Superconducting nanowire single-photon detector implemented in a 2D photonic crystal cavity: supplementary material

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This supplementary material contains further information concerning the design, fabrication, and characterization of the detectors. This includes details on the physical dimensions of the photonic crystal (PhC) and on the fabrication procedure. The uncertainty in determining the on-chip detection efficiency (OCDE) is calculated by taking all relevant contributions into account. In addition, the single-photon detection capabilities of the devices are demonstrated.

1. DETECTOR GEOMETRY

The main parameters and design rules for the cavity geometry are sketched in Fig. S1. Four regions are distinguished: Injector, front reflector, cavity, and back reflector. Table ST1 lists the parameters for the simulation results depicted in Fig. 2 of the manuscript. Table ST2 gives the parameter of the measured devices for the data presented in Fig. 3 and 4 of the manuscript and in the Supplementary Material, including the nanowire geometry.

Fig. S1. Sketch of the detector’s cavity with the lattice constant of the injector region $a_{wg}$, the reflector region $a_r$, and the cavity region $a_c$. The bold black line depicts the nanowire.
Table ST1. Device parameters for the simulation results in Fig. 2 of the manuscript. Compare Fig. S1 for explanation of the cavity parameters. $l_{nw}$, $w_{nw}$, $h_{nw}$: length, width, and thickness of the niobium nitride (NbN) nanowire.

| Figure | $r$ | $2b$, var. $n_{t2}$ | $2b$, var. $w_{nw}$ | $2c$ |
|--------|-----|---------------------|---------------------|------|
| $l_{nw}$ | 120 nm | 120 nm | 120 nm | 120 nm |
| $a_{wg}$ | 440 nm | 440 nm | 440 nm | 440 nm |
| $a_{r}$ | 380 ... 405 nm | 390 nm | 390 nm | 390 nm |
| $a_{c}$ | 390 ... 415 nm | 400 nm | 400 nm | 400 nm |
| $a_{v}$ | variable, $= a_{c}$ | 400 nm | 400 nm | 400 nm |
| $n_{wg}$ | 3 | 3 | 3 | 3 |
| $n_{rr}$ | 8 | 8 | 8 | 8 |
| $n_{c}$ | 4 | 4 | 4 | 4 |
| $n_{t2}$ | 8 | 1 ... 8 | 8 | 2 |
| $n_{v}$ | 6 | 6 | 6 | 6 |
| $W$ | 1.05 | 1.05 | 1.05 | 1.05 |
| $l_{nw}$ | 3 $\mu$m | 3 $\mu$m | 3 $\mu$m | 3 $\mu$m |
| $w_{nw}$ | 50 ... 100 nm | 70 nm | 70 nm | 70 nm |
| $h_{nw}$ | 4 nm | 4 nm | 4 nm | 4 nm |

2. DETECTOR FABRICATION

The detector fabrication consists of three Ebeam lithography steps. The samples are exposed on the electron beam writer EBPG5200Z from Raith with an acceleration voltage of 100 kV. Material depositon is performed with electron beam physical vapor deposition (PVD). If we need to fabricate solely the photonic circuitry, e.g. for the characterization of the PhC waveguides and cavities, only the steps elucidated in the final section have to be conducted.

A. NbN sputter deposition

First, a thin ($\approx 4$ nm) niobium nitride (NbN) layer is deposited by DC reactive magnetron sputtering onto a $15 \times 15$ mm$^2$ silicon-on-insulator (SOI) chip. The thickness can be obtained by measuring the sheet resistance of the film, where typical values for 4 nm NbN on SOI are around 400 $\Omega/\square$.

B. Contact pads and alignment marks

In the first fabrication step, the contact pads and the alignment marks are manufactured. A sketch of the individual steps is shown in Fig. S2. A $\approx 850$ nm thick layer of polymethyl methacrylate (PMMA) is spincoated onto the sample. The PMMA acts as a positive resist in the subsequent electron beam lithography (EBL) exposure. We develop several minutes in a mixture of methyl isobutyl ketone (MIBK):IPA 1:3.

Via electron beam PVD, a layer of chrome (Cr) serving as an adhesion promoter, a layer of gold (Au), and a final layer of Cr for improved etch resistance are deposited. Due to the undercut, the sidewalls of the resist are not covered. In the subsequent lift-off step, the resist together with the deposited material on top is removed, leaving the exposed regions covered with Au and Cr.

C. Nanowire

The nanowire fabrication step represents the next step of the detector fabrication. In Fig. S3 the corresponding steps are depicted. First, a layer of SiO$_2$ is deposited via PVD on top of the NbN layer serving as an adhesion promoter for the $\approx 135$ nm thick negative tone resist Hydrogen Silsesquioxane (HSQ) 6 % used for patterning the nanowire via Ebeam exposure. Afterwards, the unexposed HSQ is removed with tetramethylammonium hydroxide (TMAH) 25% dissolved in water. In the next step, the
layer of SiO$_2$ and NbN not covered with resist are dry etched with fluorine-based reactive ion etching (RIE). The glass cover on top of the nanowire remains, serving as a protective layer against oxidation of the NbN.

**D. Photonic circuitry**

The photonic circuitry is structured with \(\sim 450\) nm thick positive tone resist ZEP520A. The individual steps are shown in Fig. S4. An area of \(4\) µm around the photonic circuitry is exposed with fluorine-based reactive ion etching (RIE). The glass cover on top of the nanowire remains, serving as a protective layer against oxidation of the NbN.

After the exposure, the resist is developed with Xylene, followed by a reflow process at \(140^\circ\text{C}\) to reduce losses due to surface roughness.

The silicon (Si) layer is then etched in an inductively coupled plasma (ICP) with HBr and Cl$_2$ chemistry. In a final step, the residual resist on top of the photonic elements is removed in a N-Ethyl-2-pyrrolidon (NEP) bath.

**3. CAVITY CHARACTERIZATION AT ROOM TEMPERATURE**

The double heterostructure nanocavity without the nanowire was characterized and optimized at room temperature. The measurements were performed in order to find the optimal parameters for the detector’s cavity, minimizing the radiative losses inside the cavity, and maximizing the absorption efficiency. We consider a symmetric double heterostructure cavity with equal front and back reflector parameters. The transmittance spectrum can be written as

\[
T(\omega) = \frac{1}{1 + \frac{Q_{\text{rad}}}{Q} + \left(\omega^2 - \omega_0^2\right)^2 + \frac{Q^2}{Q_{\text{rad}}^2}},
\]

with \(Q = (1/Q_{\text{wg}} + 1/Q_{\text{rad}})^{-1}\) and the resonance frequency of the cavity \(\omega_0\) [1].

We measure the transmittance of the cavity and fit a Lorentzian to the data to obtain the resonance wavelength \(\lambda_{\text{res}}\) and quality factor \(Q\). This data for the symmetric cavity can then be directly related to the asymmetric type cavity, which is used in the detector. Adding the nanowire to the cavity only slightly affects \(\lambda_{\text{res}}\) and the influence of the reflector length on \(\lambda_{\text{res}}\) is small. In the experiment, the parameters of the cavity are varied in a broad range. We vary the lattice constant in the cavity region \(a_c\) and reflector region \(a_r\) simultaneously. This leads to a shift in \(\lambda_{\text{res}}\). Secondly, the reflector length is changed in discrete steps \(n_r\) of the lattice constant for both the front and back reflector.

In Fig. S5a, \(\lambda_{\text{res}}\) of mode \(M_0\) is plotted versus the reflector length \(n_r\) for varying sets of cavity parameters, which are indicated in the legend as \((a_c, a_r, r)\) (compare Fig. S1). For the same set of parameters, \(\lambda_{\text{res}}\) lies within a range of 5 nm. If both \(a_c\) and \(a_r\) are increased for a fixed \(r\), also \(\lambda_{\text{res}}\) increases. By plotting the mean values of \(\lambda_{\text{res}}\) for \((400, 390, 110)\), \((395, 385, 110)\), and \((390, 380, 110)\) versus \(a_c\) and then performing a linear fit, we can estimate the change in resonance wavelength to \((3.1\pm0.1)\) nm per 1 nm change in \(a_c\) and \(a_r\). This is in good agreement with the simulation results, where a shift in \(\lambda_{\text{res}}\) of around 4 nm was obtained. By increasing the hole radius \(r\) (e.g. purple hexagon and red square in Fig. S5a), a stronger decrease in \(\lambda_{\text{res}}\) of around 3.5 nm per \(\Delta r = 1\) nm is observed.

In Fig. S5b, the quality factor \(Q\) of mode \(M_0\) is plotted in the same fashion as in Fig. S5a for varying reflector length and cavity parameters. A clear trend of increasing \(Q\) for increasing \(n_r\) is visible, best observed for \((390, 380, 110)\) (red squares). At the same time, the effective mode volume of the cavity mode stays almost constant. For higher values of \(n_r\), \(Q\) starts to saturate, as obtained from the numerical simulation. The radiative quality factor \(Q_{\text{rad}}\) can be attained as the limit of large \(n_r\), ranging from \(Q_{\text{rad}} = 4000\) to \(8000\) depending on the cavity parameters. For a front reflector length of \(n_r = 3\), \(Q\) can be estimated to 900. For smaller \(n_r\) a clear resonance is not observable, possibly due to a much broader higher order resonance overshadowing resonance \(M_0\).

The reduced \(Q_{\text{rad}}\) in the experiment in comparison to the values obtained from the numerical simulation is due to surface roughness and imperfections introduced during fabrication, resulting in increased scattering into radiative modes of the substrate and air.

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**Fig. S4.** Fabrication of the photonic circuitry. (a) Spin coating of electron beam resist ZEP. (b) Exposure of the resist. (c) Development. (d) ICP etching. (e) Resist removal.

**Fig. S5.** (a) Resonance wavelength \(\lambda_{\text{res}}\) of the fundamental cavity mode \(M_0\) versus reflector length \(n_r\) for varying cavity parameters. (b) Quality factor \(Q\) of the same mode. Device parameters as in (a). The values in the legend are denoted as \((a_c, a_r, r)\).
4. DETECTOR CHARACTERIZATION

A. Estimation of the OCDE

The OCDE is obtained from

\[ \text{OCDE} = \frac{\text{CR} - \text{DCR}}{\phi}, \]  

where CR and DCR denote the measured count rate and dark count rate, respectively.

In order to characterize the OCDE of the superconducting nanowire single-photon detector (SNSPD), the photon flux \( \phi \) towards the detector must be calibrated. We use a calibrated light source and an on-chip balanced layout, as depicted in Fig. S8, to account for waveguide losses. We calculate the optical power \( P_{\text{det}} \) incident on the detector using

\[ P_{\text{det}} = P_{\text{in}} \gamma C S \exp(-\alpha L_{\text{det}}), \]  

where \( P_{\text{in}} \) denotes the input power from the laser, \( \gamma \) the attenuation of the optical attenuators, \( C \) the coupling efficiency of the focusing grating couplers, \( S \) the splitting ratio of the integrated Y-splitter, \( \alpha \) the propagation loss of the on-chip waveguide, and \( L_{\text{det}} \) the length from the input coupler to the detector. The power coupled out of the reference port is given by

\[ P_{\text{ref}} = P_{\text{in}} \gamma C^2 S \exp(-\alpha L_{\text{ref}}), \]  

with the length from the input to output coupler \( L_{\text{ref}} \). Assuming a splitting ratio \( S = 0.5 \) and \( L_{\text{ref}} = 2L_{\text{det}} \), the flux towards the detector can be expressed as

\[ \phi = P_{\text{det}} \frac{\lambda}{hc} = \frac{\lambda}{hc} \gamma \sqrt{0.5P_{\text{in}}P_{\text{ref}}}, \]  

with the wavelength \( \lambda \), the Planck constant \( h \), and the vacuum light velocity \( c \).

B. Estimation of the uncertainty in the OCDE

An estimate for the uncertainty in the OCDE is obtained by error propagation. With Eqs. S3 and S5, the flux towards the detector is expressed as

\[ \phi = \frac{\lambda}{hc} P_{\text{in}} \gamma C S \alpha_{\text{total}}, \]  

with the total waveguide loss \( \alpha_{\text{total}} \) from the input focusing grating coupler to the detector. We do not take into account the error on the universal constants \( h \) and \( c \), as well as the error on the laser wavelength. For independent contributions from all other parameters, the relative error in the photon flux is given as:

\[ \frac{\delta \phi}{\phi} = \sqrt{\left(\frac{\delta P_{\text{in}}}{P_{\text{in}}}\right)^2 + \left(\frac{\delta \gamma}{\gamma}\right)^2 + \left(\frac{\delta C}{C}\right)^2 + \left(\frac{\delta \alpha_{\text{total}}}{\alpha_{\text{total}}}\right)^2}. \]  

Since the DCR is several orders of magnitude smaller than typical CRs, we neglect its contribution to the uncertainty of the OCDE. Since the photon flux towards the detector \( \phi \) and the obtained CR are correlated, we consider the two uncertainties as dependent. Thus, the relative uncertainty in the OCDE can be
calculated from
\[
\delta \text{OCDE} = \left| \frac{\delta \text{CR}}{\text{CR}} \right| + \left| \frac{\delta \phi}{\phi} \right|.
\]  
(S8)

B.1. Uncertainty in the laser power
The uncertainty in the laser power is estimated from a consecutive measurement of the laser input power over 13 hours. We determine the maximum of the Allan deviation to 0.08 µW at an averaging time of 10 s (compare Fig. S9). With a mean laser input power of \( P_{\text{in}} = 14.4 \, \mu \text{W} \), the relative uncertainty is estimated to 0.5%.

B.2. Uncertainty in the attenuation
To obtain the uncertainty in the optical attenuation, we consider both the time stability and the linearity of the attenuators. The optical attenuators (HP 8156A) are characterized at a wavelength of 1530 nm. The relative uncertainty linked to the attenuators stability amounts to 0.046% and is, therefore, negligible. The characterization of the attenuators linearity gives a relative uncertainty of 3.6%. Thus, the total uncertainty in the attenuation is equal to 3.6%.

B.3. Uncertainty in the propagation loss
From the transmission measurement of three under coupled ring resonators at room temperature situated on a different chip, the propagation loss per unit length is estimated to \( \alpha_{\text{dB}} = (11 \pm 5) \, \text{dB/cm} \) in the wavelength range from 1530 nm to 1570 nm. With a detector branch length of around 400 µm, the total propagation loss is estimated to \( \alpha_{\text{total}} = (0.44 \pm 0.2) \, \text{dB/cm} \). This amounts to a relative uncertainty on the total propagation loss of 5%. In the reference branch with twice the length of the detector branch, the total propagation loss amounts to \( \alpha_{\text{total, ref}} = (0.9 \pm 0.4) \, \text{dB/cm} \). Expressed in a relative uncertainty, this is equal to 8%.

B.4. Uncertainty in the splitting ratio
From a measurement of the extinction ratio (ER) in an integrated Mach-Zehnder interferometer situated on another chip, we estimate the uncertainty in the splitting ratio of the integrated Y-splitter. The extinction ratio is given by
\[
\text{ER} = \left( \frac{1 + \frac{1 - S}{S} \exp(-\alpha L/2)}{1 - \frac{1 - S}{S} \exp(-\alpha L/2)} \right)^2.
\]  
(S9)

with the splitting ratio \( S \), the propagation loss \( \alpha \), and the path difference \( \Delta L \) in the two interferometer branches. With the propagation loss obtained in Section B.3 and a length of \( L = 100 \, \mu \text{m} \), we can estimate the splitting ratio to \( S = 0.5 \pm 0.04 \), resulting in a relative uncertainty of 8%.

B.5. Uncertainty in the coupling efficiency
The uncertainty in the coupling efficiency is estimated by considering eleven transmittance spectra from different devices through the reference branch at zero attenuation. By setting \( \gamma = 1 \) and \( \alpha_{\text{total, ref}} = \exp(-\alpha L_{\text{ref}}) \) in Eq. S4, we obtain the following equation by rearranging
\[
T = \frac{P_{\text{ref}}}{P_{\text{in}}} = C^2 S \alpha_{\text{total, ref}}.
\]  
(S10)

For independent contributions to the uncertainty of the transmittance \( T \), the relative uncertainty reads as
\[
\frac{\delta T}{T} = \sqrt{\left( \frac{\delta C}{C} \right)^2 + \left( \frac{\delta S}{S} \right)^2 + \left( \frac{\delta \alpha_{\text{total, ref}}}{\alpha_{\text{total, ref}}} \right)^2}.
\]  
(S11)

Solving the above equation for \( \delta C / C \) gives an estimation of the relative uncertainty in the coupling efficiency to
\[
\frac{\delta C}{C} = 0.5 \left[ \left( \frac{\delta T}{T} \right)^2 - \left( \frac{\delta S}{S} \right)^2 - \left( \frac{\delta \alpha_{\text{total, ref}}}{\alpha_{\text{total, ref}}} \right)^2 \right].
\]  
(S12)

The mean transmittance overlaid with the uncertainty is plotted in Fig. S10a.

Inserting the relative uncertainty in the transmittance as well as the uncertainties in the splitting ratio and in the propagation loss.
Fig. S11. Relative error in the count rate plotted versus the wavelength. To reduce fluctuations we calculate the rolling mean (black line).

Fig. S12. Relative uncertainty in the OCDE plotted versus the wavelength.

loss into Eq. S12 enables us to estimate the relative uncertainty in the coupling efficiency for each wavelength. The result is plotted in Fig. S10b. The minimum relative uncertainty amounts to 10% at a wavelength of 1518 nm.

B.6. Uncertainty in the count rate

The count rate (CR) is typically obtained by measuring ten data points for an integration time of 1 s per data point. We account for the uncertainty in the CR by considering the statistical variation in the CR for these data points at each wavelength. The resulting relative uncertainty is plotted in Fig. S11. The minimal relative uncertainty amounts to 0.3% at a wavelength of 1506 nm.

With the above obtained results, we can estimate the relative uncertainty in the OCDE with Eqs. S7 and S8 at each wavelength. The result is depicted in Fig. S12. The minimum relative uncertainty amounts to 10.5% at a wavelength of 1517.6 nm. It can be clearly seen that the main contribution to the uncertainty arises from the grating couplers.

C. Estimation of the uncertainty in the NEP

With the results of the previous section, we are able to estimate the uncertainty of the noise-equivalent power (NEP) at the resonance wavelength $\lambda_{\text{res}} = \frac{c}{\nu}$.

$$\text{NEP} = \frac{h \nu \sqrt{2 \text{DCR}}}{\text{OCDE}} \tag{S13}$$

Again, we assume the wavelength to be precise. The uncertainty in the OCDE has already been determined in Eq. S8. As before, the uncertainty in the dark count rate (DCR), $\delta_{\text{DCR}}$, is several orders of magnitude smaller than the uncertainty in the OCDE and can be neglected. In addition, errors in the absolute wavelength are neglected. It follows the simple relation:

$$\delta_{\text{NEP}} = \frac{\delta_{\text{OCDE}}}{\text{OCDE}} \tag{S14}$$

D. On-resonance OCDE improvement

The improvement of the OCDE due to the cavity is quantified by comparing the OCDE at resonance to devices without a cavity. In Fig. S13, the OCDE is plotted as a function of the bias current for three devices. The two reference devices both have a strongly reduced OCDE with a maximum value of around 4%. For one device, the nanowire is situated atop of a PhC waveguide (PhC, no cavity), and for the other device the nanowire is placed perpendicular atop of a strip waveguide (no PhC).

Fig. S13. OCDE for a device with a PhC cavity (measured at resonance) compared to two devices without cavity. For one device, the nanowire is situated atop of a PhC waveguide (PhC, no cavity), and for the other device the nanowire is placed perpendicular atop of a strip waveguide (no PhC).

E. Timing jitter

The timing jitter is measured using the setup shown in Fig. S14. A pulsed fiber laser with a repetition rate of 40.125 MHz generates a short pulse of $\approx 1$ ps. By splitting up the light with a 50/50 splitter and registering the pulse with a fast, low noise 1 GHz photodetector, we obtain a reference signal for the signal received from the SNSPD. The light passing the other arm of the splitter propagates towards the SNSPD.

Both electrical pulses received from the photodetector and the SNSPD are recorded with a fast oscilloscope (13 GHz, 40 GSa/s).
Fig. S14. Measurement setup for characterizing the timing jitter of the detector.

We start a timing measurement by triggering the rising edge of the SNSPD signal at 50% of the maximal peak height. The time difference to the reference pulse of the photodetector is then recorded in a histogram.

The timing jitter is obtained as the FWHM of a Gaussian fit to the histogram (Fig. S15a). Here, the timing jitter is obtained for device #2 in the manuscript. It is measured off-resonance at a wavelength of \( \approx 1540 \text{ nm} \), since the detector’s resonance is not within the pulsed laser’s bandwidth. Measuring the jitter at resonance might further improve the jitter due to an improved CR at the same photon flux and therefore an improved signal to noise ratio.

We obtain a timing jitter of 29 ps for a bias current of 0.81 \( I_C \). In Fig. S15b, the timing jitter is plotted as a function of the applied bias current. The timing jitter decreases with increasing bias current. This can be attributed to an improvement in the signal to noise ratio with increasing bias current [4].

The measured jitter includes the jitter contributions of the photodetector, the oscilloscope, the amplifiers, and the detector. By improving the jitter of the electronic readout, e.g. by using cryogenic instead of room-temperature amplifiers, one might further decrease the jitter, as shown in Ref. [5].

F. Single- and multi-photon detection

We demonstrate the detector’s sensitivity to single photons and investigate the multi-photon detection capabilities. The different detection regimes can be explored by illuminating the detector with varying photon fluxes at constant bias currents \( I_B \), measured for a variety of bias currents. A laser is a coherent light source obeying Poissonian photon number statistics. The probability \( P \) of finding \( n \) photons in the time interval \( \Delta \) is given by

\[
P(n, \Delta) = \frac{(\mu \Delta)^n e^{-\mu \Delta}}{n!},
\]

where \( \mu \) is the mean number of photons per unit time (photon flux \( \phi \)). For the simultaneous absorption of multiple photons, the relevant time interval is the relaxation time of the resistive hotspot, typically on the order of tens of picoseconds [6]. Since \( \mu \Delta \ll 1 \), for the employed photon fluxes, the above equation reduces to [7-9]

\[
P(n, \mu) \approx \frac{(\mu \Delta)^n}{n!}.
\]

Hence, one can directly access the number of photons contributing to the detection event. Due to the limited bandwidth of the pulsed laser, we perform this experiment with a CW laser at the resonance of the detector. Alternatively, the same experiment can be conducted with a pulsed laser and varying average photon numbers per pulse. For a detector sensitive to single photons, the obtained CR is directly proportional to the photon flux [10]. If the detector is triggered by two photons or more, the CR is proportional to \( (\mu \Delta)^2 \). We plot the CR versus the photon flux on a double logarithmic scale and perform a linear fit with a predetermined slope of either one or two.

The result is shown in Fig. S16 for a 80 nm wide nanowire (device #2 in the manuscript). The linear fits with \( n = 1 \) agrees well with the data points for higher bias currents, which reveals the single photon detection capabilities of the detector. For the smallest \( I_B = 0.43 I_C \), the fit with \( n = 2 \) does not match well with the data points. This indicates a transition region between the one-photon and two-photon detection regime.

G. Afterpulsing

Figure S17 depicts the inter-arrival time measurement from the main manuscript on a longer timescale. Two features are visible: a slight increase in the histogram counts around 5 ns, and a sharp decrease around 16 ns. We attribute the former to a slight afterpulsing behaviour, and the latter to reflections in the electronic readout circuitry effectively reducing the OCDE.

H. Critical currents

Figure S18a shows the hysteresis curve of device #3 for different incident photon fluxes. As can be readily seen, increasing the photon flux reduces the attainable critical currents. Figure S18b
Fig. S16. Single- and multi-photon statistics.

depicts the statistic of critical currents $I_C$ of all two-dimensional (2D) PhC cavity detectors under consideration, compared to the previous microbridge and the traditional U-shape design.

Fig. S17. Inter-arrival time measurement. This is the same data as in Fig. 4 of the main manuscript with extended timescale.

Fig. S18. (a) Hysteresis curves recorded for one device with $w_{nw} = 80$ nm under different illumination. The critical current is $I_C = 17.4 \, \mu$A. (b) Comparison of critical currents on the same sample, for the novel detector design (2D PhC cavity), the previous design (microbridge, [3]), and U-shape design [11]. The data points are slightly offset in the x-direction for better visibility of overlapping data points.
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