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Single-Photon Imager Based on a Superconducting Nanowire Delay Line

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Abstract: Detecting spatial and temporal information of individual photons is critical to applications in spectroscopy, communication, biological imaging, astronomical observation, and quantum-information processing. Here, we demonstrate a scalable single-photon imager using a single continuous superconducting nanowire that is not only a single-photon detector but also functions as an efficient microwave delay line. Therefore, photon detection pulses are guided in the nanowire, enabling the readout of position and time of photon absorption from the arrival times of the detection pulses at the nanowire's two ends. Experimentally, we slowed down the velocity of pulse propagation to ~2% of the speed of light. In a 19.7-mm-long nanowire meandered across an area of 286 μm × 193 μm, we were able to resolve ~590 effective pixels while simultaneously having a temporal resolution of 50 ps full-width-at-half-magnitude. The nanowire imager presents a scalable approach to realizing high-resolution photon imaging in both time and space.

Currently, quantum optics is limited by our ability to sense and process efficiently information about single photons. For example, to enhance the information-carrying capacity of a quantum channel[1] and improve security in quantum key distribution[2,3], information is typically encoded in the position and arrival time of individual photons. To determine the spatial and temporal information of photons is currently accomplished by single-photon detector (SPD) arrays. Among existing SPD array technologies, the transition edge sensor (TES) and the microwave kinetic inductance detector (MKID) provide moderate spectral information but less impressive temporal resolution (for example, the timing uncertainty, or jitter, is measured in nanoseconds for TESs[4] and microseconds for MKIDs[5]). Photomultiplier tubes and single-photon avalanche diodes have sub-1-ns timing jitter in the visible domain, but their detection performance deteriorates in the infrared, and scaling these technologies to large spatial arrays is challenging[6]. Improved timing performance of sub-20-ps timing jitter[7] and sub-10-ns recovery time[8] is possible with superconducting-nanowire single-photon detectors (SNSPDs), which also have been demonstrated to have near-unity detection efficiency[9], less than 1 dark-count per second (cps)[10], a wide spectral response from the visible to infrared[11] and greater than 10^8 cps counting rate[12]. However, attempts to create arrays of SNSPDs have had limited success[13–18]. Traditional row-column rectangular pixel arrays require large numbers of readout lines[15], while attempts at time-based and frequency-based multiplexing architectures require additional components within and between pixels, and thus suffer from low fill factors[16,18]. As a result, the current state-of-the-art SNSPD array is limited to ~ 100 pixels[15].

The typical operation of an SNSPD lacks spatial sensitivity, although the excitation caused by the absorption of a photon is localized within the nanowire. In the simplest broadly accepted detection model of an SNSPD[19], an absorbed photon generates a localized region of elevated electron temperature, that is, a hotspot, which leads to the formation of a resistive domain across the nanowire. Unfortunately, the conventional electrical readout of an SNSPD could not be used to determine the location of the resistive domain because electrically the nanowire was modelled as a lumped-element inductor in series with a non-linear dynamic resistor that represented the resistive domain[20]. In such a scheme, the relative location of the resistor and inductor cannot change the output behaviour of the circuit. For very long nanowires, in which the length exceeds the wavelength being detected, this lumped element model no longer fully describes the device behaviour. In such situations, a distributed-element model must be used [21,22].

Here, we describe an experiment in which we used a superconducting nanowire as the centre conductor in a microwave coplanar transmission line to determine the position of the hot-spot along the nanowire while simultaneously preserving information about the time of arrival of the photon. This approach uses a continuous nanowire to realise a scalable single-photon imager, which we refer to as a superconducting nanowire single-photon imager (SNSPI) to distinguish it from an SNSPD. A sketch of the SNSPI is shown in Fig. 1a. The superconducting nanowire in an SNSPI is not only designed into a single-photon sensitive detector but also functions as a microwave delay line of ultralow velocity (~2% of the speed of light in free space). Therefore, a relatively small propagation distance results in a measurable time delay[23,24]. The nanowire is terminated at each end with a Klopfenstein taper to transform from the high characteristic impedance of the nanowire to 50 Ω[25]. This ensures efficient coupling from the electrical pulses triggered by a photon detection to a 50 Ω microwave readout circuit, enabling us to extract the time and position of the absorbed photon by using the relative arrival times of the output electrical pulses at the two ends of the nanowire.

Guiding microwaves in a superconducting nanowire

The low signal-propagation velocity in an SNSPI results from the kinetic inductance of a thin superconducting nanowire. In a two-fluid model, the superconducting electrons move without resistance and have a kinetic energy of $\frac{1}{2}n_s \mathrm{m} v_s^2$($n_s$ is the superconducting electron density, m is the electron mass, and v_s is the velocity of the Cooper pairs). Alternatively, driving the superconducting electrons can be seen as kinetic inductivity, which is expressed as $\mathcal{L}_k = \frac{\mathrm{m}}{\mathrm{n_s e^2}} = \mu_0 \lambda_L^2$ (e is the elementary charge, λ_L is the London penetration depth and μ_0 is the permeability). In our experiments, the superconducting nanowire patterned from a ~7 nm thick niobium nitride film has a kinetic inductance $\mathcal{L}_k = 3.4310^{-19}\ \mathrm{H \cdot m}$, larger than its Faraday inductance by two orders of magnitude. An alternative way to study the wave propagation in the superconducting nanowire is to consider the nanowire as a plasmonic material (see supplementary information)[26,27].

To guide the detection pulses, we designed the nanowire into a coplanar waveguide (CPW) structure (its dimensions are given in Fig.1b). The signal propagation velocity is $v = 1/\sqrt{L_s C_s}$ and the characteristic impedance is $Z = \sqrt{L_s/C_s}$, where L_s and C_s are the inductance and capacitance per unit length, respectively. As we mentioned above, the kinetic inductance is much higher than the Faraday inductance in a superconducting nanowire. Therefore, there is a significant reduction of v_s and an increase of Z compared to the same structure but made from normal metals (simulation results are discussed in Methods). Experimentally, the measured velocity in the SNSPI for imaging demonstrations was 5.56 μm/ps. This microwave modification implies that a photon-sensitive nanowire can function as an efficient delay line, in which photon-detection pulses have to propagate along the nanowire for a time determined by the photon-detection position.

Operation principle of an SNSPI

The operation of the SNSPI is shown in Fig. 1a. After a photon is absorbed at location x_p at time t_p, the increase of the local resistance generates two electrical pulses of opposite polarities, which propagate with a constant velocity v towards the two ends of the transmission line, introducing delays τ_1 and τ_2, respectively. After removing the fixed delays from tapers, cables and readout electronics and extracting τ_1 and τ_2 from the arrival times of the electrical pulses, every (x_p, t_p) pair can be determined by using two linear functions: $x_p = ((\tau_2 - \tau_1)v + \mathrm{L})/2$ and $t_p = ((\tau_2 + \tau_1) - \mathrm{L}/v)/2$. Such a delay-based readout is conceptually similar to the readout of a time-multiplexed SNSPD array[16] and has also been applied in microchannel-plate detectors[28]. However, the SNSPI simultaneously acts as the detector and a delay component, without any multiplexing circuits or clock signals, resulting in a dramatically more compact design that is suitable for large-scale integration. Compared with single-pixel-based imaging technology that uses compressing sampling method to reconstruct an image[29], the SNSPI images photons that are directly projected or emitted from the object, avoiding additional coupling loss and resolution degeneration during the spatial modulation of incident light. Thus, SNSPI should exhibit faster imaging speed, higher spatial resolution and simpler apparatus than a single-pixel camera using SNSPDs[30].

Single photon imaging performance

To create a 2D image with horizontal and vertical addresses (*H*,*V*), the 1D nanowire is meandered to cover a 2D area. The spatial resolution in each direction could thus be optimised independently for particular applications (*e.g.*, near-field imaging at sub-wavelength resolution by reducing the spacing between adjacent sections of the nanowire). In our experiments, as shown in Fig. 1b, the nanowire was meandered in both the *H* direction and the *V* direction to have nearly equal spatial resolution in *H* and *V*. This double-meandered nanowire covers a rectangular area of 286 μm × 193 μm. To demonstrate the imaging process, we placed an object on top of this rectangular area and evenly illuminated photons through it to project a pattern on the nanowire (see Methods). Figure 1c shows an image of a metal mesh of a simple periodic structure whose opening holes correspond to the visible grid of circular patterns. Figure 2 shows the image construction formed by 989,897 photon detection events. A video (see supplementary online material) also demonstrates how the accumulation of detection events generated the image. In our present setup, the imaging time was limited by the acquisition speed of the oscilloscope, which had a refresh rate of only ~100 waveforms per second. As a result, most of the detection pulses from the SNSPI were not recorded. To investigate the ultimate speed of the SNSPI, we ignored the timing information of the pulse and only counted pulses from the SNSPI by using a 200 MHz counter and removing the charging effects form the amplifier[31] (see Methods for the maximum counting rate characterization). We defined the maximum counting rate (CR_{max}) as the count rate when the average detection efficiency dropped by half, which was 2 Mcps measured for 1.5 μm photons, indicating an estimated imaging time of a few seconds to construct the same image of Fig. 1c if the data processing setup were improved.

The spatial resolution of the imager was dominated by the electrical noise in the readout circuits and the speed of signal propagation in the transmission line. Consider a photon arriving at x_p resulting in pulses observed at times τ_1 and τ_2. Electrical noise contributed to variation in the determination of τ_1 and τ_2, resulting in a variation of measured x_p based on the function $x_p = ((\tau_2 - \tau_1)v + \mathrm{L})/2$. We quantified this uncertainty by defining a Gaussian point-spread function $b(x) = \exp(-x^2/2h^2)$ where $h = (\delta/\rho) \times v/2$ (δ is the standard deviation of the Gaussian distribution of electrical noise and ρ is the slope of the pulses at the discrimination threshold level). The point-spread function can be used to estimate the effective resolution as limited by electrical noise. From the waveform of the output pulses, (δ/ρ) was determined to be 4.3 ps (see Methods). Substituting the measured value of v = 5.6 μm/ps into the point-spread function $b(x)$, we have h = 12.0 μm and the full-width-at-half-magnitude f_W of $b(x)$ is 28.4 μm. The width of $b(x)$ determines the noise-limited spatial resolution, which will be compared with the measured width of the sharp peaks generated from dark counts in later discussion.

Given the point-spread function defined above, the 2D spatial resolution can be calculated by taking into account the meander geometry, from which the 1D distance x is mapped to the 2D location (H,V). In the geometry shown in Fig 1b, the vertical spatial resolution is the spacing between rows q = 13.0 μm and the horizontal spatial resolution is $f_w \times p/l_m$ = 5.6 μm, where l_m = 22.84 μm is the effective length of one meander period in each row. With these spatial resolutions, we were able to image letters with a 12.6 μm stroke width and 12.6 μm spacing between strokes (see Fig. 2d). A smaller h could be achieved by reducing the timing uncertainty j_e or slowing down v even further by using other superconducting materials with higher kinetic inductance (for example, tungsten silicide), substrates with higher dielectric constant (for example, $LaAlO_3$), or other transmission line structures (for example, microstrip lines).

The photon arrival time t_p was determined by using the equation $t_p = ((\tau_2 + \tau_1) - L/v)/2$. The temporal resolution was characterized by the timing jitter j_d defined as the time variation of the measured photon arrival times, which included both the electronic jitter from noise and intrinsic jitter from the photon detection mechanism. To precisely measure j_d, we used a 1.5 μm mode-locked laser, whose output was split into two beams. One beam was sent to the SNSPI for measuring t_p while the other beam was measured by a fast photodiode to determine a timing reference t_r with ps resolution. Figure 2f shows the histogram of $t_p - t_r$. The full-width-at-half-magnitude (FWHM) of the histogram profile gave the timing jitter, which is $j_d = 50$ ps. This value is consistent with reported timing jitters for SNSPDs and is significantly lower than the timing jitters of TESs and MKIDs.

The SNSPI also exhibited the wide optical bandwidth typical of conventional SNSPDs[11]. Figure 3a shows the photon counts versus bias current at wavelengths of 405 nm, 780 nm and 1.5 μm. At 405 nm wavelength, the internal quantum efficiency of the wire saturated, suggesting a near-unity internal quantum efficiency of the nanowire. At longer wavelengths, the quantum efficiency was reduced, as would be expected for wires that are 300 nm wide. The ground plane in the coplanar structure limited the maximum light absorptance of the nanowire to be ~10 %. Future improvement of the detection efficiency requires a narrower nanowire of high internal efficiency and an optimised structure of both slow signal velocity and high optical absorptance (*e.g.*, a microstrip line integrated in an optical cavity can have a light absorption over 50%, see simulation results in the supplementary information). Similar to SNSPDs, the SNSPI will be sensitive to the polarization of the incident light. This sensitivity can be tuned by optimising the wiring structure or adding an integrated optical cavity[32,33].

A spatial map of dark counts of the SNSPI can be created by operating the device in a well-shielded environment with no illumination (see supplementary information of the dark count maps). As shown in Fig. 3b, the total number of dark count events summed over the length of the SNSPI exhibited an exponential dependence on bias current, similar to what is measured in SNSPDs. We took images with the SNSPI at a bias current of 60 μA, where the overall dark count rate was ~ 1 cps, ensuring a high signal-to-noise ratio of the image.

Measuring the distribution of the dark counts with respect to nanowire distance offers an alternative method to characterize the spatial resolution of the SNSPI. To investigate the distribution of dark counts along the nanowire, we increased the bias current to 65 μA to have more dark counts and thus to reduce the overall acquisition time. Figure 3c shows the dark count histogram observed along the nanowire. We then calculated the FWHM s for each of the ten peaks with the highest amplitudes. The average value of s was $\bar{s} = 29.9$ μm and the variation (defined as the standard deviation) was std(s) = 0.9 μm. Those ten peaks contributed to 74% of the total dark counts, while their combined length was only ~ 2% of the total length of the nanowire, indicating that the image quality was robust against dark counts. Dark counts could also be partially subtracted from the imager based on calibration from zero-light experiments.

The widths of the dark-count peaks were slightly larger than the spatial resolution calculated from the point-spread function, which suggests a possible intrinsic length of dark-count locations, or perhaps an underestimate of the system electrical noise. To estimate the number of resolvable locations in the SNSPI, we used the measured $\bar{s}$ as the minimum length that the SNSPI was able to distinguish. With this assumption, the maximum resolvable number of pixels N_p in the SNSPI is $N_p = L_e/\bar{s} \cong 590$, where $L_e = 17.635$ mm is the effective length of a straight wire converted from the double-meandered geometry, taking into account the increase of the signal velocity in the corners. The estimated pixel density was thus ~ 10^6 pixels per cm^2. The distribution of the dark counts can also help us investigate where the dark counts originate from, *i.e.*, whether the measured dark counts are from the constrictions of the nanowire or the bends of the meandered wire[34] (see the supplementary information for dark count images).

Conclusion

In summary, we have introduced a scalable architecture for single-photon imagers with precise temporal resolution. By engineering the microwave behaviour of a photon-sensitive nanowire into a delay line with a slow velocity equal to 2% of the speed of light in free space, we demonstrated ~ 590 effective pixels, sub-20 μm spatial resolution and 50 ps FWHM temporal resolution in a 19.7 mm long superconducting nanowire. Given the reduced requirements for readout lines, the number of pixel and image area could be further scaled up by integrating multiple SNSPIs into an SNSPI-array with on-chip readout to extract the delay information of the photon-detection pulses. The image quality could be enhanced further thanks to improved optics used to focus the object image, as well as electronics with a lower noise and a higher acquisition speed. With these improvements, we expect the SNSPI to become a powerful single-photon detection tool in areas such as quantum information science, communications, single-photon imaging and spectroscopy, and even in astronomical observation.

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Author Contributions

Q.-Y. Z. and K. B. came with the initial idea. Q.-Y. Z. designed and fabricated the nanowire imager. Q.-Y. Z. and D. Z. took the optical measurements. Q.-Y. Z., N.C., F.B., and H.-Z. W. characterized initial devices. A. D. supported the superconducting films. Q.-Y. Z., A.M., and D. S. did the microwave simulations. Q.-Y. Z. analysed the data and programmed the imaging script. K. B. supervised the project. Q.-Y. Z. and K. B. wrote the paper with input from all other authors.

Figure captions:

Figure 1 | Superconducting nanowire single-photon imager (SNSPI). a, Architecture of the SNSPI. The nanowire transmission line (TL) and the impedance tapers were fabricated in coplanar-waveguide structures, where the ground plane is not shown in the sketch. **b**, A scanning-electron-micrograph of the top nine rows (out of 15 rows in total). The dimensions shown are q = 13.0 μm, h = 9.7 μm, and p = 5.4 μm. The scale bars in the inset figures are 2 μm (left) and 300 nm (right). **c**, A single-photon image of the pattern formed by light passing through a metal mesh, which was placed on top of the SNSPI with a gap of ~ 200 μm (see the imaging setup in the supplementary information). The circular periodic patterns reflect the opening holes of the mesh. The wavelength of the light was 780 nm. The image consists of data from 427,905 photon detection events. The colour of the map shows the normalized photon counts at each location. **d**, An optical image of the metal mesh, whose opening size was 43 μm and whose wire diameter was 30 μm. The scale bar is 50 μm.

Figure 2 | Spatial and temporal detections by the SNSPI. a, **and b**, Oscilloscope waveforms of output pulses from the two ends of the nanowire from three photon detection events occurring at different locations. We illuminated the device with sub-ps optical pulses from a 1.5 μm mode-locked laser. **c**, Histogram of 989,897 photon detections displayed along the 1D distance coordinate x. A 405 nm continuous-wave light-emitting diode source was used to project the object on the imager. The span of x was divided into 15 sections corresponding to the 15 rows (R1~R15) of the double-meandered nanowire. **d**, Image of an institutional logo constructed from the photon-position data (only a portion of full image region is shown). **e**, Magnified section of histogram corresponding to the bright lines included within white box in R6. **f**. Histogram of the difference between the photon arrival time t_p measured by the SNSPI and a reference time t_r. We used a 1.5 μm mode-locked laser to illuminate the SNSPI and generate t_r with ps resolution. The FWHM of the histogram profile was 50 ps, which was used for defining the timing jitter j_d.

Figure 3 | Detection performance of the SNSPI. a, Photon count rate (*PCR*) versus the bias current at wavelengths from visible to infrared. The traces are normalized to the photon counts at 65 μA, where dark counts are 1 kcps, to have less error in the measurement of net photon counts. The x axis is normalized to the switching current (67.4 μA). **b**, Overall dark counts versus bias current. **c**, Dark counts histogram over the 1D distance at a bias current of 65 μA. We selected ten peaks of highest amplitude (indicated by the arrows on top) and fit each of them with a Gaussian function, whose FWHM s is calculated. **d**, Distribution of s from the ten peaks. The average of s is $\bar{s}$ = 29.9 μm and the standard deviation is std(s) = 0.9 μm.

Methods

Device fabrication and imaging pattern preparation

The SNSPI was fabricated from a ~7 nm thick niobium nitride (NbN) thin film. The film was deposited on a 4-inch silicon wafer with a 300-nm-thick surface layer of silicon dioxide. The NbN had a critical temperature of $T_C = 10K$, a sheet resistance of $R_s = 331\ \Omega$/square, and a residual resistance ratio of $RRR = 0.8$. The kinetic inductance was $L_K = \mathrm{h} \cdot R_S / (2 \cdot \pi^2 \cdot \Delta \cdot \tanh\left(\frac{\Delta}{2 \cdot k_B \cdot T_c}\right))$ = 49 pH/square, where $\Delta = 1.76 \cdot k_B \cdot T_c \cdot \tanh\left(1.74 \cdot \sqrt{\frac{T_c}{T} - 1}\right)$ is the temperature-dependent superconducting energy gap, h is the Planck constant, k_B is the Boltzmann constant, and $T = 4.2$ K is the operating temperature[35]. The structure of the nanowire transmission line and the tapers were formed by using a 125 kV electron beam lithography tool and then transferred into the NbN layer in a CF_4 atmosphere using a reactive ion-etcher (more fabrication details are reported in previous publications of SNSPDs[36,37])

Two objects were imaged with the SNSPI. The object used to generate Fig. 1c was a stainless steel mesh (McMaster-Carr part number 34735K69) with an opening size of 43 μm and a wire diameter of 30 μm. The structure of the MIT logo image (Fig. 2d) was patterned by using photo-lithography from a lift-off process on an indium-tin-oxide (ITO) substrate. The letters were made from a bilayer of metals (50 nm thick chromium and 50 nm thick gold). For each measurement, we placed the object on top of the device, leaving a gap of about 200 μm between the mask and the device. The bias and amplification electronics, which are similar to what are used for reading conventional SNSPDs, are all at room temperature. The details of the imaging setup and electronic configuration are discussed in the supplementary information.

Microwave design of the SNSPI

We calculated the impedance and velocity of a superconducting transmission line both numerically and analytically. In the analytical calculation, we first calculate the capacitance and inductance of a conventional coplanar waveguide (CPW) made from lossless metal and then replaced the inductance with the total of the kinetic inductance and the geometrical inductance. As shown in supplementary Fig. 1a, both methods showed similar values.

We used the Klopfenstein taper for transforming the nanowire impedance to 50 Ω to preserve the fast rising edge of a photon detection pulse. In order to verify the taper's performance, we fabricated a 17 mm long NbN taper without a photon-sensitive nanowire at the middle. The taper was designed into a CPW structure with a fixed 3 μm gap to the ground plane and a signal line whose width smoothly changed from 88 μm at the two ends to 10 μm in the centre. In order to characterize the superconducting taper without switching it to the normal by the input signals, the narrowest width of the nanowire in the centre was designed to 10 μm to have a switching current of 0.4 mA.

The bandwidth of the taper was measured by a network analyser (see supplementary Fig. 1b). The pass band of the taper started at 0.7 GHz, which was able to cover the spectrum of the fast edge triggered by photon absorption. The performance of the taper also validated the calculation of the superconducting transmission line. Although the pass band stopped at 2.4 GHz due to the loss of the PCB board and the bonding wires, the bandwidth was sufficient to support the read of the fast output pulses.

We demonstrated the pulse propagation by sending a pulse into the taper and measuring the output pulse from the other end. A 200-ps-wide electrical pulse (Avtech, AVMP-2-C-P-EPIA) was split into two. One pulse was acquired by a 6 GHz oscilloscope as a timing reference, while the other pulse was fed into the taper and its transmitted signal was acquired by another channel of the oscilloscope. We also compared the transmitted signal from the taper to the transmitted signal from a 50 Ω transmission line with the same length (corresponding to a delay of 94 ps) but made from a PCB. The delay difference between a PCB transmission line and the taper was 760 ps, indicating the superconducting taper slowed down the average velocity to 11% of a PCB transmission line. The amplitude of the transmitted signal from a taper reduced to 60% of the transmitted signal from the PCB transmission line; however, the rising edge of the pulse was well preserved, verifying that the taper helped the propagation of the fast pulse through a wire of mismatched impedance.

In the SNSPI used for taking images, the taper on each end was designed to have a bandwidth whose band pass started at 0.8 GHz. Each taper has an overall length of 27 mm, with its width smoothly changing from 105 μm to 300 nm. As shown in Fig. 2a, the rising edge of the photon detection pulses was about 240 ps without any reflection, ensuring the precise measurements of delay times τ_1 and τ_2.

Imaging processing algorithm

The raw imaging data was derived from the histogram of differential time $\Delta t = \tau_2 - \tau_1$ of photon counts acquired by the oscilloscope. The purpose of the image processing was to map the photon count C_n at each time bin Δt_n to the intensity I_n at the corresponding 2D locations (H_n,V_n). First, we calculated the effective 1D distance x from the layout of the double-meandered nanowire, taking into account the effective length of the corner (the corner's effective length was chosen to be 0.68 of its physical length based on numerical simulation of the propagation time through a corner) so that we determined a look-up table mapping x_n to (H_n,V_n). Secondly, we interpolated the histogram data with a finer time step of 0.045 ps and then converted Δt_n to x_n by using the formula $x_n = \frac{\Delta t_n \times v + L_e}{2}$, where v = 5.56 μm/ps was the velocity and L = 17.635 mm was the effective length. Thus, we were able to map the time bin t_n for each photon detection number C_n to the 1D distance x_n. Finally, we set a 2D image frame with grid sizes of 0.5 μm in both directions, where the 2D locations (H_n,V_n) were sorted. For each (H_n,V_n), the intensity was set to the photon count C_n whose corresponding time bin was t_n and the 1D distance was x_n. To reduce the mapping time, we spread the photon count C_n along the meandered nanowire at (H_n,V_n) in the 2D image, where the photon counts were distributed according to a Gaussian weight function with a standard deviation of 5 μm. During the mapping process, we shifted t_n with a constant time to correct for the difference of the delays from electrical connections to the two ends of the wire, and adjusted the velocity to result in a better image quality. The success of the tuning was evaluated by checking the alignments of neighbouring rows.

Instead of using the histogram data, the image can be also constructed from compilation of single-photon detection events to offer a real-time single-photon video. To use the same image algorithm discussed previously, raw data of (Δt, 1) was used, where each time difference was assigned to one photon count. The Supplementary Video shows a demonstration of such a video by taking the original differential arrival times from the oscilloscope.

Maximum counting rate of the SNSPI

The imaging time was limited by the counting rate of the SNSPI and the acquisition speed of the readout. In our present setup, we used a 6 GHz real-time oscilloscope because of its sub-ps intrinsic timing jitter. However, the oscilloscope had a refresh rate of ~100 waveforms per second, which was the bottleneck that limited the overall imaging time. To investigate the ultimate speed of the SNSPI, we ignored the timing information of the pulse and counted pulses from the SNSPI using a 200 MHz counter. We defined the maximum counting rate (CR_{max}) as the count rate when the average detection efficiency dropped by half. As shown in supplementary Fig. 2, CR_{max}, was 2 Mcps measured for 1.5 μm photons. The measured CR_{max} indicated the imaging time for an image such as the one shown in Fig.1c or Fig. 2d would require a few seconds if the oscilloscope bottleneck were removed by using a faster readout. The measured CR_{max} was lower than typical SNSPDs because it had a higher total kinetic inductance (estimated to be ~ 3 μH due to the long wire and the tapers), increasing the time for the bias current in the nanowire to recover[8]. CR_{max} could be increased by incorporating series resistors at each end of the nanowire[20].

Data Availability Statement (DAS)

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.