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Los, J. W.Niels; Sidorova, Mariia; Lopez-Rodriguez, Bruno; Qualm, Patrick; Chang, Jin; Steinhauer, Stephan; Zwiller, Val; Zadeh, Iman Esmaeil

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J. W. Niels Los,[1,a)] Mariia Sidorova,[2,3] Bruno Lopez-Rodriguez,[4] Patrick Qualm,[4] Jin Chang,[5] Stephan Steinhauer,[6] Val Zwiller,[6] and Iman Esmaeil Zadeh[1,4,b)]

AFFILIATIONS

[1] Single Quantum B.V., 2628 CH Delft, The Netherlands
[2] School of Physical and Mathematical Science, Nanyang Technological University, 21 Nanyang Link, SPMS-PAP-02-12c, 637371, Singapore
[3] German Aerospace Center (DLR), Institute of Optical Sensor Systems, Rutherfordstr. 2, 12489 Berlin, Germany
[4] Department of Imaging Physics, Delft University of Technology, 2628CN Delft, The Netherlands
[5] Kavli Institute of Nanoscience, Department of Quantum Nanoscience, Delft University of Technology, 2628CJ Delft, The Netherlands
[6] Department of Applied Physics, Royal Institute of Technology (KTH), SE-106 01 Stockholm, Sweden

[a)] **Electronic mail:** n.los@singlequantum.com
[b)] **Author to whom correspondence should be addressed:** i.esmaeilzadeh@tudelft.nl

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ABSTRACT

Since their first demonstration in 2001 [Gol'tsman *et al.*, Appl. Phys. Lett. **79**, 705–707 (2001)], superconducting-nanowire single-photon detectors (SNSPDs) have witnessed two decades of great developments. SNSPDs are the detector of choice in most modern quantum optics experiments and are slowly finding their way into other photon-starved fields of optics. Until now, however, in nearly all experiments, SNSPDs were used as "binary" detectors, meaning that they could only distinguish between 0 and > =1 photons, and photon number information was lost. Recent research has demonstrated proof-of-principle photon-number resolution (PNR) SNSPDs counting 2–5 photons. The photon-number-resolving capability is highly demanded in various quantum-optics experiments, including Hong–Ou–Mandel interference, photonic quantum computing, quantum communication, and non-Gaussian quantum state preparation. In particular, PNR detectors at the wavelength range of 850–950 nm are of great interest due to the availability of high-quality semiconductor quantum dots (QDs) [Heindel *et al.*, Adv. Opt. Photonics **15**, 613–738 (2023)] and high-performance cesium-based quantum memories [Ma *et al.*, J. Opt. **19**, 043001 (2017)]. In this paper, we demonstrate NbTiN-based SNSPDs with >94% system detection efficiency, sub-11 ps timing jitter for one photon, and sub-7 ps for 2 photons. More importantly, our detectors resolve up to 7 photons using conventional cryogenic electric readout circuitry. Through theoretical analysis, we show that the PNR performance of demonstrated detectors can be further improved by enhancing the signal-to-noise ratio and bandwidth of our readout circuitry. Our results are promising for the future of optical quantum computing and quantum communication.

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I. INTRODUCTION

Photons, owing to their unique characteristics, serve as promising candidates for various quantum experiments and applications. Modern lasers are capable of producing monochromatic, coherent, and highly directional light, enabling the precise manipulation of photons and matter. Together with state-of-the-art single-photon emitters[1,2] and high-performance single-photon detectors, they provide a promising avenue for the future implementation of quantum computers and networks.[3] With classical optics being a well-established theory, a comprehensive understanding of its classical aspects allows us to direct our attention toward exploring the non-classical quantum effects.[4] This understanding has prompted numerous fundamental tests of quantum mechanics within the

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realm of quantum optics as well as applications, including reconstructing arbitrary light source statistics,[5] quantum communication and cryptography,[6] non-Gaussian quantum state preparation,[7] quantum-enhanced imaging,[8] LiDAR,[9] and photonic quantum computing.[10] Among these cutting-edge experiments, photon-number resolution (PNR), which refers to the capability of a detector to resolve the number of incident photons that are closely spaced in time, plays a crucial role.

Among all technologies for single-photon detection, superconducting nanowire single-photon detectors (SNSPDs)[11,12] have demonstrated superior performance in terms of system detection efficiency (>98%),[13–15] low timing jitter (<10 ps),[16,17] low dark count rates (10^{-4} Hz),[18] and high count rates (>100 Mcps) from the visible to the mid-infrared range. Recently, the operating temperature of SNSPDs has started to gradually increase,[19–21] making SNSPDs even more attractive for applications. Nevertheless, SNSPDS, so far, were mostly used as binary detectors, distinguishing photon numbers zero and higher than zero. In the past few years, work has demonstrated photon number resolution (PNR) protocols and capabilities, along with some fundamental applications.[22–28] One of the technologies for single-photon detection is Transition-Edge Sensors (TESs),[29] which offer intrinsic photon-number-resolution but at a greater cost of system complexity and timing performance. Several studies have demonstrated the use of these detectors with single-photon sources and on-chip information processing, among others.[30–33] Nevertheless, TES detectors usually operate at millikelvin temperatures, require complex readouts, have a timing resolution in the order of nanoseconds, and have microsecond recovery times.[34] Using a simple scheme, it was recently demonstrated that SNSPDs can also achieve photon number resolution by analyzing the output signal waveform.[22,23] Other schemes, including arranging nanowires in a series array and multiplexing photons over space or the frequency domain, have also been demonstrated.[35–41] Due to practical nanofabrication and implementation complexity, single-mode fiber-coupled SNSPDs are preferred to be used for most quantum optics experiments, leading to the challenge of how to resolve multiple photon events with a simple meander-shape SNSPD without introducing any extra components. Until now, most efforts were focused on the telecom bands, leaving studies of the performance at shorter wavelengths underexplored. The combination of high-resolution photon-number-resolving capabilities with high detection efficiency and time resolution at lower wavelengths would enable a plethora of applications. The wavelength range of 850–950 nm is of particular interest as it includes some of the most promising quantum emitters as well as high-performance cesium-based quantum memories.[42,43]

II. BASIC CONCEPT AND MEASUREMENT SCHEMES

A schematic of the underlying principle of detecting photon numbers is depicted in Fig. 1. Upon photon absorption in a suerconducting nanowire, thphoton energy is transferred to electrons and phonons. Since this energy is orders of magnitude greater than the binding energy of the Cooper pairs (given by the superconducting gap), a small non-superconducting region known as a "hotspot" is created. Whether by diffusion of quasi-particles or nucleation and dynamics of vortices, a normal domain across the wire is formed, and the wire undergoes a transition into the resistive state. This blocks the superconducting current, resulting in a voltage spike that is then amplified and registered by the readout circuit. Subsequently, a relaxation process restores the superconductivity of the device.

When multiple photons arrive, several hot spots are created along the nanowire. However, usual readout schemes for SNSPDs are not able to show a difference in the output signal. By using a low noise amplifier, a signal proportional to the number of photons can be detected on the oscilloscope. Using an appropriate signal processing protocol, photon-number resolution can be achieved.

III. INTRINSIC PNR CAPABILITIES OF SNSPD

To explore the intrinsic ability of SNSPD to resolve the photon number encoded in the rising edge of its pulses, we first consider aspects that are crucial for accurate photon-number resolution and then outline practical guidelines for improving SNSPDs' PNR efficiency.

A. Counting statistics

To correctly reconstruct the statistics of incident light using SNSPD, one has to account for (i) the probability $P_\eta^N(n|q)$ that $n \le q$ photons are detected from q incident photons and (ii) the probability $P(n|n+1)$ to discriminate between the arrival times of SNSPD's pulses initiated by n and $n+1$ photons. The latter is particularly important to avoid underestimating events with higher photon numbers.

A common approach is to treat a uniformly illuminated device as a spatially multiplexed N-element array ($N \approx 10^3$) of identical detectors with uniform detection efficiency (η). Here, the size of each independent element is defined by the length of a normal domain (≈1 μm). For $q \ll N$, the probability that more than one photon will hit the same element is very small (<1% for $q = 5$ and <5% for $q = 10$), and the probability in (i) is strongly influenced by the detection efficiency η. This probability has been derived in previous studies (e.g., Ref. 44): $P_\eta^N(n|q) = \frac{N!}{n!(N-n)!}\sum_{j=0}^{n}(-1)^j\frac{n!}{j!(n-j)!}\left[(1-\eta)+(n-j)\frac{\eta}{N}\right]^q$. It incorporates non-ideal efficiency $\eta < 1$ and accounts for the likelihood of multiple photons hitting the same element [Fig. 1(a)]. Given the normally distributed arrival times of the detector's voltage pulses, the probability in (ii) accounts for the overlapping coefficient between the normal distributions of their respective pulses, given by $P(n|n+1) = \frac{1}{2}\left[\mathrm{erf}\left(\frac{c-\mu_{n+1}}{\sigma_{n+1}\sqrt{2}}\right) - \mathrm{erf}\left(\frac{c-\mu_n}{\sigma_n\sqrt{2}}\right)\right]$ [Fig. 1(b)]. Here, c is the distribution's intersection point, and $\mathrm{erf}(x)$ is the error function. The mean μ and the standard deviation σ are linked to the pulse risetime t_R and the jitter σ. According to the electrothermal model (similar to Ref. 45 with non-linear thermal equations as in Ref. 46), $t_R \propto n^{-0.3}$ and $\sigma \propto t_R$ (here, noise-dominated jitter is assumed[17,47]). Reducing the σ/t_R ratio allows for near-ideal photon-number resolution [see Fig. 1(b); the limited amplifier bandwidth will result in a sharp cut-off, not shown].

Assuming a unity detection efficiency, the PNR limit is reached when the SNSPD jitter exceeds the interarrival time of adjacent multiphoton voltage pulses. Longer voltage risetimes also extend the interarrival time and, therefore, the range of photon numbers. Although the jitter decreases for higher photon numbers,[48] it is constrained by the readout electronics noise. Given a reasonable noise jitter of 5 ps, our model shows that the PNR limit scales roughly as

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$0.02t_{R1}$ (t_{R1} is the rising time of the single-photon voltage pulse). For instance, with a 500 ps risetime, a resolution of up to 10 photons can be achieved.

B. Strategies for enhancing PNR efficiency

Analysis of the counting statistics has revealed that for accurate photon number resolution, high system detection efficiency is crucial to SNSPDs. Although multi-photons absorbed at the same nanowire site cannot be resolved, these are extremely rare events due to the high number ($>1 \times 10^3$) of independent absorption sites.

To improve SNSPD's PNR efficiency toward near-ideal photon-number resolution, the jitter-to-risetime ratio (σ/t_R) must be minimized [see Fig. 1(b)]. This involves reducing jitter, e.g., by implementing low-noise, broad-bandwidth cryogenic electronics. In principle, since t_R can be increased (decreased) by introducing a series (shunt) inductor, this could, in turn, influence PNR capabilities. A different approach would be to engineer the material and geometric parameters of the nanowire itself. Particularly beneficial are as follows (more details in Ref. 49): (a) increasing the nanowire length, (b) reducing its sheet resistance, (c) reducing the nanowire width, and (d) worsening the acoustic match between the film and substrate. In addition, materials with a higher critical temperature can offer lower intrinsic timing jitter, thus improving PNR capabilities.

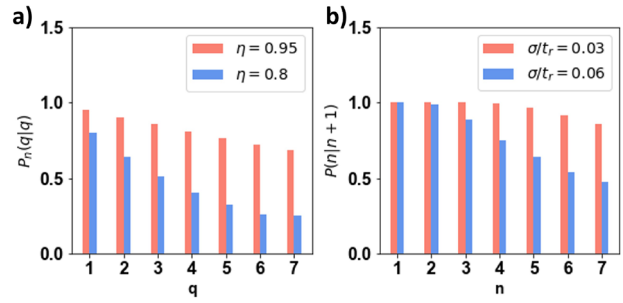

FIG. 2. (a) The probability that all incident photons are detected. (b) The probability of discriminating between the arrival times of detector pulses initiated by n and $n+1$ photons for two jitter-to-risetime ratios (σ/t_R) is indicated in the legend.

In scenarios where photons do not hit the device simultaneously but arrive with a delay, their number can still be resolved. In this case, the maximum delay is determined by a combination of the domain lifetime and the instant current through the device. At one-third of the domain lifetime, the current decreases by half, resulting in a drop in detection efficiency [Fig. 4(b)]. Strategies focusing on

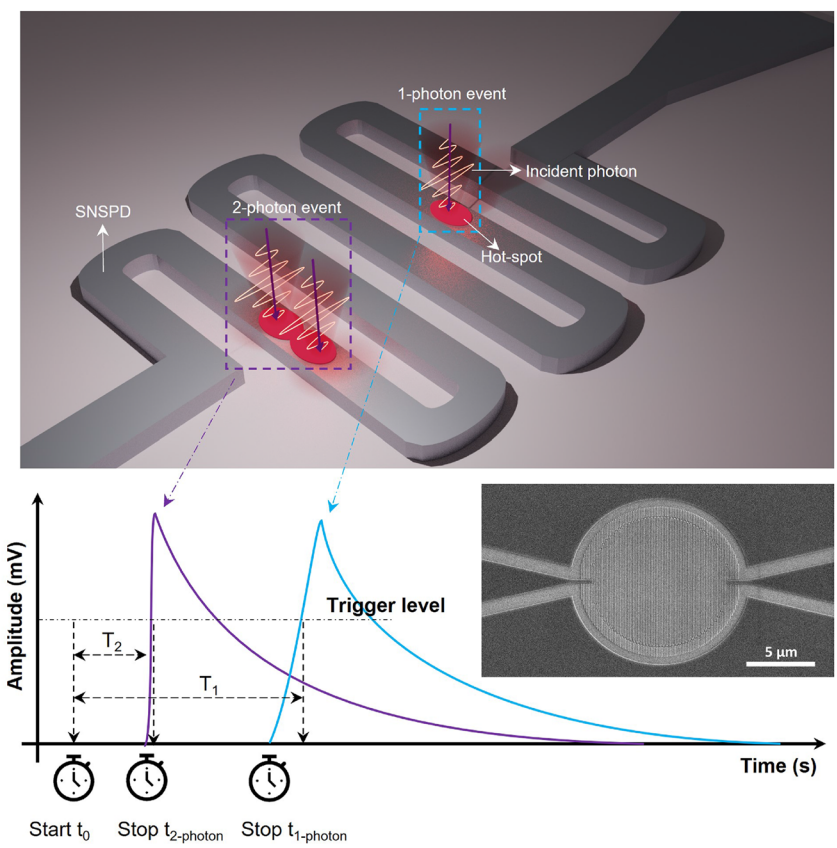

FIG. 1. An illustration of a SNSPD impinged by multiple photons. The number of photons that are absorbed by the detector modifies the rising edge of the detection pulse and, hence, can be used to resolve the photon number. Inset: Scanning electron microscope image of a similar SNSPD to the ones used in this study.

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increasing the domain lifetime (a, b, d) are also beneficial in this case. It is worth mentioning that electro-thermal models relying on a propagating domain wall (e.g., Ref. 50) can also be applicable for the case of delayed domains (e.g., one has to double the domain's wall velocity at the moment when the second photon is absorbed).

IV. EXPERIMENTAL METHODS

Superconducting single-photon detectors were made from NbTiN thin films deposited by DC magnetron sputtering. The thickness of the NbTiN film is 10 nm, and it is patterned into a 70 nm wide nanowire with a period of 140 nm (corresponding to a fill factor of 50%) covering a circular area with a radius of 6 μm. See the inset in Fig. 2 for an SEM image of an SNSPD. The devices are fabricated on top of a DBR stack to maximize the absorption around a wavelength of 940 nm. The distance between the detector and the tip of the fiber is controlled using non-deformable metal spacers, with their thickness determined by finite-difference time-domain (FDTD) simulations (Lumerical). The detectors are tested in a Gifford–McMahon cryocooler with an operating temperature of 2.5 K,[51] well below the critical temperature of the superconducting films, and are optically addressed using a polarization-maintaining fiber.

A schematic of the experimental setup used during these experiments can be seen in Fig. 3(a). As a continuous wave light source, we used a tunable laser (SpectraPhysics Millennia eV Model 3910), and for the pulsed measurements, a 1064 nm picosecond laser (Ekspla FPS15 with a pulse length of 2.3 ps) with a pulse picker allowed pulse repetition rates of 20 kHz–40 MHz. The pulsed measurements are performed at a repetition rate of 1012 kHz to ensure the events are well separated in time and, therefore, do not influence each other.

The detectors are DC-biased at about 0.97 of the switching current (I_{sw} = 37.5 μA), while the one with the highest efficiency is biased at around 17.5 μA (I_{sw} = 18 μA). At this bias current, the dark count rate of the detectors was about 40 cps. The device is connected to a low-noise cryogenic amplifier (about 2 GHz bandwidth) using cryogenic coaxial cables (3 dB/m loss at 1 GHz). An oscilloscope (Lecroy Waverunner 8404, 40 GS/s, and 4 GHz bandwidth) is used to perform the timing jitter measurements, where we also measure the distribution between the detector pulse and the output signal of a fast reference photodiode inside the Ekspla pulsed laser. In this setup, the jitter and photon-number-resolving behavior of the detector are investigated. For the extraction of the graphs and representation, the signal waveform of the oscilloscope is processed using a customized MATLAB script. For the measurements, the pulse count rate is fixed, and consequently, a timing jitter measurement is performed until 200k events are collected. This is repeated for a range of skew levels to determine at what trigger level the optimal photon-number-resolving results are achieved. Figure 3(b) shows a plot of the photon events occurring at different times obtained by varying the trigger level configurations from 100 to 800 mV in steps of 100 mV. The later photon arrival time for higher trigger levels in the waterfall plot is a result of the pulse risetime.

V. PHOTON NUMBER RESOLUTION UP TO 7 PHOTONS

As discussed before, we used a picosecond pulsed laser at 1064 nm to characterize the PNR capabilities of our detectors. Since our detectors are optimized for 850–950 nm (the DBR cavity is optimized for that wavelength range), the absorption and, hence, the efficiency are significantly lower at 1064 nm (~40%). Therefore, we verified the photon number resolving capabilities of our detectors using a method that does not require taking into account detector efficiency (a more practical approach) as follows: (1) We use a pulsed laser and create arrival time histograms similar to Fig. 3(b). (2) We ascribe each peak to a photon number, e.g., 1, 2, etc. (an ansatz). (3) We calculate the total number of detected photons (equivalent to the number of absorbed photons if internal detection efficiency is unity) by integrating over the curve of each peak and multiplying it by the assumed photon number. The outcome is then the total number of detected photons. (4) Given the known number of detected photons and the repetition rate of the laser, we can calculate the average detected photon number per pulse and, hence, make a prediction for the expected photon number distribution (based on the Poisson distribution). (5) Finally, we contrast the predicted vs measured distributions. Examples are shown in Fig. 4. While, as demonstrated

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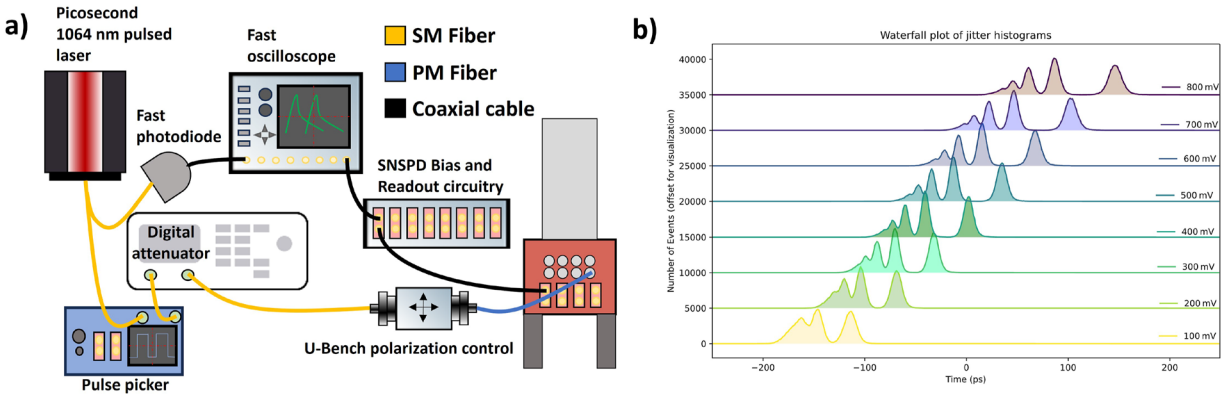

FIG. 3. (a) Experimental setup for testing the PNR capabilities of the studied SNSPDs. (b) Waterfall plot of jitter measurements for trigger level sweep to determine the optimal setting for the PNR measurement, achieved at 700 mV.

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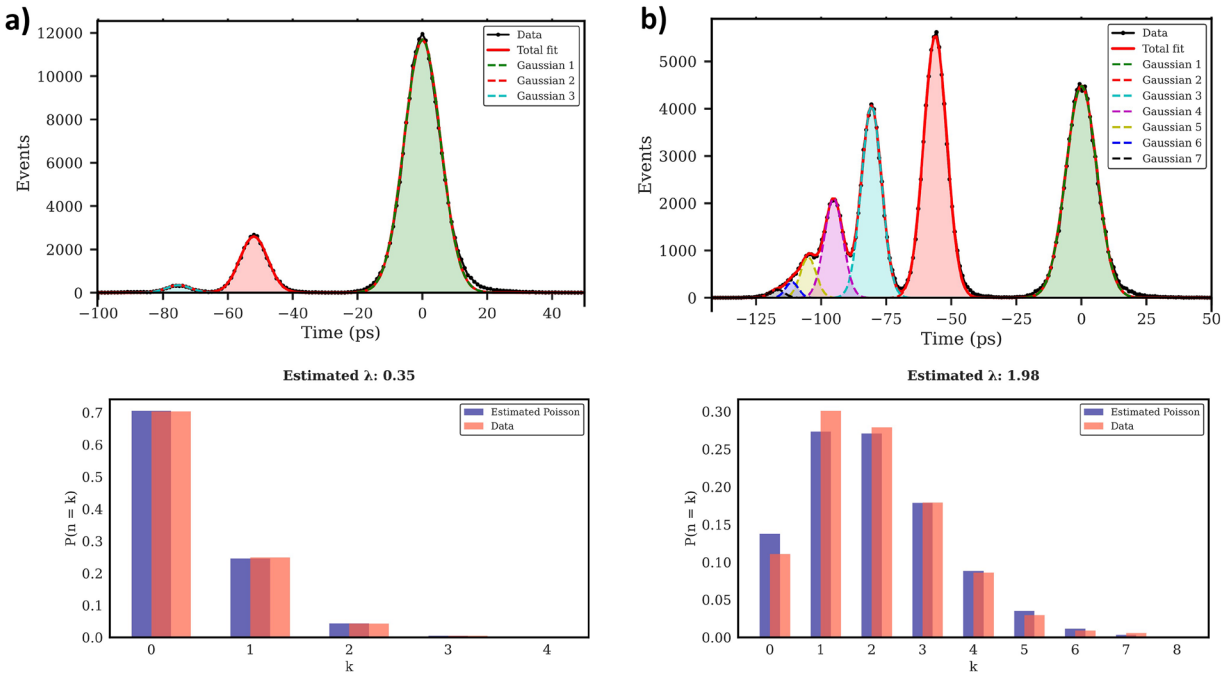

FIG. 4. PNR experiments at a trigger level of 700 mV and an average pulse count rate of (a) 350 kcps and (b) 900 kcps and their corresponding reconstructed photon statistics. For both measurements, the laser repetition rate is fixed at 1012 kHz. The measured photon number zero is contrary to expectations, slightly lower than the expected value, which we attribute to the low extinction ratio of our pulse picker, effectively causing an increase in measured photon number one.

in Fig. 4, the predicted vs measured photon numbers are in good agreement, it is clear that the distribution for photon number zero is overestimated while the peaks for photon numbers 1 and 2 are slightly underestimated, in contradiction with the expected behaviors shown in Fig. 1. These discrepancies arise from the relatively poor extinction ratio of our pulse picker (20 dB; see Sec. 4 of the supplementary material).

The detector with the best photon-number resolving capabilities was analyzed at different photon fluxes. The optimal trigger level at which 7 photon events can be distinguished is found at 700 mV. In Figs. 4(a) and 4(b), multiple photon events can be resolved, from 3 to 7 photons, corresponding to the used photon fluxes of 350 and 900 kcps, respectively. Using known photon statistics, it is possible to reconstruct the expected behavior and compare it with the experimentally obtained data. Reconstructing the photon statistics using the Poissonian distribution shows that the data matches the theoretical estimation with high overlap. At small mean photon numbers [$\lambda = 0.35$ in Fig. 4(a)], the estimated Poisson probabilities are nearly identical to those obtained in the experiments. However, at higher mean photon numbers [$\lambda = 1.98$ in Fig. 4(b)], there are discrepancies, especially for photon numbers $k = 0 - 2$. We attribute this to the finite suppression of the unwanted pulses by the laser pulse picker in our setup, an issue that deteriorates as the mean photon number increases.

Our theoretical analysis indicates that an increase in the detection efficiency, when operating at 850–950 nm, would expand PNR capabilities over a wider range of photon numbers [Fig. 1(a)]. Even though the time jitter of the detectors decreases for shorter wavelengths,[52] the time response of SNSPDs is not expected to be as strongly affected by the wavelength change as it would be by a change in photon number. The change in the energy of a photon can only have a potential influence on the diameter of the hotspot, which is quickly and, to a large extent, screened by the joule heating of the nanowire. In contrast, two non-localized photons would create two independent hot spots, each growing and contributing to a change in the rise time of the pulse. The results obtained at 1064 nm provide a lower limit to what can be expected in the optimal 850–950 nm range.

VI. HIGH SYSTEM DETECTION EFFICIENCY AND PHOTON NUMBER RESOLUTION

Another detector with high efficiency at 940 nm was analyzed to show that photon number resolution behavior can also be achieved, and the results from this study are shown in Fig. 5. To measure the efficiency of the detector, the photon flux going to the detector was determined with a reference arm, and the relative optical power between these fibers was measured by using two Newport power-meters, as explained in our previous work.[13] The system detection efficiency of the detector was measured at 940 nm with an optical power between 1.88 and 2.00 nW measured using a NIST traceable power-meter (818-SL-L Newport, uncertainty 1.1%). Consequently, the power was attenuated by around 45 dB with free-space OD plates. The attenuation was determined by measuring the power

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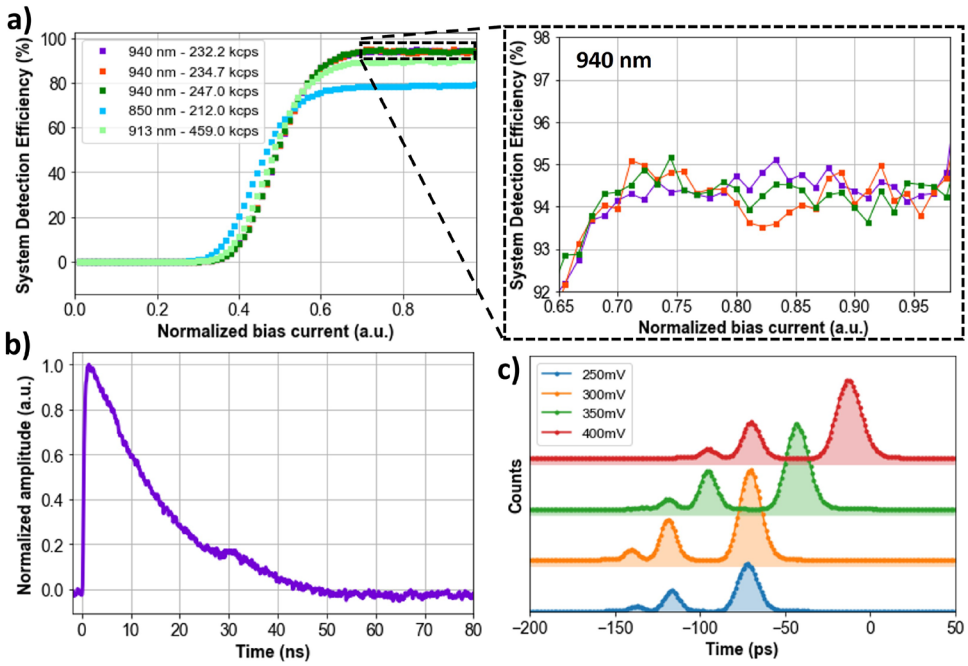

FIG. 5. (a) System detection efficiency curves of the detector under study: we measured an average efficiency of 94.5% at the wavelength of 940 nm taken from three consecutive measurements (with similar input photon fluxes). System detection efficiencies for 850 and 913 nm are shown in blue and light green, respectively. (b) Typical voltage pulse from the studied detector. (c) Photon number resolving capabilities of the detector with different voltage trigger levels.

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from a reference arm using another Newport power-meter (818-IR Newport, linearity 0.5%). The averaged SDE over three measurements, shown in Fig. 5(a), was 94.5%. The efficiency of the detector was also measured between 850 nm (76%) and 913 nm (90%), and the measurements, together with the inset, can be found in Sec. 3 of the supplementary material, along with the experimental approach and setup to measure the efficiency in Sec. I. In all the measurements, we considered the fiber-air reflection (3.4% at 940 nm) that causes an underestimation of the photon flux, calculated using the transfer matrix method. The uncertainty in the system detection efficiency was calculated to be 1.4%, and the considerations can be found in Sec. 2 of the supplementary material. The behavior of the photon count rate as a function of the bias current is shown in Fig. 5(a). For this detector, the time jitter at 1064 nm was 18.4 ps.

A typical graph of a histogram of photon events as a function of time is shown in Fig. 5(c). The visibility of the photon peaks can be optimized by adjusting the skew level to an optimal value. By fitting the time response of the consecutive histograms to Gaussian-shaped curves, four peaks can be resolved when the skew level is 200 mV.

VII. CONCLUSIONS

Superconducting nanowire single-photon detectors with high efficiencies (around 94.5% at 940 nm) and high timing resolution (18.4 ps at 1064 nm) have demonstrated photon-number-resolving behavior. Most importantly, for a detector of similar characteristics, we demonstrate a photon-number-resolution of up to 7 photons, corroborated by applying photon statistics. In addition, we propose strategies to further expand PNR capabilities toward higher photon numbers by optimizing the detector material properties and geometric parameters. In conclusion, the demonstration opens the path to interesting experiments with these detectors in photonic quantum computing, quantum communication, and in combination with semiconductor quantum dots and cesium-based quantum memories.

SUPPLEMENTARY MATERIAL

See the supplementary material for the description of the setup for measurements of system detection efficiency, uncertainty analysis, additional efficiency measurements for the detectors, and demonstration of the finite suppression of photon counts by the Ekspla pulse picker.

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AUTHOR DECLARATIONS

Conflict of Interest

J. W. Niels Los (full-time) and I.E.Z. (part-time) are employed by Single Quantum B. V. and may profit financially.

Author Contributions

J. W. Niels Los: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Software (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Mariia Sidorova**: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Software (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Bruno Lopez-Rodriguez**: Data curation (equal); Formal analysis (equal); Investigation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Patrick Qualm**: Data curation (equal); Investigation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Jin Chang**: Conceptualization (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Stephan Steinhauer**: Investigation (equal); Resources (equal); Supervision (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Val Zwiller**: Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Iman Esmaeil Zadeh**: Conceptualization (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

REFERENCES

[1] I. Aharonovich, D. Englund, and M. Toth, "Solid-state single-photon emitters," Nat. Photonics **10**, 631–641 (2016).

[2] L. Zhai, G. N. Nguyen, C. Spinnler, J. Ritzmann, M. C. Löbl, A. D. Wieck, A. Ludwig, A. Javadi, and R. J. Warburton, "Quantum interference of identical photons from remote GaAs quantum dots," Nat. Nanotechnol. **17**, 829–833 (2022).

[3] U. Leonhardt, *Essential Quantum Optics: From Quantum Measurements to Black Holes* (Cambridge University Press, 2010).

[4] C. Fabre and N. Treps, "Modes and states in quantum optics," Rev. Mod. Phys. **92**, 035005 (2020).

[5] A. Classen, F. Waldmann, S. Giebel, R. Schneider, D. Bhatti, T. Mehringer, and J. von Zanthier, "Superresolving imaging of arbitrary one-dimensional arrays of thermal light sources using multiphoton interference," Phys. Rev. Lett. **117**, 253601 (2016).

[6] N. Lütkenhaus and M. Jahma, "Quantum key distribution with realistic states: Photon-number statistics in the photon-number splitting attack," New J. Phys. **4**, 44 (2002).

[7] D. Menzies and R. Filip, "Gaussian-optimized preparation of non-Gaussian pure states," Phys. Rev. A **79**, 012313 (2009).

[8] A. Meda, E. Losero, N. Samantaray, F. Scafirimuto, S. Pradyumna, A. Avella, I. Ruo-Berchera, and M. Genovese, "Photon-number correlation for quantum enhanced imaging and sensing," J. Opt. **19**, 094002 (2017).

[9] L. Cohen, E. S. Matekole, Y. Sher, D. Istrati, H. S. Eisenberg, and J. P. Dowling, "Thresholded quantum LIDAR: Exploiting photon-number-resolving detection," Phys. Rev. Lett. **123**, 203601 (2019).

[10] Y.-H. Deng, Y.-C. Gu, H.-L. Liu, S.-Q. Gong, H. Su, Z.-J. Zhang, H.-Y. Tang, M.-H. Jia, J.-M. Xu, M.-C. Chen, J. Qin, L.-C. Peng, J. Yan, Y. Hu, J. Huang, H. Li, Y. Li, Y. Chen, X. Jiang, L. Gan, G. Yang, L. You, L. Li, H.-S. Zhong, H. Wang, N.-L. Liu, J. J. Renema, C.-Y. Lu, and J.-W. Pan, "Gaussian boson sampling with pseudo-photon-number-resolving detectors and quantum computational advantage," Phys. Rev. Lett. **131**, 150601 (2023).

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

[12] J. Chang, J. Gao, I. Esmaeil Zadeh, A. W. Elshaari, and V. Zwiller, "Nanowire-based integrated photonics for quantum information and quantum sensing," Nanophotonics **12**, 339–358 (2023).

[13] J. 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 $(99.5^{+0.5}_{-2.07})$% system detection efficiency and high time resolution," APL Photonics **6**, 036114 (2021).

[14] D. V. Reddy, R. R. Nerem, 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).

[15] P. 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).

[16] B. Korzh, Q.-Y. Zhao, J. P. Allmaras, S. Frasca, T. M. Autry, E. A. Bersin, A. D. Beyer, R. M. Briggs, B. Bumble, M. Colangelo, G. M. Crouch, A. E. Dane, T. Gerrits, A. E. Lita, F. Marsili, G. Moody, C. Peña, E. Ramirez, J. D. Rezac, N. Sinclair, M. J. Stevens, A. E. Velasco, V. B. Verma, E. E. Wollman, S. Xie, D. Zhu, P. D. Hale, M. Spiropulu, K. L. Silverman, R. P. Mirin, S. W. Nam, A. G. Kozorezov, M. D. Shaw, and K. K. Berggren, "Demonstration of sub-3 ps temporal resolution with a superconducting nanowire single-photon detector," Nat. Photonics **14**, 250–255 (2020).

[17] I. Esmaeil Zadeh, J. W. Los, R. B. Gourgues, J. Chang, A. W. Elshaari, J. R. Zichi, Y. J. van Staaden, J. P. Swens, N. Kalhor, A. Guardiani *et al.*, "Efficient single-photon detection with 7.7 ps time resolution for photon-correlation measurements," Acs Photonics **7**, 1780–1787 (2020).

[18] L. Zhang, L. Kang, J. Chen, Y. Zhong, Q. Zhao, T. Jia, C. Cao, B. Jin, W. Xu, G. Sun, and P. Wu, "Ultra-low dark count rate and high system efficiency single-photon detectors with 50 nm-wide superconducting wires," Appl. Phys. B **102**, 867–871 (2011).

[19] J. Chang and I. Esmaeil Zadeh, "Superconducting single-photon detectors get hot," Nat. Nanotechnol. **18**, 322–323 (2023).

[20] I. Charaev, D. Bandurin, A. Bollinger, I. Phinney, I. Drozdov, M. Colangelo, B. Butters, T. Taniguchi, K. Watanabe, X. He *et al.*, "Single-photon detection using high-temperature superconductors," Nat. Nanotechnol. **18**, 343–349 (2023).

[21] R. L. Merino, P. Seifert, J. D. Retamal, R. K. Mech, T. Taniguchi, K. Watanabe, K. Kadowaki, R. H. Hadfield, and D. K. Efetov, "Two-dimensional cuprate nanodetector with single telecom photon sensitivity at T = 20 K," 2D Mater. **10**, 021001 (2023).

[22] C. Cahall, K. L. Nicolich, N. T. Islam, G. P. Lafyatis, A. J. Miller, D. J. Gauthier, and J. Kim, "Multi-photon detection using a conventional superconducting nanowire single-photon detector," Optica **4**, 1534–1535 (2017).

[23] D. Zhu, M. Colangelo, C. Chen, B. A. Korzh, F. N. Wong, M. D. Shaw, and K. K. Berggren, "Resolving photon numbers using a superconducting nanowire with impedance-matching taper," Nano Lett. **20**, 3858–3863 (2020).

[24] L. Stasi, G. Gras, R. Berrazouane, M. Perrenoud, H. Zbinden, and F. Bussières, "Fast high-efficiency photon-number-resolving parallel superconducting nanowire single-photon detector," Phys. Rev. Appl. **19**, 064041 (2023).

[25] S. I. Davis, A. Mueller, R. Valivarthi, N. Lauk, L. Narvaez, B. Korzh, A. D. Beyer, O. Cerri, M. Colangelo, K. K. Berggren, M. D. Shaw, S. Xie, N. Sinclair,

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and M. Spiropulu, "Improved heralded single-photon source with a photon-number-resolving superconducting nanowire detector," Phys. Rev. Appl. **18**, 064007 (2022).

[26]S. Sempere-Llagostera, G. S. Thekkadath, R. B. Patel, W. S. Kolthammer, and I. A. Walmsley, "Reducing $g^{(2)}(0)$ of a parametric down-conversion source via photon-number resolution with superconducting nanowire detectors," Opt. Express **30**(2), 3138–3147 (2022).

[27]G. Sauer, M. Kolarczik, R. Gomez, J. Conrad, and F. Steinlechner, "Resolving photon numbers using ultra-high-resolution timing of a single low-jitter superconducting nanowire detector," arXiv:2310.12472 [quant-ph] (2023).

[28]T. Schapeler, N. Lamberty, T. Hummel, F. Schlue, M. Stefszky, B. Brecht, C. Silberhorn, and T. J. Bartley, "How well can superconducting nanowire single-photon detectors resolve photon number?," arXiv:2310.12471 [quant-ph] (2023).

[29]K. Irwin and G. Hilton, "Transition-edge sensors," in *Cryogenic Particle Detection*, edited by C. Enss (Springer, Berlin, Heidelberg, 2005), pp. 63–150.

[30]M. von Helversen, J. Böhm, M. Schmidt, M. Gschrey, J.-H. Schulze, A. Strittmatter, S. Rodt, J. Beyer, T. Heindel, and S. Reitzenstein, "Quantum metrology of solid-state single-photon sources using photon-number-resolving detectors," New J. Phys. **21**, 035007 (2019).

[31]B. Calkins, P. L. Mennea, A. E. Lita, B. J. Metcalf, W. S. Kolthammer, A. Lamas-Linares, J. B. Spring, P. C. Humphreys, R. P. Mirin, J. C. Gates *et al.*, "High quantum-efficiency photon-number-resolving detector for photonic on-chip information processing," Opt. Express **21**, 22657–22670 (2013).

[32]D. Fukuda, G. Fujii, T. Numata, K. Amemiya, A. Yoshizawa, H. Tsuchida, H. Fujino, H. Ishii, T. Itatani, S. Inoue, and T. Zama, "Titanium superconducting photon-number-resolving detector," IEEE Trans. Appl. Supercond. **21**, 241–245 (2011).

[33]M. Schmidt, M. von Helversen, M. López, F. Gericke, E. Schlottmann, T. Heindel, S. Kück, S. Reitzenstein, and J. Beyer, "Photon-number-resolving transition-edge sensors for the metrology of quantum light sources," J. Low Temp. Phys. **193**, 1243–1250 (2018).

[34]L. A. Morais, T. Weinhold, M. P. de Almeida, J. Combes, A. Lita, T. Gerrits, S. W. Nam, A. G. White, and G. Gillett, "Precisely determining photon-number in real-time," arXiv:2012.10158 (2020).

[35]W. Zhang, J. Huang, C. Zhang, L. You, C. Lv, L. Zhang, H. Li, Z. Wang, and X. Xie, "A 16-pixel interleaved superconducting nanowire single-photon detector array with a maximum count rate exceeding 1.5 GHz," IEEE Trans. Appl. Supercond. **29**, 2200204 (2019).

[36]S. 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).

[37]Y. Guan, H. Li, L. Zhang, D. Dong, H. Wang, Q. Chen, S. Guo, B. Zhang, X. Zhang, Z. Yang *et al.*, "Approaching pixel-level readout of SNSPD array by inductor-shaping pulse," Appl. Phys. Lett. **123**, 042602 (2023).

[38]S. Miki, T. Yamashita, Z. Wang, and H. Terai, "A 64-pixel NbTiN superconducting nanowire single-photon detector array for spatially resolved photon detection," Opt. Express **22**, 7811–7820 (2014).

[39]A. N. Vetlugin, F. Martinelli, S. Dong, and C. Soci, "Photon number resolution without optical mode multiplication," Nanophotonics **12**, 505–519 (2023).

[40]J. Huang, X. Zhang, W. Zhang, Y. Wang, C. Lv, G. Xu, X. Liu, H. Li, Z. Wang, and L. You, "Improving photon number resolvability of a superconducting nanowire single-photon detector array using a level comparator circuit," Supercond. Sci. Technol. **37**, 055005 (2024).

[41]L.-D. Kong, T.-Z. Zhang, X.-Y. Liu, H. Li, Z. Wang, X.-M. Xie, and L.-X. You, "Large-inductance superconducting microstrip photon detector enabling 10 photon-number resolution," Adv. Photonics **6**, 016004 (2024).

[42]M. E. Reimer, G. Bulgarini, N. Akopian, M. Hocevar, M. B. Bavinck, M. A. Verheijen, E. P. Bakkers, L. P. Kouwenhoven, and V. Zwiller, "Bright single-photon sources in bottom-up tailored nanowires," Nat. Commun. **3**, 737 (2012).

[43]H. He, P.-F. Yang, P.-F. Zhang, G. Li, and T.-C. Zhang, "Single-photon source with sub-MHz linewidth for cesium-based quantum information processing," Front. Phys. **18**, 61303 (2023).

[44]M. Fitch, B. Jacobs, T. Pittman, and J. Franson, "Photon-number resolution using time-multiplexed single-photon detectors," Phys. Rev. A **68**, 043814 (2003).

[45]J. K. 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).

[46]M. Sidorova, A. D. Semenov, H.-W. Hübers, S. Gyger, and S. Steinhauer, "Phonon heat capacity and self-heating normal domains in NbTiN nanostrips," Supercond. Sci. Technol. **35**, 105005 (2022).

[47]M. Sidorova, A. Semenov, H.-W. Hübers, I. Charaev, A. Kuzmin, S. Doerner, and M. Siegel, "Physical mechanisms of timing jitter in photon detection by current-carrying superconducting nanowires," Phys. Rev. B **96**, 184504 (2017).

[48]M. Sidorova, A. Semenov, H.-W. Hübers, A. Kuzmin, S. Doerner, K. Ilin, M. Siegel, I. Charaev, and D. Vodolazov, "Timing jitter in photon detection by straight superconducting nanowires: Effect of magnetic field and photon flux," Phys. Rev. B **98**, 134504 (2018).

[49]The strategies (a–d) are based on the following insights: (a) Increasing the nanowire length leads to a higher total kinetic inductance, consequently slowing down current dynamics, which increases domain lifetimes. The impact on geometric jitter is considered negligible in single-ended readout, as evidenced in previous studies.[17,47] (b) The sheet resistance is inversely proportional to the theoretical critical current [A. Semenov, A. Engel, H.–W. Hübers, K. Il'in, and M. Siegel, "Spectral cut–off in the efficiency of the resistive state formation caused by absorption of a single–photon in current-carrying superconducting nano–strips," Eur. Phys. J. B 47, 495–501 (2005)]. Consequently it affects the pulse amplitude and, eventually, the noise jitter. (c) Although the SNSPD detection microscopic model [D. Y. Vodolazov, N. Manova, Y. P. Korneeva, and A. Korneev, "Timing jitter in nbn superconducting microstrip single-photon detector," Phys. Rev. Appl. **14**, 044041 (2020)] predicts that the jitter does not depend on the wire width at currents near the theoretical limit, in practice these regimes are hardly to be achieved. Empirical evidence (e.g., Ref. 17) points to a reduction in jitter with width. (d) Worsening the acoustic match between the film and the substrate slows down domain cooling via.

[50]A. J. Kerman, J. K. 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).

[51]J. Chang, J. W. Los, R. Gourgues, S. Steinhauer, S. Dorenbos, S. F. Pereira, H. P. Urbach, V. Zwiller, and I. Esmaeil Zadeh, "Efficient mid-infrared single-photon detection using superconducting NbTiN nanowires with high time resolution in a Gifford-McMahon cryocooler," Photonics Res. **10**, 1063–1070 (2022).

[52]G. G. Taylor, E. N. MacKenzie, B. Korzh, D. V. Morozov, B. Bumble, A. D. Beyer, J. P. Allmaras, M. D. Shaw, and R. H. Hadfield, "Mid-infrared timing jitter of superconducting nanowire single-photon detectors," Appl. Phys. Lett. **121**, 214001 (2022).

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