

wavelength blackbody photons) is reduced as the temperature increases.⁷⁶ Therefore, in a system in which blackbody radiation is well filtered out, the signal to noise ratio (SNR) often decreases as the temperature is increased.

The timing properties of SNSPDs (recovery time and time jitter) have been thoroughly studied: Early on, the recovery time of NbN SNSPDs was found to be limited by their kinetic inductance,⁷⁷ revealing an intrinsic trade-off between large-area devices and fast recovery times. A more systematic electro-thermal model⁷⁸ was presented to better explain the detection dynamics with a practical solution to shorten recovery time by adding a resistor in series to SNSPDs. However, in the same work, it was demonstrated that there is a limit to reducing SNSPDs recovery times, this limit is dictated by electro-thermal feedback and hence depends on the substrate material, on the superconductor, temperature, bias, critical current, as well as on the SNSPD's kinetic inductance. While detectors with very fast electrical recovery time (<1 ns) have been demonstrated, it has also been shown that the electrical recovery time (extracted from the pulse traces) is not necessarily the same as the detector recovery time.⁷⁹ Alternatively, multi-pixel⁵⁶ and multi-element structures⁸⁰ were proposed and demonstrated to increase the active area without sacrificing time performance and even offering photon number resolution prospects.⁸¹

Since SNSPDs typically cover areas of hundreds of square micrometers and the electrical signal propagates through the detector with finite speed, photons detected at different locations generate detection pulses that reach the readout circuit at different times, leading to a geometrical jitter.⁸² In 2017,⁸³ the influence of Fano fluctuations on timing jitter was also reported. In the same year, timing jitter caused by distributed electronic and geometric inhomogeneity of a superconducting nanowire⁸⁴ was analyzed. Also, vortex-crossing-induced jitter was systematically studied, and the theoretical limit of SNSPDs' intrinsic timing jitter was estimated to be around 1 ps.⁸⁵ Another study, based on the two-temperature model coupled with the modified time-dependent Ginzburg–Landau equation,⁸⁶ argued that photon absorption location on a current-carrying superconducting strip has direct influence on the minimal achievable time jitter. The minimum jitter was shown to depend on the critical temperature of the superconducting film. This was calculated to be of the order 0.8 ps for a nanowire with a width of 130 nm made from a typical NbN superconducting films with a critical temperature of 10 K. Narrower nanowires can potentially improve the minimum achievable jitter. If no other fundamental limitation for time jitter is discovered, ultimately, the time jitter would be limited by the dynamics of suppression of superconductivity (pair breaking) which depends on material, temperature, and the optical excitation density.⁸⁷

D. Scope and content of this perspective

After summarizing the history and development of SNSPDs over the past two decades, we highlight the leading theories to explain the operation mechanism and provide the status quo and state-of-the-art in SNSPD technology (Sec. II). A selected number of current and potential future applications are discussed in Sec. III. Finally, we provide an outlook for future development (Sec. IV). For a more in-depth and technical review of SNSPD's working principle, intrinsic limitations, and design solutions, we refer the readers to Ref. 88.

II. SNSPD DETECTION MECHANISMS AND STATE-OF-THE-ART

A. SNSPD detection mechanisms

This section gives an overview of the leading physical models of the detection mechanisms in SNSPDs, providing a qualitative description to understand basic working principles and device physics. We consider the most common SNSPD implementation, based on a superconducting nanowire (width 50–100 nm) patterned from a thin film (thickness 5–10 nm) using a top-down nanofabrication process. The nanowire, often designed as a meandering structure, is “DC-biased” close to the device's critical current via a bias tee, and low noise amplifiers and counting electronics are used to detect single-photon events and register corresponding voltage pulses. A phenomenological model of the detection process was proposed in the initial reports on SNSPDs^{22,89} and has been revised in the following two decades. To allow for quantitative modeling and design optimizations, the detection process⁹⁰ was divided into subsequent steps (see Fig. 1): (I) photon absorption; (II) creation of quasiparticles and phonons combined with their diffusion; (III) emergence of a non-superconducting nanowire segment; (IV) re-direction of bias current in readout circuitry, leading to a voltage pulse; and (V) detector recovery.

(I) The initial absorption of a single photon within the active detector area is well described by a classical electromagnetic theory. This allows for the use of established modeling tools⁹² to optimize optical absorption in the superconducting layer for a desired wavelength range. The absorption of a visible or near-infrared photon results in (II) the formation and expansion of a cloud of quasiparticles, which is initiated by the relaxation of the photo-excited electron and followed by the creation, multiplication, and diffusion of quasiparticles and phonons. These processes are governed by electron-electron, electron-phonon, as well as phonon-phonon interactions and their characteristic timescales,⁹³ whereas the diffusion constants as well as the ratio of the heat capacities of electrons and phonons are crucial for the spatiotemporal relaxation dynamics. This downconversion process is modeled through deterministic kinetic equations for electrons and phonons⁹⁴ or through a stochastic loss of excitation energy into the

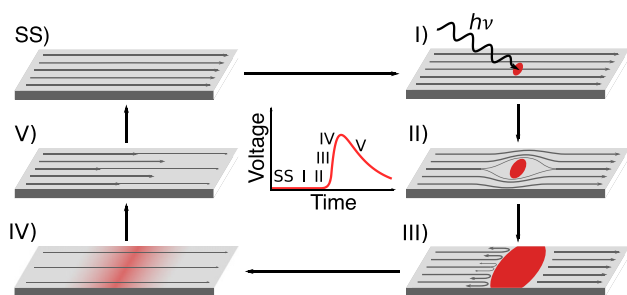


FIG. 1. Macroscopic explanation of the detection mechanism (based on Refs. 22, 78, and 89). In the steady state (SS), the superconducting thin-film strip is current biased. Photon absorption (I) leads to the creation of quasi-particles and phonons (II). This leads to the formation of a normal-conducting part of the strip (III). Redirection of the current toward the readout electronics allows a recovery of the superconducting state (IV), which leads to a return of the current (V) to its initial value. This reset dynamics is limited by the kinetic inductance of the device. Center: The voltage readout signal with each step labeled. Adapted with permission from Allmaras *et al.*, *Nano Lett.* **20**, 2163–2168 (2020). Copyright 2020 American Chemical Society.⁹¹

substrate.⁸³ An instability of the superconducting state emerges due to the quasiparticle cloud, linked with a local reduction of the superconducting order parameter, re-distribution of the current density, and lowering of the effective critical current density. Combining ideas from deterministic and stochastic models allows to describe a complete set of measurements qualitatively,^{95,96} but these existing models require further developments to be able to fully describe the physical processes quantitatively. This instability can lead to a photon detection event, associated with (III) parts of the nanowire transitioning to a non-superconducting state. Following initial descriptions relying on a normal-conducting “hotspot,” models of the SNSPD detection mechanism have been refined, underlining the importance of magnetic vortices.^{47,97,98} For further details on the mechanisms governing the local emergence of a non-superconducting segment of the detector area, we refer to Engel *et al.*⁹⁰ Subsequently, the resistive region of the nanowire grows due to internal Joule heating.⁷⁸ The increasing resistance, on the order of several k Ω ,⁷⁸ leads to (IV) the re-direction of the bias current from the nanowire toward the readout electronics. The circuit behavior can be described using lumped element models^{99,100} or planar microwave simulations. Once the resistive area has sufficiently cooled down, (V) superconductivity is restored and the current flowing through the nanowire returns to its initial value, whereas the dynamics are governed by the kinetic inductance of the device.^{77,78} In cases where the resistive domain does not cooldown rapidly enough, the detector latches due to thermal runaway and no further photons can be detected until the device is actively reset.¹⁰¹

While models for step (I), (IV), and (V) can be used to predict and develop successful designs, models for step (II) and (III) are missing such capabilities. The fluctuations beyond the initial downconversion cascade, the non-equilibrium state of electron-phonon baths, and the missing element of intrinsic dark counts are examples for open problems and challenges for the future.

B. State-of-the-art SNSPDs

In the section below, we discuss advances with regard to the superconducting materials used for production of SNSPDs,

nanofabrication, multi-pixel detectors, the nano- and micro-wire SNSPDs, wavelength range, state-of-the-art performance, and characterization of SNSPDs that has led to detectors with > 98% SDE.^{44,46,102}

1. Superconducting materials and nano-fabrication of SNSPDs

SNSPDs have been made out of dozens of superconductors. The material selection for the superconducting film can be based on various factors, but the motivations for specific choices can mainly be divided into two groups: optical properties such as absorption at different wavelengths and superconducting properties such as critical temperature and critical current density. In practice, other parameters may also be taken into account, for example, for photons with higher energy the use of higher critical temperature superconductors might be preferred to simplify the cryo-cooling system while for mid-infrared detectors (beyond 2–3 μm), low-gap amorphous superconductors such as MoSi and WSi have so far been the main option. In Table I, we present an overview of some leading results based on different superconducting materials. In addition to the highlighted superconducting materials in Table I, another important class of superconducting materials that have been subject of research are the high T_c superconductors. High- T_c SNSPDs are a topic of long-standing discussions with reports of dark counts¹⁰³ and signatures of single-photon operation¹⁰⁴ on the one hand and skepticism¹⁰⁵ on the other hand. Therefore, further studies are required to understand the limits and potentially unlock the use of these promising platforms.

Production of high performance SNSPDs involves various nanofabrication technologies. Starting from a commercial substrate (typically silicon), the first fabrication step involves the deposition of a distributed Bragg reflector to enhance the optical absorption. (Metal based reflectors are also possible^{42,46} but less common and nano-antennas can also be integrated^{117,118} to enhance optical absorption.) A superconducting thin film (typically 4–10 nm) is then deposited on top of the mirror layer. The electrical contacts are formed by means of optical or e-beam lithography, metal deposition (evaporation or sputtering), and liftoff. The nanowire detector can be formed using a single

TABLE I. Overview of some SNSPD leading works on different material platforms.

Material	Efficiency/time jitter	Temperature	Wavelength
NbN (Refs. 43 and 45)	92%–98.2%/40–106.1 ps	0.8–2.1 K	1550–1590 nm ^a
NbTiN (Refs. 42 and 46)	92%–99.5%/14.8–34 ps	2.5–2.8 K	1290–1500 nm ^b
WSi (Refs. 41 and 44)	93%–98%/150 ps	120 mK–< 2 K ^c	1550 nm
MoGe (Ref. 106)	20%/69–187 ps	250 mK–2.5 K	1550 nm
MoRe (Ref. 107)	—/—	9.7 K	—
MoSi (Refs. 108–110)	80%–87% /26–76 ps	0.8–1.2 K ^d	1550 nm
NbRe (Ref. 111)	—/35 ps	2.8 K	500–1550 nm
NbTiN (Ref. 76)	15%–82% /30–70 ps	2.5–6.2 K	400–1550 nm
NbSi (Ref. 112)	—/—	300 mK	1100–1900 nm
TaN (Ref. 113)	—/—	0.6–2 K	600–1700 nm
MgB ₂ (Refs. 114–116)	—/—	3–5 K	Visible

^aOptimal performance at < 1 K while an SDE of 90%–95% was achieved at 2.1 K. Time jitter depends on temperature and design. Errorbar for 98.2% efficiency was $\pm 1\%$.

^bErrorbar for 99.5% efficiency was (–2.07, +0.5)%.

^cOperation up to ~ 2 K possible at the cost of higher time jitter,⁴¹ temperature and jitter measurements are not mentioned in Ref. 44. Errorbar for efficiency measurements was $\pm 0.5\%$.

^dIn Ref. 109, an operating temperature of 2.3 K was demonstrated with added cost of higher time jitter and lower internal efficiency saturation.

electron-beam lithography step followed by reactive ion etching. For detector packaging and to achieve stable and efficient operation, coupling to an optical fiber is crucial, which is typically done with self-aligned schemes requiring additional lithographic steps combined with deep etching of the substrate (micro-machining using a Bosch process). The complete process is illustrated in Fig. 2.

Deposition of the superconducting layer is a crucial step, and its quality has a direct impact on the detector performance. This is typically performed by magnetron sputtering and can yield nanocrystalline or amorphous layers. Excellent deposition uniformity and nanofabrication processes are required to ensure manufacturing of devices with reproducible and consistent superconducting properties. In this regard, amorphous materials such as WSi and MoSi as well as optimized crystalline films with relatively larger thicknesses (8–12 nm)^{59,119} are considered more forgiving and thus favorable for high-yield detector fabrication. In addition, plasma-enhanced atomic layer deposition^{120,121} and single-crystalline molecular beam epitaxy¹²² growth of NbN were recently demonstrated as viable and potentially high-yield alternatives for SNSPD fabrication.

2. Wavelength range

SNSPDs have been demonstrated to operate from the x-ray to the mid-infrared wavelength range. In 2012, soft x-ray detection was demonstrated.¹²³ In contrast to the standard detection mechanism, where photons are absorbed in the meander, for x-ray detection the absorbance in thin superconducting layers with thicknesses around 10 nm is low and absorption in the substrate plays a major role.^{124,125} Due to the significant higher particle energy, x-ray detectors can have saturated intrinsic efficiency at considerably larger geometrical

parameters, which can increase x-ray absorption in the superconductor to a few percent.^{126,127} SNSPDs for UV photons have reached efficiencies of >85%, dark count rates of 0.25 counts per hour and timing jitter < 60 ps.¹²⁸ By engineering film deposition to optimize energy sensitivity, WSi detectors were shown with a saturated internal efficiency at 10 μm ¹²⁹ in 2020. Although beyond the scope of single-photon detection, it is worth mentioning that SNSPD structures can also be used to detect α and β particles.¹³⁰

3. Multipixel SNSPDs

In systems with a small number of superconducting single-photon detectors such as fiber-coupled multi-pixel arrays,⁵⁹ a straightforward way to address individual detection channels is through spatial multiplexing of the biasing and RF detection signals through several coaxial lines. As multi-pixel arrays scale in size, a limit on the number of coaxial lines is set by the cryostat cooling power.¹³¹ Multipixel readout techniques for SNSPDs are under development, a row-column readout of pixels for a 32 \times 32 detector-array using only 64 electrical connections was demonstrated.¹³² This method is very attractive as the number of required RF lines is only 2*N*, for arrays consisting of *N*² detectors, though this approach does not allow for simultaneous readout of all pixels. Time-domain multiplexing is another approach, where a single superconducting transmission line is used to address several detectors on the same chip.^{133–137} One of the main challenges of this approach is the fast propagation speed of the electrical signal in the superconducting transmission-lines, approaching the speed of light, which limits the possibility for dense packing of detectors.¹³⁴ Dispersion engineering was recently used to reduce group velocity of the detection signal in the superconducting transmission-line by orders of magnitude. Both planar and multi-layered structures were used to control the group velocity of the detection signals.^{133,135–137} Another promising route for scalable readout of multipixel SNSPDs is the use of single flux quantum (SFQ) logic.^{138–143} Frequency multiplexing was also demonstrated for SNSPDs,¹⁴⁴ where several resonant cavities operating at different radio frequencies are coupled to individual detectors on a single transmission-line. For the latter, a challenge in large scale systems is the complexity involved with matching resonant frequencies of the cavities to the driving radio frequency tones. Alternatively, amplitude coding of the detection signals of SNSPDs provides another approach for multiplexing.^{145,146} The advantage is the simplicity of fabrication and readout method using a voltage division circuit. On the other hand, the drawback is the need for on-chip resistors to set different amplitude levels, which dissipate heat, and additionally the size of the array is limited by the leakage current in different branches.¹³⁶

4. Nanowire vs microwire detectors

SNSPDs have typical nanowires widths in the range of 40–120 nm. These devices show exceptional performance but require complex nanofabrication. Recently, detectors with wide micrometer lines were reported: Superconducting microstrip single-photon detectors (SMSPDs).¹⁴⁷ These devices have, compared to SNSPDs, far larger critical currents and lower kinetic inductance, making them suitable for the fabrication of large-area detectors as shown in a number of recent works.^{148–151} For example, Ref. 149 demonstrates devices with meander widths of 1 and 3 μm and active areas up to 400 \times 400 μm^2

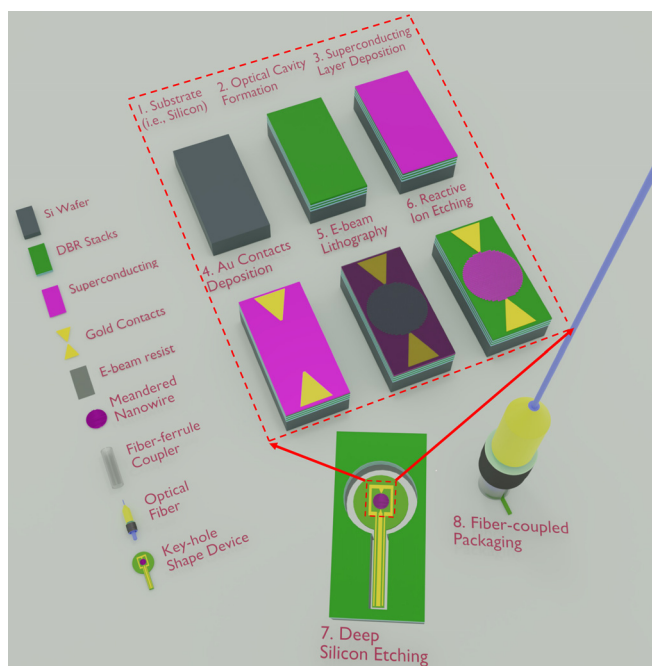


FIG. 2. Illustration of the process flow for fabricating SNSPDs from a bare silicon substrate to a fiber-coupled device. For details see main text.

with excellent light detection in micro-strips fabricated by conventional optical lithography.¹⁵¹ Additionally, very recently, high performance single-photon detection (SDE > 90%) was demonstrated.⁶⁸ Since this a relatively new research direction, there are limited reports on time resolution;¹⁵² wavelength limits and high count-rate performances are yet to be reported.

III. SNSPD APPLICATIONS

In this section, we review a non-exhaustive number of established and emerging applications of SNSPDs.

A. Quantum optics, information processing, quantum communication, and integrated quantum photonics

SNSPDs have been the detectors of choice in landmark quantum information processing experiments, i.e., on large scale boson sampling⁶ and record breaking quantum communication experiments.^{153–155} Also high performance SNSPDs played a major role in the loophole-free test of local realism based on Bell experiment.¹⁵⁶ A recent promising direction for application of SNSPDs in quantum information promising is its integration with ion-trap.¹⁵⁷ For an up-to-date review on the use of SNSPDs in quantum technologies, we refer to Ref. 105.

Complex quantum photonics integrated circuits require many on-chip single-photon detectors. SNSPD in traveling wave geometry,^{39,40} with its outstanding performance and small footprint, serves as an excellent candidate for this function in photonic integrated circuits. Waveguide-integrated SNSPDs have already been used for on-chip single qubit quantum optics experiments,^{158,159} to demonstrate on-chip two qubit quantum interference,¹⁶⁰ and for on-chip secure quantum communication.¹⁶¹ SNSPDs were integrated in different nano-photonics platforms such as Si,^{40,162–168} SiN,^{158–160,169–174} GaAs,^{39,174–177} AlN,^{174,178} LiNbO₃,^{174,179,180} Ta₂O₅,¹⁸¹ and diamond.^{182,183} In Ref. 184, the performance of most of these earlier SNSPD nano-photonics platforms is reviewed. Integrated SNSPDs have also demonstrated sub-nanosecond recovery time.^{165,181} Another important aspect in sophisticated integrated quantum photonics circuitry is the reliability of photonics elements. It has been shown¹⁷³ that by fabricating traveling wave SNSPDs buried under photonic waveguides, one can determinedly ensure that only the best performing detectors are integrated. Further development of integrated SNSPDs, as envisioned in Sec. IV B can significantly enhance the role of SNSPDs in future quantum nanophotonics circuits.

B. Light detection and ranging (LIDAR)

LIDAR is an optical measurement technique for studying environmental parameters such as the atmosphere, vegetation, as well as remote objects. The detector performance influences the resolution, acquisition time, and maximum range. It has been shown that SNSPDs outperform conventional Geiger-mode avalanche photodiodes both in low noise environments and, under appropriate operation, in noisy (high background) environments.^{7,8} SNSPDs were used for measuring sea fog in an area 180-km in diameter.¹⁸⁵ Kilometer-range, high resolution imaging at telecom wavelength has also been demonstrated.¹⁸⁶ Another promising direction with encouraging recent results is single-photon LIDAR beyond 2000 nm, a wavelength range with both reduced solar flux and atmospheric absorption.⁹

C. Mass spectrometry

SNSPDs offer excellent potential for applications in the field of mass spectrometry, where impacts of single ions can be measured. They show exceptional sensitivity and, additionally, operate at a convenient (particularly considering the size and the heat load of common mass spectrometry chambers) temperature of 2–5 K that is within the operating temperature range of relatively inexpensive Gifford-McMahon and pulsed-tube cryostats. The feasibility of sub-nanosecond detection using these detectors has already been demonstrated.^{12,187} In Addition, a proof of principle for detection of neutral and low energy particles was demonstrated.^{188,189} Superconducting nanowire detectors do not rely on the secondary electron mechanism, and their detection mechanism is based on the creation of high energy quasiparticles by the impact, allowing for 100% detection efficiency even for macromolecules.¹⁹⁰ While SNSPDs offer excellent performances, until recently their active area had been limited. With the development of SNSPD arrays (employing any of several existing multiplexing techniques), kilo-pixel detectors have been introduced¹³² that can cover much larger areas, and by interfacing SNSPD arrays and cryogenically cooled electronics (see Sec. IV A), even larger arrays are expected to become available.

D. Diffuse correlation spectroscopy

Biological tissues are strongly diffusive media. Diffused optical imaging is a functional medical imaging modality that uses the lower attenuation of near-infrared light to probe physiological parameters in the tissue such as oxy- and deoxyhemoglobin.¹⁵ The light transport in these tissues is mainly dominated by scattering, and it has been shown that achievable resolution (the half-width of the point-spread function) scales with thickness.¹⁹¹ Recently, SNSPDs have been considered for improving the performance of diffuse correlation spectroscopy.¹⁹²

E. Optical time domain reflectometry (OTDR)

To identify the position of losses and scattering along optical fiber networks, reflection of a laser pulse is measured and timing yields information on the fault position.¹⁹³ The ability to operate at the single-photon level, with the outstanding time resolution and low dark counts of SNSPDs, allows for OTDR measurements to be carried out over the longest possible distances and yield cm resolution.^{10,11,194} Additionally, OTDR can be used to implement fiber-optic distributed Raman sensor for absolute temperature measurements.^{195,196}

F. Future applications

In neuromorphic computing, SNSPDs were recently proposed both as a direct platform for neuromorphic computing^{197,198} and in conjunction with on-chip semiconducting photon sources.^{199,200} Neuromorphic computing is the discipline that produces neural-inspired computational platforms and architectures. Carver Mead in the late 1980s has come a long way and has had important results such as beating humans in the game of Go.²⁰¹

In astronomy, SNSPDs are finding uses for exoplanet transit spectroscopy, in deep space optical communication, as well as in the search for dark matter. Detecting such particles places stringent requirements on the detector, SNSPDs have been shown to be suitable candidates for direct detection of dark-matter particles from the halo

of milky way directly creating an excitation in a detector on Earth of sub-GeV particles.⁵³ Another application is wideband optical communication to satellites. The limited power available on satellites places stringent requirements on the downlink detectors, with yet stronger requirements if the emitter is further away, as for a deep space probe. These requirements have shed light on SNSPDs^{202–206} for downlink, and possibly for uplink.

Nearly 70 years after the pioneering intensity correlation experiments by Hanbury-Brown and Twiss,²⁰⁷ there is a growing interest in temporal correlation spectroscopy to achieve a high angular resolution in studies of celestial light sources with star light correlation spectroscopy. Temporal intensity interferometry in comparison with conventional direct interferometry has the advantages of having a simplified implementation. This is because no light recombination or physical delay lines are needed and as a result the correlation will be insensitive to environmental turbulences. Recently, using avalanche photodiodes with an active area of 100 μm^2 , time jitter of 500 ps and integrating for 70.5 h, temporal intensity interferometry (photon bunching) experiments were carried on three bright stars. Currently available SNSPD technology readily offers ~ 5 folds improvements of SNR as compared to Ref. 14. Future SNSPD developments will push the boundaries of this field even further.

Advances in single-photon detection at mid-infrared wavelengths^{208,209} have led to a growing interest in mid-infrared spectroscopy with SNSPDs.^{210,211} Recently, Wollman *et al.*,²¹² for the origins space telescope concept, studied the potentials of SNSPDs as a tool to probe bio-signatures in exoplanets atmospheres: using a mid-infrared spectrometer, they will study small spectral changes in a star light due to the absorption or emission from a transiting exoplanet atmosphere. The wavelengths range from 2.8 to 20 μm is of particular interest, because it contains absorption lines of many important molecules vital for life; SNSPD based sensors are promising candidates for exoplanet transit spectroscopy.

Positron emission tomography (PET)¹⁶ is a routinely used functional imaging technology to visualize changes in metabolic and physiological activities as well as chemical regional composition inside the body. PET is an important tool in cancer therapy and with the help of radiotracers, it can retrieve quantitative information about location and concentration of tumor cells. The high time-resolution of SNSPDs integrated with scintillators²¹³ will allow to reach the 10-picosecond PET challenge.^{214,215} Combining SNSPDs with various types of scintillators (particularly cryogenic scintillators) is an exciting research field for SNSPD and PET but also for the broader high-energy physics community.

In biomedical imaging, SNSPDs open new possibilities: the weak emission from oxygen singlet at 1270 nm can readily be measured, operation further in the infrared allows for deeper imaging in biological samples where scattering is lower and specific molecules can be tracked.

For some quantum computation implementations, an important challenge is to funnel large amounts of data in and out of cryostats operating at mK temperatures with limited cooling power. This limits the classical approach of using coaxial lines, the use of optical fibers to communicate at the single-photon level using SNSPDs with systems operating at mK offers the prospects of a very large data bandwidth with very low thermal loads.

IV. OUTLOOK

After a review of current and future applications of SNSPDs in Sec. III, we present two important envisioned SNSPD developments that could further boost the impact of SNSPDs in science and technology.

A. Large SNSPD arrays with integrated cryogenic electronics

Addressing the readout challenge of large SNSPD arrays, i.e., accessing and processing large amounts of data generated at cryogenic temperatures, is imperative for high-end imaging applications. As discussed in Sec. II B 3, each readout technique has specific advantages and disadvantages. We envision future large-scale systems with hybrid cryogenic RF readout techniques utilizing different readout schemes in different sub-systems. Additionally, dispersion engineering is a powerful tool that can be used to tailor the properties of the superconducting transmission lines for better footprints or to boost the operating bandwidth.^{216,217}

For applications requiring large SNSPD arrays (e.g., high resolution imaging and spectroscopy), it is essential to integrate cryogenic readout circuits close to the SNSPD and separate them from processing units (comparators, counters, time to digital converters, and digital processing units) operating at higher temperatures. Connections among these units must have high RF transmission while providing high thermal isolation (i.e., low thermal conduction, see, for example, Ref. 218). Such an envisioned system is illustrated in Fig. 3: The array sensor is connected via superconducting transmission lines to the pixel addressing and pulse pre-amplification electronics (illustrated as addressing and analog amplifiers in the figure) within the first cryogenic stage. Low thermal conductivity coaxial links are used to connect the first cryogenic stage to the second stage (30–50 K). The second cryogenic stage is where further complex processing are performed which may include (but be not limited to) triggering, pulse counting, time to digital converters for time stamping, data compression, and serializers able to handle the large data stream. We foresee successful implementation of large area, high density imaging sensors such as the one shown in Fig. 3 can bring about a step change to many imaging applications discussed in Sec. III. A further step could be the integration of such a sensor in compact cryo-coolers,²¹⁹ making it even more attractive for applications, where size and power consumption are important decision-making factors such as equipment integrated in satellites.

B. SNSPD-based re-configurable integrated quantum photonics

Using SNSPDs for conditional reconfiguration of quantum photonics circuits based on detection events, as illustrated in Fig. 4, can facilitate quantum communication schemes such as teleportation, entanglement swapping, and quantum repeaters. Such schemes rely on performing a (Bell-state) measurement on a photonic qubit, then feed-forward the resulting detection electrical signal to conditionally modify another photonic qubit on the same or a different chip. This comes as a challenge though, the timescale for the voltage signal of SNSPDs is on the order of nanoseconds, necessitating delaying optical signals on the chip by a similar timescale to allow for conditional reconfiguration of the circuit based on detection events. To overcome

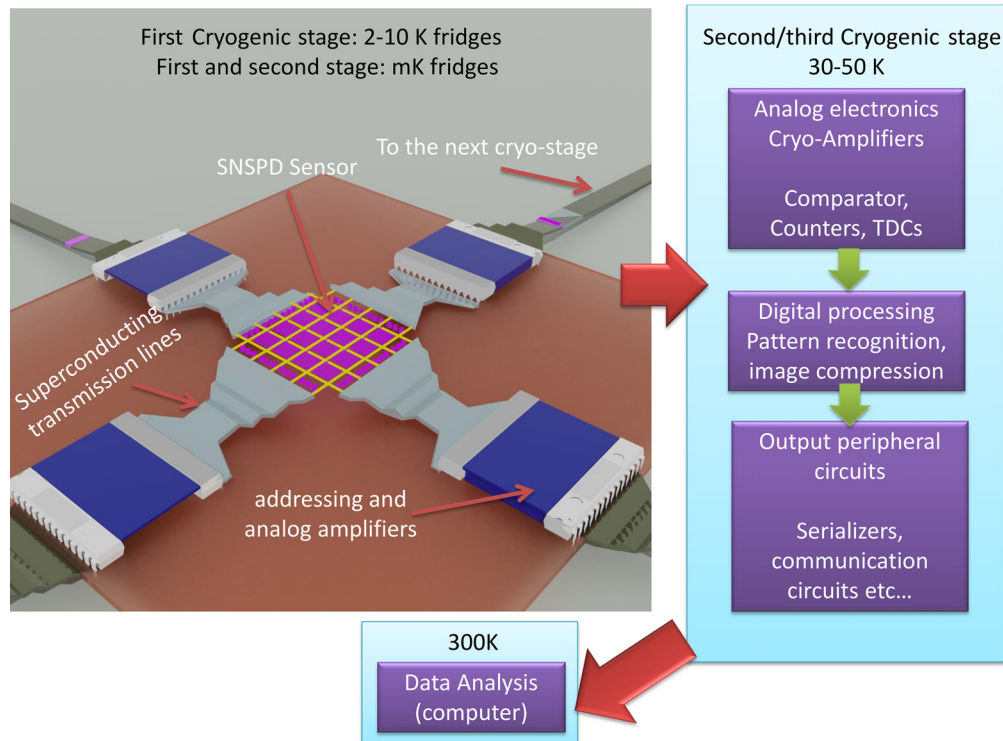


FIG. 3. Concept illustration of a large SNSPD based imaging sensor: the pixels are addressed, and the SNSPD pulses are amplified using the first cryogenic stage readout circuitry connected to the sensor via superconducting transmission lines. The pre-amplified analog signals are then passed to the second cryogenic stage for further processing which includes pulse counting, time to digital converters (TDC), data compression, and finally serializers. A processing unit at room temperature receives and analyzes the pre-processed data.

such a challenge, ultra-fast on-chip SNSPDs must be implemented, in combination with heat-free fast re-configurable photonic circuits and ultra-low loss optical delay lines to match the electrical signal delay. An important step toward such a goal was recently demonstrated by realizing waveguide integrated SNSPDs with thin-film lithium niobate

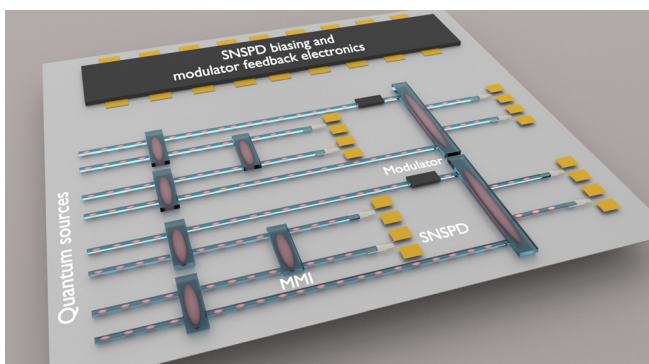


FIG. 4. Concept illustration of a single-photon reconfigurable quantum photonic circuit consisting of quantum sources, beam splitters that are implemented here using multimode interferometers (MMI), electro-optic modulators, and SNSPDs. Detection signals from quantum interference outcome between different qubits are processed by the feedback-electronics module to apply qubit rotations on-chip.

circuits, which can deliver the needed modulation for fast routing of single photons on-chip.²²⁰ Another interesting application for such re-configurable circuits is quantum simulators for implementing sampling problems, quantum transport simulations, or disordered quantum systems. The integration of efficient sources and detectors with low-loss optical waveguides on the same chip will significantly advance the scalability prospects for photonic quantum simulators.

V. CONCLUSION

In this perspective, we reviewed the evolution of SNSPDs, the state-of-the-art, working mechanisms, fabrication methods, material platforms, readout schemes, applications, and disruptive enabled technologies. Our goal is to provide a dynamic multidisciplinary picture targeted toward both the community of SNSPD researchers and scientists working on overlapping lines of research, where this technology can have important impact. An outlook for future developments of SNSPD is also provided along with two key envisioned enabling developments to boost the impact of SNSPD in science and technology.

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DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

REFERENCES

- ¹A. Einstein, “On a heuristic point of view concerning the generation and transformation of light,” *A. Einstein, Ann. Phys.* **17**, 132 (1905); *Annalen der Physik* **322**(6), 132–148 (1905); *American Journal of Physics* **33**, 367 (1965).
- ²D. Bouwmeester and A. Zeilinger, “The physics of quantum information: Basic concepts,” in *The Physics of Quantum Information* (Springer, 2000), pp. 1–14.
- ³C. H. Bennett and D. P. DiVincenzo, “Quantum information and computation,” *Nature* **404**, 247–255 (2000).
- ⁴Y.-A. Chen, Q. Zhang, T.-Y. Chen, W.-Q. Cai, S.-K. Liao, J. Zhang, K. Chen, J. Yin, J.-G. Ren, Z. Chen, S.-L. Han, Q. Yu, K. Liang, F. Zhou, X. Yuan, M.-S. Zhao, T.-Y. Wang, X. Jiang, L. Zhang, W.-Y. Liu, Y. Li, Q. Shen, Y. Cao, C.-Y. Lu, R. Shu, J.-Y. Wang, L. Li, N.-L. Liu, F. Xu, X.-B. Wang, C.-Z. Peng, and J.-W. Pan, “An integrated space-to-ground quantum communication network over 4,600 kilometres,” *Nature* **589**, 214–219 (2021).
- ⁵H. J. Kimble, “The quantum internet,” *Nature* **453**, 1023–1030 (2008).
- ⁶H.-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, “Quantum computational advantage using photons,” *Science* **370**(6523), 1460–1463 (2020).
- ⁷D. Salvoni, M. Ejrnaes, L. Parlato, A. Sannino, A. Boselli, G. P. Pepe, R. Cristiano, and X. Wang, “Lidar techniques for a SNSPD-based measurement,” *J. Phys.: Conf. Ser.* **1182**, 012014 (2019).
- ⁸C. Wu, W. Xing, L. Xia, H. Huang, and C. Xu, “Receiver performance characteristics of single-photon lidar in a strong background environment,” *Appl. Opt.* **58**, 102–108 (2019).
- ⁹G. G. Taylor, D. Morozov, N. R. Gemmill, K. Erotokritou, S. Miki, H. Terai, and R. H. Hadfield, “Photon counting lidar at 2.3 μm wavelength with superconducting nanowires,” *Opt. Express* **27**, 38147–38158 (2019).
- ¹⁰J. Hu, Q. Zhao, X. Zhang, L. Zhang, X. Zhao, L. Kang, and P. Wu, “Photon-counting optical time-domain reflectometry using a superconducting nanowire single-photon detector,” *J. Lightwave Technol.* **30**, 2583–2588 (2012).
- ¹¹C. 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).
- ¹²N. Zen, A. Casaburi, S. Shiki, K. Suzuki, M. Ejrnaes, R. Cristiano, and M. Ohkubo, “1 mm ultrafast superconducting stripline molecule detector,” *Appl. Phys. Lett.* **95**, 172508 (2009).
- ¹³R. Sobolewski, A. Verevkin, G. Gol’tsman, A. Lipatov, and K. Wilsher, “Ultrafast superconducting single-photon optical detectors and their applications,” *IEEE Trans. Appl. Supercond.* **13**, 1151–1157 (2003).
- ¹⁴W. Guerin, A. Dussaux, M. Fouché, G. Labeyrie, J.-P. Rivet, D. Vernet, F. Vakili, and R. Kaiser, “Temporal intensity interferometry: Photon bunching in three bright stars,” *Mon. Not. R. Astron. Soc.* **472**, 4126–4132 (2017).
- ¹⁵I. Nissila, T. Noponen, J. Heino, T. Kajava, and T. Katila, “Diffuse optical imaging,” in *Advances in Electromagnetic Fields in Living Systems. Advances in Electromagnetic Fields in Living Systems*, edited by J. C. Lin (Springer, Boston, MA, 2005).
- ¹⁶D. L. Bailey, D. W. Townsend, P. Valk, and M. Maisy, *Positron Emission Tomography: Basic Sciences* (Springer, 2005).
- ¹⁷D. Twerenbold, J. Vuilleumier, D. Gerber, A. Tadsen, B. van den Brandt, and P. M. Gillevet, “Detection of single macromolecules using a cryogenic particle detector coupled to a biopolymer mass spectrometer,” *Appl. Phys. Lett.* **68**, 3503–3505 (1996).
- ¹⁸D. Renker, “Geiger-mode avalanche photodiodes, history, properties and problems,” *Nucl. Instrum. Methods Phys. Res. Sect. A* **567**, 48–56 (2006).
- ¹⁹D. Renker and E. Lorenz, “Advances in solid state photon detectors,” *J. Instrum.* **4**, P04004 (2009).
- ²⁰R. Foord, R. Jones, C. Oliver, and E. Pike, “The use of photomultiplier tubes for photon counting,” *Appl. Opt.* **8**, 1975–1989 (1969).
- ²¹P. Cushman and R. Rusack, “A photomultiplier tube incorporating an avalanche photodiode,” *Nucl. Instrum. Methods Phys. Res. Sect. A* **333**, 381–390 (1993).
- ²²G. 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).
- ²³R. H. Hadfield, “Single-photon detectors for optical quantum information applications,” *Nat. Photonics* **3**, 696–705 (2009).
- ²⁴Y. Makhlin, G. Schön, and A. Shnirman, “Quantum-state engineering with josephson-junction devices,” *Rev. Mod. Phys.* **73**, 357 (2001).
- ²⁵J. Clarke and A. I. Braginski, *The SQUID Handbook* (Wiley Online Library, 2004), Vol. 1.
- ²⁶J. Zmuidzinas and P. L. Richards, “Superconducting detectors and mixers for millimeter and submillimeter astrophysics,” *Proc. IEEE* **92**, 1597–1616 (2004).
- ²⁷S. Seliverstov, S. Maslennikov, S. Ryabchun, M. Finkel, T. Klapwijk, N. Kaurova, Y. Vachtomin, K. Smirnov, B. Voronov, and G. Goltsman, “Fast and sensitive terahertz direct detector based on superconducting antenna-coupled hot electron bolometer,” *IEEE Trans. Appl. Supercond.* **25**, 1–4 (2014).
- ²⁸D. H. Andrews, W. F. Brucksch, W. T. Ziegler, and E. R. Blanchard, “Attenuated superconductors i. for measuring infra-red radiation,” *Rev. Sci. Instrum.* **13**, 281–292 (1942).
- ²⁹A. J. Miller, S. W. Nam, J. M. Martinis, and A. V. Sergienko, “Demonstration of a low-noise near-infrared photon counter with multiphoton discrimination,” *Appl. Phys. Lett.* **83**, 791–793 (2003).
- ³⁰K. D. Irwin and G. C. Hilton, “Transition-Edge Sensors,” *Cryogenic Particle Detection*, edited by Enns Christian, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 63–150.
- ³¹A. Verevkin, J. Zhang, R. Sobolewski, A. Lipatov, O. Okunev, G. Chulkova, A. Korneev, K. Smirnov, G. Gol’tsman, and A. Semenov, “Detection efficiency of large-active-area nbn single-photon superconducting detectors in the ultraviolet to near-infrared range,” *Appl. Phys. Lett.* **80**, 4687–4689 (2002).
- ³²J. Zhang, N. Boiadjeva, G. Chulkova, H. Deslandes, G. Goltsman, A. Korneev, P. Kouminov, M. Leibowitz, W. Lo, R. Malinsky, O. Okunev, A. Pearlman, W. Slys, K. Smirnov, C. Tsao, A. Verevkin, B. Voronov, K. Wilsher, and R. Sobolewski, “Noninvasive cmos circuit testing with nbn superconducting single-photon detectors,” *Electron. Lett.* **39**(2), 1086–1088 (2003).
- ³³R. H. Hadfield, J. L. Habif, J. Schlafer, R. E. Schwall, and S. W. Nam, “Quantum key distribution at 1550 nm with twin superconducting single-photon detectors,” *Appl. Phys. Lett.* **89**, 241129 (2006).
- ³⁴H. Takesue, S. W. Nam, Q. Zhang, R. H. Hadfield, T. Honjo, K. Tamaki, and Y. Yamamoto, “Quantum key distribution over a 40-dB channel loss using superconducting single-photon detectors,” *Nat. Photonics* **1**, 343–348 (2007).

- ³⁵X. Hu, T. Zhong, J. E. White, E. A. Dauler, F. Najafi, C. H. Herder, F. N. Wong, and K. K. Berggren, "Fiber-coupled nanowire photon counter at 1550 nm with 24% system detection efficiency," *Opt. Lett.* **34**, 3607–3609 (2009).
- ³⁶X. Hu, E. A. Dauler, R. J. Molnar, and K. K. Berggren, "Superconducting nanowire single-photon detectors integrated with optical nano-antennae," *Opt. Express* **19**, 17–31 (2011).
- ³⁷K. M. Rosfjord, J. K. Yang, E. A. Dauler, A. J. Kerman, V. Anant, B. M. Voronov, G. N. Gol'tsman, and K. K. Berggren, "Nanowire single-photon detector with an integrated optical cavity and anti-reflection coating," *Opt. Express* **14**, 527–534 (2006).
- ³⁸V. B. Verma, F. Marsili, S. Harrington, A. E. Lita, R. P. Mirin, and S. W. Nam, "A three-dimensional, polarization-insensitive superconducting nanowire avalanche photodetector," *Appl. Phys. Lett.* **101**, 251114 (2012).
- ³⁹J. P. Sprengers, A. Gaggero, D. Sahin, S. Jahanmirinejad, G. Frucci, F. Mattioli, R. Leoni, J. Beetz, M. Lermer, M. Kamp, S. Höfling, R. Sanjines, and A. Fiore, "Waveguide superconducting single-photon detectors for integrated quantum photonic circuits," *Appl. Phys. Lett.* **99**, 181110 (2011).
- ⁴⁰W. H. P. Pernice, C. Schuck, O. Minaeva, M. Li, G. N. Goltsman, A. V. Sergienko, and H. X. Tang, "High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits," *Nat. Commun.* **3**, 1325 (2012).
- ⁴¹F. Marsili, V. B. Verma, J. A. Stern, S. Harrington, A. E. Lita, T. Gerrits, I. Vayshenker, B. Baek, M. D. Shaw, R. P. Mirin *et al.*, "Detecting single infrared photons with 93% system efficiency," *Nat. Photonics* **7**, 210–214 (2013).
- ⁴²I. Esmail Zadeh, J. W. N. Los, R. B. M. Gourgues, V. Steinmetz, G. Bulgarini, S. M. Dobrovolskiy, V. Zwiller, and S. N. Dorenbos, "Single-photon detectors combining high efficiency, high detection rates, and ultra-high timing resolution," *APL Photonics* **2**, 111301 (2017).
- ⁴³W. Zhang, L. You, H. Li, J. Huang, C. Lv, L. Zhang, X. Liu, J. Wu, Z. Wang, and X. Xie, "Nbn superconducting nanowire single photon detector with efficiency over 90% at 1550 nm wavelength operational at compact cryocooler temperature," *Sci. China Phys. Mech. Astron.* **60**, 120314 (2017).
- ⁴⁴D. V. Reddy, R. R. Norem, S. W. Nam, R. P. Mirin, and V. B. Verma, "Superconducting nanowire single-photon detectors with 98% system detection efficiency at 1550 nm," *Optica* **7**, 1649–1653 (2020).
- ⁴⁵P. Hu, H. Li, L. You, H. Wang, Y. Xiao, J. Huang, X. Yang, W. Zhang, Z. Wang, and X. Xie, "Detecting single infrared photons toward optimal system detection efficiency," *Opt. Express* **28**, 36884–36891 (2020).
- ⁴⁶J. Chang, J. Los, J. Tenorio-Pearl, N. Noordzij, R. Gourgues, A. Guardiani, J. Zichi, S. Pereira, H. Urbach, V. Zwiller *et al.*, "Detecting telecom single photons with 99.5–2.07+0.5% system detection efficiency and high time resolution," *APL Photonics* **6**, 036114 (2021).
- ⁴⁷L. N. Bulaevskii, M. J. Graf, and V. G. Kogan, "Vortex-assisted photon counts and their magnetic field dependence in single-photon superconducting detectors," *Phys. Rev. B* **85**, 014505 (2012).
- ⁴⁸T. Yamashita, S. Miki, K. Makise, W. Qiu, H. Terai, M. Fujiwara, M. Sasaki, and Z. Wang, "Origin of intrinsic dark count in superconducting nanowire single-photon detectors," *Appl. Phys. Lett.* **99**, 161105 (2011).
- ⁴⁹J. Chang, I. E. Zadeh, J. W. Los, J. Zichi, A. Fognini, M. Gevers, S. Dorenbos, S. F. Pereira, P. Urbach, and V. Zwiller, "Multimode-fiber-coupled superconducting nanowire single-photon detectors with high detection efficiency and time resolution," *Appl. Opt.* **58**, 9803–9807 (2019).
- ⁵⁰H. Shibata, K. Shimizu, H. Takesue, and Y. Tokura, "Ultimate low system dark-count rate for superconducting nanowire single-photon detector," *Opt. Lett.* **40**, 3428–3431 (2015).
- ⁵¹W. Zhang, X. Yang, H. Li, L. You, C. Lv, L. Zhang, C. Zhang, X. Liu, Z. Wang, and X. Xie, "Fiber-coupled superconducting nanowire single-photon detectors integrated with a bandpass filter on the fiber end-face," *Supercond. Sci. Technol.* **31**, 035012 (2018).
- ⁵²S. Chen, L. You, W. Zhang, X. Yang, H. Li, L. Zhang, Z. Wang, and X. Xie, "Dark counts of superconducting nanowire single-photon detector under illumination," *Opt. Express* **23**, 10786–10793 (2015).
- ⁵³Y. Hochberg, I. Charaev, S.-W. Nam, V. Verma, M. Colangelo, and K. K. Berggren, "Detecting sub-gev dark matter with superconducting nanowires," *Phys. Rev. Lett.* **123**, 151802 (2019).
- ⁵⁴L. You, X. Yang, Y. He, W. Zhang, D. Liu, W. Zhang, L. Zhang, L. Zhang, X. Liu, S. Chen *et al.*, "Jitter analysis of a superconducting nanowire single photon detector," *AIP Adv.* **3**, 072135 (2013).
- ⁵⁵Q. Zhao, L. Zhang, T. Jia, L. Kang, W. Xu, J. Chen, and P. Wu, "Intrinsic timing jitter of superconducting nanowire single-photon detectors," *Appl. Phys. B* **104**, 673–678 (2011).
- ⁵⁶E. A. Dauler, B. S. Robinson, A. J. Kerman, J. K. Yang, K. M. Rosfjord, V. Anant, B. Voronov, G. Gol'tsman, and K. K. Berggren, "Multi-element superconducting nanowire single-photon detector," *IEEE Trans. Appl. Supercond.* **17**, 279–284 (2007).
- ⁵⁷V. Shcheslavskiy, P. Morozov, A. Divochiy, Y. Vakhtomin, K. Smirnov, and W. Becker, "Ultrafast time measurements by time-correlated single photon counting coupled with superconducting single photon detector," *Rev. Sci. Instrum.* **87**, 053117 (2016).
- ⁵⁸J. Wu, L. You, S. Chen, H. Li, Y. He, C. Lv, Z. Wang, and X. Xie, "Improving the timing jitter of a superconducting nanowire single-photon detection system," *Appl. Opt.* **56**, 2195–2200 (2017).
- ⁵⁹I. Esmail 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. Kalthor, 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, "Efficient single-photon detection with 7.7 ps time resolution for photon-correlation measurements," *ACS Photonics* **7**, 1780–1787 (2020).
- ⁶⁰B. Korzh, Q.-Y. Zhao, J. P. Allmaras, S. Frasca, T. M. Autry, E. A. Bersin, A. D. Dane, R. M. Briggs, B. Bumble, M. Colangelo *et al.*, "Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector," *Nat. Photonics* **14**, 250–255 (2020).
- ⁶¹B. Korzh, Q.-Y. Zhao, S. Frasca, D. Zhu, E. Ramirez, E. Bersin, M. Colangelo, A. E. Dane, A. D. Beyer, J. Allmaras, E. E. Wollman, K. K. Berggren, and M. D. Shaw, "Wsi superconducting nanowire single photon detector with a temporal resolution below 5 ps," in *Conference on Lasers and Electro-Optics* (Optical Society of America, 2018), p. FW3F.3.
- ⁶²R. H. Hadfield, P. A. Dalgarno, J. A. O'Connor, E. Ramsay, R. J. Warburton, E. J. Gansen, B. Baek, M. J. Stevens, R. P. Mirin, and S. W. Nam, "Submicrometer photoresponse mapping of nanowire superconducting single-photon detectors," *Appl. Phys. Lett.* **91**, 241108 (2007).
- ⁶³A. J. Kerman, E. A. Dauler, J. K. Yang, K. M. Rosfjord, V. Anant, K. K. Berggren, G. N. Gol'tsman, and B. M. Voronov, "Constriction-limited detection efficiency of superconducting nanowire single-photon detectors," *Appl. Phys. Lett.* **90**, 101110 (2007).
- ⁶⁴J. R. Clem and K. K. Berggren, "Geometry-dependent critical currents in superconducting nanocircuits," *Phys. Rev. B* **84**, 174510 (2011).
- ⁶⁵D. Henrich, P. Reichensperger, M. Hofherr, J. Meckbach, K. Il'in, M. Siegel, A. Semenov, A. Zotova, and D. Y. Vodolozov, "Geometry-induced reduction of the critical current in superconducting nanowires," *Phys. Rev. B* **86**, 144504 (2012).
- ⁶⁶H. Hortensius, E. Driessen, T. Klapwijk, K. Berggren, and J. Clem, "Critical-current reduction in thin superconducting wires due to current crowding," *Appl. Phys. Lett.* **100**, 182602 (2012).
- ⁶⁷M. K. Akhlaghi, H. Atikian, A. Eftekharian, M. Loncar, and A. H. Majedi, "Reduced dark counts in optimized geometries for superconducting nanowire single photon detectors," *Opt. Express* **20**, 23610–23616 (2012).
- ⁶⁸G.-Z. Xu, W.-J. Zhang, L.-X. You, J.-M. Xiong, X.-Q. Sun, H. Huang, X. Ou, Y.-M. Pan, C.-L. Lv, H. Li *et al.*, "Superconducting microstrip single-photon detector with system detection efficiency over 90% at 1550 nm," *arXiv:2101.05407* (2021).
- ⁶⁹A. Banerjee, R. M. Heath, D. Morozov, D. Hemakumara, U. Nasti, I. Thayne, and R. H. Hadfield, "Optical properties of refractory metal based thin films," *Opt. Mater. Express* **8**, 2072–2088 (2018).
- ⁷⁰V. Anant, A. J. Kerman, E. A. Dauler, J. K. Yang, K. M. Rosfjord, and K. K. Berggren, "Optical properties of superconducting nanowire single-photon detectors," *Opt. Express* **16**, 10750–10761 (2008).
- ⁷¹S. Dorenbos, E. Reiger, N. Akopian, U. Perinetti, V. Zwiller, T. Zijlstra, and T. Klapwijk, "Superconducting single photon detectors with minimized polarization dependence," *Appl. Phys. Lett.* **93**, 161102 (2008).

- ⁷²F. Zheng, R. Xu, G. Zhu, B. Jin, L. Kang, W. Xu, J. Chen, and P. Wu, "Design of a polarization-insensitive superconducting nanowire single photon detector with high detection efficiency," *Sci. Rep.* **6**(1), 11 (2016).
- ⁷³L. Redaelli, V. Zwiller, E. Monroy, and J. Gérard, "Design of polarization-insensitive superconducting single photon detectors with high-index dielectrics," *Supercond. Sci. Technol.* **30**, 035005 (2017).
- ⁷⁴X. Chi, K. Zou, C. Gu, J. Zichi, Y. Cheng, N. Hu, X. Lan, S. Chen, Z. Lin, V. Zwiller *et al.*, "Fractal superconducting nanowire single-photon detectors with reduced polarization sensitivity," *Opt. Lett.* **43**, 5017–5020 (2018).
- ⁷⁵Y. Meng, K. Zou, N. Hu, X. Lan, L. Xu, J. Zichi, S. Steinhauer, V. Zwiller, and X. Hu, "Fractal superconducting nanowire avalanche photodetector at 1550 nm with 60% system detection efficiency and 1.05 polarization sensitivity," *Opt. Lett.* **45**, 471–474 (2020).
- ⁷⁶R. 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).
- ⁷⁷A. 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).
- ⁷⁸J. 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).
- ⁷⁹C. Autebert, G. Gras, E. Amri, M. Perrenoud, M. Caloz, H. Zbinden, and F. Bussi eres, "Direct measurement of the recovery time of superconducting nanowire single-photon detectors," *J. Appl. Phys.* **128**, 074504 (2020).
- ⁸⁰E. A. Dauler, A. J. Kerman, B. S. Robinson, J. K. Yang, B. Voronov, G. Gol'tsman, S. A. Hamilton, and K. K. Berggren, "Photon-number-resolution with sub-30-ps timing using multi-element superconducting nanowire single photon detectors," *J. Mod. Opt.* **56**, 364–373 (2009).
- ⁸¹A. Divochiy, F. Marsili, D. Bitauld, A. Gaggero, R. Leoni, F. Mattioli, A. Korneev, V. Seleznev, N. Kaurova, O. Minaeva, G. Gol'tsman, K. G. Lagoudakis, M. Benkhaoul, F. L evy, and A. Fiore, "Superconducting nanowire photon-number-resolving detector at telecommunication wavelengths," *Nat. Photonics* **2**, 302–306 (2008).
- ⁸²N. Calandri, Q.-Y. Zhao, D. Zhu, A. Dane, and K. K. Berggren, "Superconducting nanowire detector jitter limited by detector geometry," *Appl. Phys. Lett.* **109**, 152601 (2016).
- ⁸³A. Kozorezov, C. Lambert, F. Marsili, M. Stevens, V. Verma, J. Allmaras, M. Shaw, R. Mirin, and S. W. Nam, "Fano fluctuations in superconducting-nanowire single-photon detectors," *Phys. Rev. B* **96**, 054507 (2017).
- ⁸⁴Y. Cheng, C. Gu, and X. Hu, "Inhomogeneity-induced timing jitter of superconducting nanowire single-photon detectors," *Appl. Phys. Lett.* **111**, 062604 (2017).
- ⁸⁵H. Wu, C. Gu, Y. Cheng, and X. Hu, "Vortex-crossing-induced timing jitter of superconducting nanowire single-photon detectors," *Appl. Phys. Lett.* **111**, 062603 (2017).
- ⁸⁶D. Y. Vodolazov, "Minimal timing jitter in superconducting nanowire single-photon detectors," *Phys. Rev. Appl.* **11**, 014016 (2019).
- ⁸⁷J. Demsar, "Non-equilibrium phenomena in superconductors probed by femto-second time-domain spectroscopy," *J. Low Temp. Phys.* **201**, 676–709 (2020).
- ⁸⁸I. Holzman and Y. Ivry, "Superconducting nanowires for single-photon detection: Progress, challenges, and opportunities," *Adv. Quantum Technol.* **2**, 1800058 (2019).
- ⁸⁹A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Phys. C: Supercond.* **351**, 349–356 (2001).
- ⁹⁰A. Engel, J. J. Renema, K. Il'in, and A. Semenov, "Detection mechanism of superconducting nanowire single-photon detectors," *Supercond. Sci. Technol.* **28**, 114003 (2015).
- ⁹¹J. P. Allmaras, E. E. Wollman, A. D. Beyer, R. M. Briggs, B. A. Korzh, B. Bumble, and M. D. Shaw, "Demonstration of a thermally coupled row-column snspd imaging array," *Nano Lett.* **20**, 2163–2168 (2020).
- ⁹²K. A. Sunter and K. K. Berggren, "Optical modeling of superconducting nanowire single photon detectors using the transfer matrix method," *Appl. Opt.* **57**, 4872–4883 (2018).
- ⁹³A. Engel and A. Schilling, "Numerical analysis of detection-mechanism models of superconducting nanowire single-photon detector," *J. Appl. Phys.* **114**, 214501 (2013).
- ⁹⁴D. Y. Vodolazov, "Single-photon detection by a dirty current-carrying superconducting strip based on the kinetic-equation approach," *Phys. Rev. Appl.* **7**, 034014 (2017).
- ⁹⁵J. Allmaras, A. Kozorezov, B. Korzh, K. Berggren, and M. Shaw, "Intrinsic timing jitter and latency in superconducting nanowire single-photon detectors," *Phys. Rev. Appl.* **11**, 034062 (2019).
- ⁹⁶J. P. Allmaras, "Modeling and development of superconducting nanowire single-photon detectors," Ph.D. thesis (California Institute of Technology, 2020).
- ⁹⁷A. N. Zotova and D. Y. Vodolazov, "Photon detection by current-carrying superconducting film: A time-dependent ginzburg-landau approach," *Phys. Rev. B* **85**, 024509 (2012).
- ⁹⁸J. J. Renema, R. Gaudio, Q. Wang, Z. Zhou, A. Gaggero, F. Mattioli, R. Leoni, D. Sahin, M. J. A. de Dood, A. Fiore, and M. P. van Exter, "Experimental test of theories of the detection mechanism in a nanowire superconducting single photon detector," *Phys. Rev. Lett.* **112**, 117604 (2014).
- ⁹⁹A. Semenov, P. Haas, H.-W. H ubers, K. Ilin, M. Siegel, A. Kirste, D. Drung, T. Schurig, and A. Engel, "Intrinsic quantum efficiency and electro-thermal model of a superconducting nanowire single-photon detector," *J. Mod. Opt.* **56**, 345–351 (2009).
- ¹⁰⁰Q.-Y. Zhao, D. F. Santavicca, D. Zhu, B. Noble, and K. K. Berggren, "A distributed electrical model for superconducting nanowire single photon detectors," *Appl. Phys. Lett.* **113**, 082601 (2018).
- ¹⁰¹A. J. Kerman, J. K. W. Yang, R. J. Molnar, E. A. Dauler, and K. K. Berggren, "Electrothermal feedback in superconducting nanowire single-photon detectors," *Phys. Rev. B* **79**, 100509 (2009).
- ¹⁰²A. Verevkin, C. Williams, G. N. Gol'tsman, R. Sobolewski, and G. Gilbert, "Single-photon superconducting detectors for practical high-speed quantum cryptography," in *International Conference on Quantum Information* (Optical Society of America, 2001), p. PA3.
- ¹⁰³M. Ejrnaes, L. Parlato, R. Arpaia, T. Bauch, F. Lombardi, R. Cristiano, F. Tafuri, and G. Pepe, "Observation of dark pulses in 10 nm thick ybco nano-strips presenting hysteretic current voltage characteristics," *Supercond. Sci. Technol.* **30**, 12LT02 (2017).
- ¹⁰⁴M. 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 yba2cu3o7-x nanowires," *Nat. Commun.* **11**, 763 (2020).
- ¹⁰⁵L. You, "Superconducting nanowire single-photon detectors for quantum information," *Nanophotonics* **9**, 2673–2692 (2020).
- ¹⁰⁶V. B. Verma, A. E. Lita, M. R. Vissers, F. Marsili, D. P. Pappas, R. P. Mirin, and S. W. Nam, "Superconducting nanowire single photon detectors fabricated from an amorphous mo0.75ge0.25 thin film," *Appl. Phys. Lett.* **105**, 022602 (2014).
- ¹⁰⁷I. Milostnaya, A. Korneev, M. Tarkhov, A. Divochiy, O. Minaeva, V. Seleznev, N. Kaurova, B. Voronov, O. Okunev, G. Chulkova, K. Smirnov, and G. Gol'tsman, "Superconducting single photon nanowire detectors development for ir and thz applications," *J. Low Temp. Phys.* **151**, 591–596 (2008).
- ¹⁰⁸Y. P. Korneeva, M. Y. Mikhailov, Y. P. Pershin, N. Manova, A. Divochiy, Y. B. Vakhtomin, A. Korneev, K. Smirnov, A. Sivakov, A. Y. Devizenko *et al.*, "Superconducting single-photon detector made of mosi film," *Supercond. Sci. Technol.* **27**, 095012 (2014).
- ¹⁰⁹V. B. Verma, B. Korzh, F. Bussi eres, R. D. Horansky, S. D. Dyer, A. E. Lita, I. Vayshenker, F. Marsili, M. D. Shaw, H. Zbinden, R. P. Mirin, and S. W. Nam, "High-efficiency superconducting nanowire single-photon detectors fabricated from mosi thin-films," *Opt. Express* **23**, 33792–33801 (2015).
- ¹¹⁰M. Caloz, M. Perrenoud, C. Autebert, B. Korzh, M. Weiss, C. Sch onenberger, R. J. Warburton, H. Zbinden, and F. Bussi eres, "High-detection efficiency and low-timing jitter with amorphous superconducting nanowire single-photon detectors," *Appl. Phys. Lett.* **112**, 061103 (2018).
- ¹¹¹C. Cirillo, J. Chang, M. Caputo, J. Los, S. Dorenbos, I. Esmail Zadeh, and C. Attanasio, "Superconducting nanowire single photon detectors based on disordered nbre films," *Appl. Phys. Lett.* **117**, 172602 (2020).
- ¹¹²S. N. Dorenbos, P. Forn-D iaz, T. Fuse, A. H. Verbruggen, T. Zijlstra, T. M. Klapwijk, and V. Zwiller, "Low gap superconducting single photon detectors for infrared sensitivity," *Appl. Phys. Lett.* **98**, 251102 (2011).

- ¹¹³A. Engel, A. Aeschbacher, K. Inderbitzin, A. Schilling, K. Il'in, M. Hofherr, M. Siegel, A. Semenov, and H.-W. Hübers, "Tantalum nitride superconducting single-photon detectors with low cut-off energy," *Appl. Phys. Lett.* **100**, 062601 (2012).
- ¹¹⁴H. Shibata, T. Akazaki, and Y. Tokura, "Fabrication of mgb₂ nanowire single-photon detector with meander structure," *Appl. Phys. Express* **6**, 023101 (2013).
- ¹¹⁵S. Cherednichenko, N. Acharya, E. Novoselov, and V. Drakinskiy, "Low kinetic inductance superconducting mgb₂ nanowire photon detectors with a 100 picosecond relaxation time," [arXiv:1911.01480](https://arxiv.org/abs/1911.01480) (2019).
- ¹¹⁶S. Cherednichenko, N. Acharya, E. Novoselov, and V. Drakinskiy, "Ir- and visible- light single photon detection in superconducting mgb₂ nanowires," [arXiv:1911.01652](https://arxiv.org/abs/1911.01652) (2019).
- ¹¹⁷R. M. Heath, M. G. Tanner, T. D. Drysdale, S. Miki, V. Giannini, S. A. Maier, and R. H. Hadfield, "Nanoantenna enhancement for telecom-wavelength superconducting single photon detectors," *Nano Lett.* **15**, 819–822 (2015).
- ¹¹⁸Q. Xue, G. Song, and R. Jiao, "Amplification of absorption induced by localized surface plasmons in superconducting nanowire single-photon detector," *Plasmonics* **14**, 117–123 (2019).
- ¹¹⁹J. Zichi, J. Chang, S. Steinhauer, K. Von Fieandt, J. W. Los, G. Visser, N. Kalhor, T. Lettner, A. W. Elshaari, I. E. Zadeh *et al.*, "Optimizing the stoichiometry of ultrathin nbtin films for high-performance superconducting nanowire single-photon detectors," *Opt. Express* **27**, 26579–26587 (2019).
- ¹²⁰R. Cheng, S. Wang, and H. Tang, "Superconducting nanowire single-photon detectors fabricated from atomic-layer-deposited nbn," *Appl. Phys. Lett.* **115**, 241101 (2019).
- ¹²¹E. Knehr, A. Kuzmin, D. Y. Vodolazov, M. Ziegler, S. Doerner, K. Ilin, M. Siegel, R. Stolz, and H. Schmidt, "Nanowire single-photon detectors made of atomic layer-deposited niobium nitride," *Supercond. Sci. Technol.* **32**, 125007 (2019).
- ¹²²R. Cheng, J. Wright, H. G. Xing, D. Jena, and H. X. Tang, "Epitaxial niobium nitride superconducting nanowire single-photon detectors," *Appl. Phys. Lett.* **117**, 132601 (2020).
- ¹²³K. Inderbitzin, A. Engel, A. Schilling, K. Il'in, and M. Siegel, "An ultra-fast superconducting nb nanowire single-photon detector for soft x-rays," *Appl. Phys. Lett.* **101**, 162601 (2012).
- ¹²⁴D. Perez de Lara, M. Ejrnaes, A. Casaburi, M. Lisitskiy, R. Cristiano, S. Pagano, A. Gaggero, R. Leoni, G. Golt'sman, and B. Voronov, "Feasibility investigation of nbn nanowires as detector in time-of-flight mass spectrometers for macromolecules of interest in biology (proteins)," *J. Low Temp. Phys.* **151**, 771–776 (2008).
- ¹²⁵A. Branny, P. Didier, J. Zichi, I. E. Zahed, S. Steinhauer, V. Zwiller, and U. Vogt, "X-ray induced secondary particle counting with thin NbTiN nanowire superconducting detector," *IEEE Transactions on Applied Superconductivity* **1–1** (2021).
- ¹²⁶K. Inderbitzin, A. Engel, and A. Schilling, "Soft x-ray single-photon detection with superconducting tantalum nitride and niobium nanowires," *IEEE Trans. Appl. Supercond.* **23**, 2200505 (2013).
- ¹²⁷X. Zhang, Q. Wang, and A. Schilling, "Superconducting single x-ray photon detector based on w_{0.8}si_{0.2}," *AIP Adv.* **6**, 115104 (2016).
- ¹²⁸E. E. Wollman, V. B. Verma, A. D. Beyer, R. M. Briggs, B. Korzh, J. P. Allmaras, F. Marsili, A. E. Lita, R. P. Mirin, S. W. Nam, and M. D. Shaw, "Uv superconducting nanowire single-photon detectors with high efficiency, low noise, and 4 k operating temperature," *Opt. Express* **25**, 26792–26801 (2017).
- ¹²⁹V. Verma, B. Korzh, A. Walter, A. Lita, R. Briggs, M. Colangelo, Y. Zhai, E. Wollman, A. Beyer, J. Allmaras *et al.*, "Single-photon detection in the mid-infrared up to 10 micron wavelength using tungsten silicide superconducting nanowire detectors," [arXiv:2012.09979](https://arxiv.org/abs/2012.09979) (2020).
- ¹³⁰H. Azzouz, S. N. Dorenbos, D. De Vries, E. B. Ureña, and V. Zwiller, "Efficient single particle detection with a superconducting nanowire," *AIP Adv.* **2**, 032124 (2012).
- ¹³¹S. Steinhauer, S. Gyger, and V. Zwiller, "Progress on large-scale superconducting nanowire single-photon detectors," *Appl. Phys. Lett.* **118**, 100501 (2021).
- ¹³²E. 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).
- ¹³³R. Cheng, C.-L. Zou, X. Guo, S. Wang, X. Han, and H. X. Tang, "Broadband on-chip single-photon spectrometer," *Nat. Commun.* **10**, 1–7 (2019).
- ¹³⁴M. Hofherr, M. Arndt, K. Il'in, D. Henrich, M. Siegel, J. Toussaint, T. May, and H.-G. Meyer, "Time-tagged multiplexing of serially biased superconducting nanowire single-photon detectors," *IEEE Trans. Appl. Supercond.* **23**, 2501205 (2013).
- ¹³⁵Q.-Y. Zhao, D. Zhu, N. Calandri, A. E. Dane, A. N. McCaughan, F. Bellei, H.-Z. Wang, D. F. Santavicca, and K. K. Berggren, "Single-photon imager based on a superconducting nanowire delay line," *Nat. Photonics* **11**, 247 (2017).
- ¹³⁶D. Zhu, Q.-Y. Zhao, H. Choi, T.-J. Lu, A. E. Dane, D. Englund, and K. K. Berggren, "A scalable multi-photon coincidence detector based on superconducting nanowires," *Nat. Nanotechnol.* **13**, 596–601 (2018).
- ¹³⁷A. W. Elshaari, A. Iovan, S. Gyger, I. E. Zadeh, J. Zichi, L. Yang, S. Steinhauer, and V. Zwiller, "Dispersion engineering of superconducting waveguides for multi-pixel integration of single-photon detectors," *APL Photonics* **5**, 111301 (2020).
- ¹³⁸S. Miki, H. Terai, T. Yamashita, K. Makise, M. Fujiwara, M. Sasaki, and Z. Wang, "Superconducting single photon detectors integrated with single flux quantum readout circuits in a cryocooler," *Appl. Phys. Lett.* **99**, 111108 (2011).
- ¹³⁹T. Ortlepp, M. Hofherr, L. Fritzsche, S. Engert, K. Ilin, D. Rall, H. Toepfer, H.-G. Meyer, and M. Siegel, "Demonstration of digital readout circuit for superconducting nanowire single photon detector," *Opt. Express* **19**, 18593–18601 (2011).
- ¹⁴⁰H. Terai, T. Yamashita, S. Miki, K. Makise, and Z. Wang, "Low-jitter single flux quantum signal readout from superconducting single photon detector," *Opt. Express* **20**, 20115–20123 (2012).
- ¹⁴¹S. Miki, S. Miyajima, M. Yabuno, T. Yamashita, T. Yamamoto, N. Imoto, R. Ikuta, R. A. Kirkwood, R. H. Hadfield, and H. Terai, "Superconducting coincidence photon detector with short timing jitter," *Appl. Phys. Lett.* **112**, 262601 (2018).
- ¹⁴²M. Yabuno, S. Miyajima, S. Miki, and H. Terai, "Scalable implementation of a superconducting nanowire single-photon detector array with a superconducting digital signal processor," *Opt. Express* **28**, 12047–12057 (2020).
- ¹⁴³N. Takeuchi, F. China, S. Miki, S. Miyajima, M. Yabuno, N. Yoshikawa, and H. Terai, "Scalable readout interface for superconducting nanowire single-photon detectors using aqfp and rsfq logic families," *Opt. Express* **28**, 15824–15834 (2020).
- ¹⁴⁴S. Doerner, A. Kuzmin, S. Wuensch, I. Charaev, F. Boes, T. Zwick, and M. Siegel, "Frequency-multiplexed bias and readout of a 16-pixel superconducting nanowire single-photon detector array," *Appl. Phys. Lett.* **111**, 032603 (2017).
- ¹⁴⁵A. Gaggero, F. Martini, F. Mattioli, F. Chiarello, R. Cernansky, A. Politi, and R. Leoni, "Amplitude-multiplexed readout of single photon detectors based on superconducting nanowires," *Optica* **6**, 823–828 (2019).
- ¹⁴⁶J. Tiedau, T. Schapeler, V. Anant, H. Fedder, C. Silberhorn, and T. J. Bartley, "Single-channel electronic readout of a multipixel superconducting nanowire single photon detector," *Opt. Express* **28**, 5528–5537 (2020).
- ¹⁴⁷Y. P. Korneeva, D. Y. Vodolazov, A. V. Semenov, I. N. Florya, N. Simonov, E. Baeva, A. A. Korneev, G. N. Goltsman, and T. M. Klapwijk, "Optical single-photon detection in micrometer-scale nbn bridges," *Phys. Rev. Appl.* **9**, 064037 (2018).
- ¹⁴⁸D. Vodolazov, I. Florya, N. Manova, E. Smirnov, A. Korneev, M. Mikhailov, G. Goltsman, and T. Klapwijk, "Single photon detection in micron scale nbn and a-mosi superconducting strips," *EPJ Web Conf.* **190**, 04010 (2018).
- ¹⁴⁹I. 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).
- ¹⁵⁰S. S. Ustavshchikov, M. Y. Levichev, I. Y. Pashenkin, A. M. Klushin, and D. Y. Vodolazov, "Approaching depairing current in dirty thin superconducting strip covered by low resistive normal metal," *Supercond. Sci. Technol.* **34**, 015004 (2021).
- ¹⁵¹J. Chiles, S. M. Buckley, A. Lita, V. B. Verma, J. Allmaras, B. Korzh, M. D. Shaw, J. M. Shainline, R. P. Mirin, and S. W. Nam, "Superconducting microwire detectors based on wsi with single-photon sensitivity in the near-infrared," *Appl. Phys. Lett.* **116**, 242602 (2020).

- ¹⁵²D. Vodolazov, N. Manova, Y. Korneeva, and A. Korneev, "Timing jitter in nbn superconducting microstrip single-photon detector," *Phys. Rev. Appl.* **14**, 044041 (2020).
- ¹⁵³A. Boaron, G. Boso, D. Rusca, C. Vulliez, C. Autebert, M. Caloz, M. Perrenoud, G. Gras, F. Bussi eres, M.-J. Li, D. Nolan, A. Martin, and H. Zbinden, "Secure quantum key distribution over 421 km of optical fiber," *Phys. Rev. Lett.* **121**, 190502 (2018).
- ¹⁵⁴Y. Yu, F. Ma, X.-Y. Luo, B. Jing, P.-F. Sun, R.-Z. Fang, C.-W. Yang, H. Liu, M.-Y. Zheng, X.-P. Xie, W.-J. Zhang, L.-X. You, Z. Wang, T.-Y. Chen, Q. Zhang, X.-H. Bao, and J.-W. Pan, "Entanglement of two quantum memories via fibres over dozens of kilometres," *Nature* **578**, 240–245 (2020).
- ¹⁵⁵J.-P. Chen, C. Zhang, Y. Liu, C. Jiang, W. Zhang, X.-L. Hu, J.-Y. Guan, Z.-W. Yu, H. Xu, J. Lin, M.-J. Li, H. Chen, H. Li, L. You, Z. Wang, X.-B. Wang, Q. Zhang, and J.-W. Pan, "Sending-or-not-sending with independent lasers: Secure twin-field quantum key distribution over 509 km," *Phys. Rev. Lett.* **124**, 070501 (2020).
- ¹⁵⁶L. K. Shalm, E. Meyer-Scott, B. G. Christensen, P. Bierhorst, M. A. Wayne, M. J. Stevens, T. Gerrits, S. Glancy, D. R. Hamel, M. S. Allman, K. J. Coakley, S. D. Dyer, C. Hodge, A. E. Lita, V. B. Verma, C. Lambrocco, E. Tortorici, A. L. Migdall, Y. Zhang, D. R. Kumor, W. H. Farr, F. Marsili, M. D. Shaw, J. A. Stern, C. Abell an, W. Amaya, V. Pruneri, T. Jennewein, M. W. Mitchell, P. G. Kwiat, J. C. Bienfang, R. P. Mirin, E. Knill, and S. W. Nam, "Strong loophole-free test of local realism," *Phys. Rev. Lett.* **115**, 250402 (2015).
- ¹⁵⁷S. 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).
- ¹⁵⁸S. Khasminskaya, F. Pyatkov, K. Slowik, S. Ferrari, O. Kahl, V. Kovalyuk, P. Rath, A. Vetter, F. Hennrich, M. M. Kappes, G. Gol'tsman, A. Korneev, C. Rockstuhl, R. Krupke, and W. H. P. Pernice, "Fully integrated quantum photonic circuit with an electrically driven light source," *Nat. Photonics* **10**, 727–732 (2016).
- ¹⁵⁹L. Elsinger, R. Gourgues, I. E. Zadeh, J. Maes, A. Guardiani, G. Bulgarini, S. F. Pereira, S. N. Dorenbos, V. Zwiller, Z. Hens, and D. Van Thourhout, "Integration of colloidal pbs/cds quantum dots with plasmonic antennas and superconducting detectors on a silicon nitride photonic platform," *Nano Lett.* **19**, 5452–5458 (2019).
- ¹⁶⁰C. Schuck, X. Guo, L. Fan, X. Ma, M. Poot, and H. X. Tang, "Quantum interference in heterogeneous superconducting-photonic circuits on a silicon chip," *Nat. Commun.* **7**, 10352 (2016).
- ¹⁶¹F. Beutel, H. Gehring, M. A. Wolff, C. Schuck, and W. Pernice, "Detector-integrated on-chip qkd receiver for ghz clock rates," *NPJ Quantum Inf.* **7**, 40 (2021).
- ¹⁶²C. Schuck, W. H. P. Pernice, O. Minaeva, M. Li, G. Gol'tsman, A. V. Sergienko, and H. X. Tang, "Matrix of integrated superconducting single-photon detectors with high timing resolution," *IEEE Trans. Appl. Supercond.* **23**, 2201007 (2013).
- ¹⁶³F. 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).
- ¹⁶⁴J. Li, R. A. Kirkwood, L. J. Baker, D. Bosworth, K. Erotokritou, A. Banerjee, R. M. Heath, C. M. Natarajan, Z. H. Barber, M. Sorel, and R. H. Hadfield, "Nano-optical single-photon response mapping of waveguide integrated molybdenum silicide (mosi) superconducting nanowires," *Opt. Express* **24**, 13931–13938 (2016).
- ¹⁶⁵A. Vetter, S. Ferrari, P. Rath, R. Alaei, O. Kahl, V. Kovalyuk, S. Diewald, G. N. Goltsman, A. Korneev, C. Rockstuhl, and W. H. P. Pernice, "Cavity-enhanced and ultrafast superconducting single-photon detectors," *Nano Lett.* **16**, 7085–7092 (2016).
- ¹⁶⁶S. Buckley, J. Chiles, A. N. McCaughan, G. Moody, K. L. Silverman, M. J. Stevens, R. P. Mirin, S. W. Nam, and J. M. Shainline, "All-silicon light-emitting diodes waveguide-integrated with superconducting single-photon detectors," *Appl. Phys. Lett.* **111**, 141101 (2017).
- ¹⁶⁷M. K. Akhlaghi, E. Schelew, and J. F. Young, "Waveguide integrated superconducting single-photon detectors implemented as near-perfect absorbers of coherent radiation," *Nat. Commun.* **6**, 8233 (2015).
- ¹⁶⁸J. M unzberg, A. Vetter, F. Beutel, W. Hartmann, S. Ferrari, W. H. P. Pernice, and C. Rockstuhl, "Superconducting nanowire single-photon detector implemented in a 2d photonic crystal cavity," *Optica* **5**, 658–665 (2018).
- ¹⁶⁹P. Cavalier, J.-C. Villegier, P. Feautrier, C. Constancias, and A. Morand, "Light interference detection on-chip by integrated snspd counters," *AIP Adv.* **1**, 042120 (2011).
- ¹⁷⁰C. Schuck, W. H. P. Pernice, and H. X. Tang, "Nbn superconducting nanowire detectors for visible and telecom wavelengths single photon counting on si3n4 photonic circuits," *Appl. Phys. Lett.* **102**, 051101 (2013).
- ¹⁷¹C. Schuck, W. H. P. Pernice, and H. X. Tang, "Waveguide integrated low noise nbn nanowire single-photon detectors with milli-hz dark count rate," *Sci. Rep.* **3**, 1893 (2013).
- ¹⁷²A. D. Beyer, R. M. Briggs, F. Marsili, J. D. Cohen, S. M. Meenehan, O. J. Painter, and M. D. Shaw, "Waveguide-coupled superconducting nanowire single-photon detectors," in *2015 Conference on Lasers and Electro-Optics (CLEO)* (2015), pp. 1–2.
- ¹⁷³R. Gourgues, I. E. Zadeh, A. W. Elshaari, G. Bulgarini, J. W. N. Los, J. Zichi, D. Dalacu, P. J. Poole, S. N. Dorenbos, and V. Zwiller, "Controlled integration of selected detectors and emitters in photonic integrated circuits," *Opt. Express* **27**, 3710–3716 (2019).
- ¹⁷⁴S. Steinhauer, L. Yang, S. Gyger, T. Lettner, C. Errando-Herranz, K. D. J ons, 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).
- ¹⁷⁵G. Reithmaier, M. Kaniber, F. Flassig, S. Lichtmanecker, K. M uller, A. Andrejew, J. Vučkovi c, R. Gross, and J. J. Finley, "On-chip generation, routing, and detection of resonance fluorescence," *Nano Lett.* **15**, 5208–5213 (2015).
- ¹⁷⁶G. E. Digeronimo, M. Petruzzella, S. Birindelli, R. Gaudio, S. Fattah Poor, F. W. Van Otten, and A. Fiore, "Integration of single-photon sources and detectors on gaas," *Photonics* **3**, 55 (2016).
- ¹⁷⁷M. Kaniber, F. Flassig, G. Reithmaier, R. Gross, and J. J. Finley, "Integrated superconducting detectors on semiconductors for quantum optics applications," *Appl. Phys. B* **122**, 115 (2016).
- ¹⁷⁸D. Zhu, H. Choi, T. Lu, Q. Zhao, A. Dane, F. Najafi, D. R. Englund, and K. K. Berggren, "Superconducting nanowire single-photon detector on aluminum nitride," in *2016 Conference on Lasers and Electro-Optics (CLEO)* (2016), pp. 1–2.
- ¹⁷⁹M. G. Tanner, L. S. E. Alvarez, W. Jiang, R. J. Warburton, Z. H. Barber, and R. H. Hadfield, "A superconducting nanowire single photon detector on lithium niobate," *Nanotechnology* **23**, 505201 (2012).
- ¹⁸⁰J. P. H opker, M. Bartnick, E. Meyer-Scott, F. Thiele, S. Krapick, N. Montaut, M. Santandrea, H. Herrmann, S. Lengeling, R. Ricken, V. Quiring, T. Meier, A. Lita, V. Verma, T. Gerrits, S. W. Nam, C. Silberhorn, and T. J. Bartley, "Towards integrated superconducting detectors on lithium niobate waveguides," in *Quantum Photonic Devices*, edited by C. Soci, M. Agio, and K. Srinivasan (SPIE, 2017), Vol. 10358, pp. 21–27.
- ¹⁸¹M. A. Wolff, S. Vogel, L. Splitthoff, and C. Schuck, "Superconducting nanowire single-photon detectors integrated with tantalum pentoxide waveguides," *Sci. Rep.* **10**, 17170 (2020).
- ¹⁸²H. Atikian, S. Meesala, M. Burek, Y.-I. Sohn, J. Israelian, A. Patri, N. Clarke, A. Sipahigil, R. Evans, D. Sukachev, R. Westervelt, M. Lukin, and M. Loncar, "Novel fabrication of diamond nanophotonics coupled to single-photon detectors," *SPIE Newsroom* (2017).
- ¹⁸³O. Kahl, S. Ferrari, P. Rath, A. Vetter, C. Nebel, and W. H. P. Pernice, "High efficiency on-chip single-photon detection for diamond nanophotonic circuits," *J. Lightwave Technol.* **34**, 249–255 (2016).
- ¹⁸⁴S. Ferrari, C. Schuck, and W. Pernice, "Waveguide-integrated superconducting nanowire single-photon detectors," *Nanophotonics* **7**, 1725–1758 (2018).
- ¹⁸⁵J. Zhu, Y. Chen, L. Zhang, X. Jia, Z. Feng, G. Wu, X. Yan, J. Zhai, Y. Wu, Q. Chen, X. Zhou, Z. Wang, C. Zhang, L. Kang, J. Chen, and P. Wu, "Demonstration of measuring sea fog with an snspd-based lidar system," *Sci. Rep.* **7**, 15113 (2017).
- ¹⁸⁶A. McCarthy, N. J. Krichel, N. R. Gemmell, X. Ren, M. G. Tanner, S. N. Dorenbos, V. Zwiller, R. H. Hadfield, and G. S. Buller, "Kilometer-range, high resolution depth imaging via 1560 nm wavelength single-photon detection," *Opt. Express* **21**, 8904–8915 (2013).

- ¹⁸⁷A. Casaburi, M. Ejrnaes, N. Zen, M. Ohkubo, S. Pagano, and R. Cristiano, "Thicker, more efficient superconducting strip-line detectors for high throughput macromolecules analysis," *Appl. Phys. Lett.* **98**, 023702 (2011).
- ¹⁸⁸M. Marksteiner, A. Divochij, M. Sclafani, P. Haslinger, H. Ulbricht, A. Korneev, A. Semenov, G. Gol'tsman, and M. Arndt, "A superconducting NbN detector for neutral nanoparticles," *Nanotechnology* **20**, 455501 (2009).
- ¹⁸⁹M. Sclafani, M. Marksteiner, F. M. Keir, A. Divochij, A. Korneev, A. Semenov, G. Gol'tsman, and M. Arndt, "Sensitivity of a superconducting nanowire detector for single ions at low energy," *Nanotechnology* **23**, 065501 (2012).
- ¹⁹⁰R. Cristiano, M. Ejrnaes, A. Casaburi, N. Zen, and M. Ohkubo, "Superconducting nano-strip particle detectors," *Supercond. Sci. Technol.* **28**, 124004 (2015).
- ¹⁹¹J. A. Moon, R. Mahon, M. D. Duncan, and J. Reintjes, "Resolution limits for imaging through turbid media with diffuse light," *Opt. Lett.* **18**, 1591–1593 (1993).
- ¹⁹²D. Tamborini, V. Anant, B. A. Korzh, M. D. Shaw, S. A. Carp, and M. A. Franceschini, "Superconducting nanowire single-photon detectors for diffuse correlation spectroscopy," in *Biophotonics Congress: Optics in the Life Sciences Congress 2019 (BODA, BRAIN, NTM, OMA, OMP)* (Optical Society of America, 2019), p. BW1A.5.
- ¹⁹³P. Eraerds, M. Legre, J. Zhang, H. Zbinden, and N. Gisin, "Photon counting otdr: Advantages and limitations," *J. Lightwave Technol.* **28**, 952 (2010).
- ¹⁹⁴Q. 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).
- ¹⁹⁵M. 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).
- ¹⁹⁶S. 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).
- ¹⁹⁷E. Toomey, K. Segall, and K. K. Berggren, "Design of a power efficient artificial neuron using superconducting nanowires," *Front. Neurosci.* **13**, 933 (2019).
- ¹⁹⁸E. Toomey, K. Segall, M. Castellani, M. Colangelo, N. Lynch, and K. K. Berggren, "Superconducting nanowire spiking element for neural networks," *Nano Lett.* **20**, 8059–8066 (2020).
- ¹⁹⁹J. M. Shainline, S. M. Buckley, R. P. Mirin, and S. W. Nam, "Superconducting optoelectronic circuits for neuromorphic computing," *Phys. Rev. Appl.* **7**, 034013 (2017).
- ²⁰⁰A. N. McCaughan, V. B. Verma, S. M. Buckley, J. P. Allmaras, A. G. Kozorezov, A. N. Tait, S. W. Nam, and J. M. Shainline, "A superconducting thermal switch with ultrahigh impedance for interfacing superconductors to semiconductors," *Nat. Electron.* **2**, 451–456 (2019).
- ²⁰¹D. Silver, J. Schrittwieser, K. Simonyan, I. Antonoglou, A. Huang, A. Guez, T. Hubert, L. Baker, M. Lai, A. Bolton, Y. Chen, T. Lillicrap, F. Hui, L. Sifre, G. van den Driessche, T. Graepel, and D. Hassabis, "Mastering the game of go without human knowledge," *Nature* **550**, 354–359 (2017).
- ²⁰²B. S. Robinson, A. J. Kerman, E. A. Dauler, R. J. Barron, D. O. Caplan, M. L. Stevens, J. J. Carney, S. A. Hamilton, J. K. Yang, and K. K. Berggren, "781 mbit/s photon-counting optical communications using a superconducting nanowire detector," *Opt. Lett.* **31**, 444–446 (2006).
- ²⁰³A. Biswas, M. Srinivasan, S. Piazzolla, and D. Hoppe, "Deep space optical communications," in *Free-Space Laser Communication and Atmospheric Propagation XXX*, edited by H. Hemmati and D. M. Boroson (SPIE, 2018), Vol. 10524, pp. 242–252.
- ²⁰⁴M. E. Grein, A. J. Kerman, E. A. Dauler, O. Shatrovov, R. J. Molnar, D. Rosenberg, J. Yoon, C. E. DeVoe, D. V. Murphy, B. S. Robinson, and D. M. Boroson, "Design of a ground-based optical receiver for the lunar laser communications demonstration," in *2011 International Conference on Space Optical Systems and Applications (ICSOS)* (2011), pp. 78–82.
- ²⁰⁵D. G. Messerschmitt, P. Lubin, and I. Morrison, "Challenges in scientific data communication from low-mass interstellar probes," *Astrophys. J. Suppl. Ser.* **249**, 36 (2020).
- ²⁰⁶B. S. Robinson, D. M. Boroson, D. A. Burianeck, and D. V. Murphy, "Overview of the lunar laser communications demonstration," in *Free-Space Laser Communication Technologies XXIII*, edited by H. Hemmati (SPIE, 2011), Vol. 7923, pp. 9–12.
- ²⁰⁷R. Hanbury Brown, R. C. Jennison, and M. K. D. Gupta, "Apparent angular sizes of discrete radio sources: Observations at jodrell bank, manchester," *Nature* **170**, 1061–1063 (1952).
- ²⁰⁸F. Marsili, V. B. Verma, M. J. Stevens, J. A. Stern, M. D. Shaw, A. J. Miller, D. Schwarzer, A. Wodtke, R. P. Mirin, and S. W. Nam, "Mid-infrared single-photon detection with tungsten silicide superconducting nanowires," in *Cleo: 2013* (Optical Society of America, 2013), p. CTu1H.1.
- ²⁰⁹Q. 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 $\text{Mo}_0.8\text{Si}_{1.2}$ nanowire," [arXiv:2011.06699](https://arxiv.org/abs/2011.06699) (2020).
- ²¹⁰L. Chen, D. Schwarzer, V. B. Verma, M. J. Stevens, F. Marsili, R. P. Mirin, S. W. Nam, and A. M. Wodtke, "Mid-infrared laser-induced fluorescence with nanosecond time resolution using a superconducting nanowire single-photon detector: New technology for molecular science," *Acc. Chem. Res.* **50**, 1400–1409 (2017).
- ²¹¹L. Chen, D. Schwarzer, J. A. Lau, V. B. Verma, M. J. Stevens, F. Marsili, R. P. Mirin, S. W. Nam, and A. M. Wodtke, "Ultra-sensitive mid-infrared emission spectrometer with sub-ns temporal resolution," *Opt. Express* **26**, 14859–14868 (2018).
- ²¹²E. E. Wollman, V. B. Verma, A. B. Walter, J. Chiles, B. Korzh, J. P. Allmaras, Y. Zhai, A. E. Lita, A. N. McCaughan, E. Schmidt, S. Frasca, R. P. Mirin, S.-W. Nam, and M. D. Shaw, "Recent advances in superconducting nanowire single-photon detector technology for exoplanet transit spectroscopy in the mid-infrared," *J. Astron. Telesc. Instrum. Syst.* **7**, 1–10 (2021).
- ²¹³D. R. Schaart, S. Ziegler, and H. Zaidi, "Achieving 10 ps coincidence time resolution in tof-pet is an impossible dream," *Med. Phys.* **47**, 2721–2724 (2020).
- ²¹⁴P. Lecoq, C. Morel, J. O. Prior, D. Visvikis, S. Gundacker, E. Auffray, P. Krizan, R. M. Turtos, D. Thers, E. Charbon, J. Varela, C. de La Taille, A. Rivetti, D. Breton, J.-F. Pratte, J. Nuyts, S. Surti, S. Vandenbergh, P. Marsden, K. Parodi, J. M. Benlloch, and M. Benoit, "Roadmap toward the 10 ps time-of-flight PET challenge," *Phys. Med. Biol.* **65**, 21RM01 (2020).
- ²¹⁵P. Lecoq, "Pushing the limits in time-of-flight pet imaging," *IEEE Trans. Radiat. Plasma Med. Sci.* **1**, 473–485 (2017).
- ²¹⁶A. Lai, T. Itoh, and C. Caloz, "Composite right/left-handed transmission line metamaterials," *IEEE Microwave Mag.* **5**, 34–50 (2004).
- ²¹⁷M. Mirhosseini, E. Kim, V. S. Ferreira, M. Kalae, A. Sipahigil, A. J. Keller, and O. Painter, "Superconducting metamaterials for waveguide quantum electrodynamics," *Nat. Commun.* **9**, 3706 (2018).
- ²¹⁸E. Smith, R. De Alba, N. Zhelev, R. Bennett, V. Adiga, H. Solanki, V. Singh, M. Deshmukh, and J. Parpia, "Compact, inexpensive coaxial terminations and wiring for low temperature rf applications," *Cryogenics* **52**, 461–464 (2012).
- ²¹⁹N. R. Gemmill, M. Hills, T. Bradshaw, T. Rawlings, B. Green, R. M. Heath, K. Tsimvrakidis, S. Dobrovolskiy, V. Zwiller, S. N. Dorenbos, M. Crook, and R. H. Hadfield, "A miniaturized 4 k platform for superconducting infrared photon counting detectors," *Supercond. Sci. Technol.* **30**, 11LT01 (2017).
- ²²⁰E. Lomonte, M. A. Wolff, F. Beutel, S. Ferrari, C. Schuck, W. H. Pernice, and F. Lenzini, "Single-photon detection and cryogenic reconfigurability in lithium niobate nanophotonic circuits," [arXiv:2103.10973](https://arxiv.org/abs/2103.10973) (2021).