High Speed Travelling Wave Single-Photon Detectors With Near-Unity Quantum Efficiency

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Ultrafast, high quantum efficiency single photon detectors are among the most sought-after elements in modern quantum optics and quantum communication. Close-to-unity photon detection efficiency is essential for scalable measurement-based quantum computation¹-³, quantum key distribution⁴, and loophole-free Bell experiments⁵. However, imperfect modal matching and finite photon absorption rates have usually limited the maximum attainable detection efficiency of single photon detectors⁶. Here we demonstrate a superconducting nanowire detector⁷ atop nanophotonic waveguides and achieve single photon detection efficiency up to 94% at telecom wavelengths. Our detectors are fully embedded in a scalable, low loss silicon photonic circuit⁸-¹⁰ and provide ultrashort timing jitter of 18ps at multi-GHz detection rates. Exploiting this high temporal resolution we demonstrate ballistic photon transport in silicon ring resonators. The direct implementation of such a detector with high quantum efficiency, high detection speed and low jitter time on chip overcomes a major barrier in integrated quantum photonics.

Single photon detectors (SPDs) with high detection efficiency play a crucial role in modern quantum optics and information science that utilize photonic qubits as information carriers¹¹. The availability of fast photon-counting detectors with close-to-unity efficiency is a prerequisite for measurement-based quantum computation and will significantly enhance the throughput of optical quantum communication systems¹². On a more fundamental level, highly efficient SPDs will also allow for loophole-free Bell experiments⁵ and guarantee that protocols based on quantum nonlocality outperform their classical counterparts¹³. The need for high efficiency photon detectors has recently become ever more pressing as quantum computation and communication applications come into reach of current technology, which is evident from recent progress in developing integrated photonic circuitry¹⁴,¹⁵. However, universal and scalable quantum computation is possible with single photons and linear optics only if efficient qubit measurements can be performed. At present low photon detection efficiencies limit the success probability of quantum gate operations and therefore the scalability of quantum optical circuits. Both the generation of highly entangled graph states for one-way quantum computation¹⁶ and the measurement-induced multi-qubit operations in teleportation-based schemes¹ rely on large numbers of high-efficiency single photon detectors, which to-date are still realized off-chip. Therefore a scalable and efficient detector architecture is highly desirable to move beyond few qubit operations.

Besides efficiency and scalability, high temporal resolution is another key feature required in quantum optics and quantum information processing. The manipulation and processing of qubits
at GHz rates is becoming a necessity for quantum computers and quantum communication systems to pace up with their classical counterparts\textsuperscript{17,18}. Single photon detectors combining high efficiency with high speed will lead to improved performance of active feed forward\textsuperscript{19}, which is an essential element of cluster state quantum computing and error correction schemes, as well as entanglement manipulation and quantum communication over longer distances with higher bit rates\textsuperscript{20,21}. Similarly, a major challenge in integrated quantum photonics lies in reliably discriminating alternative optical paths for generating time-bin or path entanglement where picosecond time resolution is desired.

Current state-of-the-art single photon detectors are still far away from reaching such a combination of high speed and efficiency. Silicon avalanche photo-detectors (APDs), that are widely used for visible light detection, have, at best, quantum efficiency of 65\%, accompanied by significant dead time (> 65ns)\textsuperscript{22} and rather high timing jitter\textsuperscript{23}. While single photon measurement in the visible spectrum is important for a wide range of applications, efficient detectors in the near infrared (NIR) are necessary to employ the modern optical fiber infrastructure for quantum communication purposes. InGaAs single photon detectors can count NIR photons in the telecom bands but usually have only moderate quantum efficiency (~10-25\%)\textsuperscript{24,25}. Furthermore, such detectors are plagued by high noise (dark counts) and must run in gated mode. So far the best contender in terms of quantum efficiency is the transition edge sensor (TES)\textsuperscript{26,27}. Unfortunately, these devices are rather slow and must be operated in a dilution refrigerator at millikelvin temperatures.

Here we present an integrated single photon detector that operates at 1550nm wavelength with high detection efficiency, high speed and low timing jitter. We employ superconducting nanowires to achieve single-photon resolution at more easily obtainable liquid Helium temperature. Using a travelling wave design\textsuperscript{28} provides near-perfect absorption of incoming photons and allows for high counting rates. Efficient coupling between propagating optical waves and the superconducting thin film allows us to drastically reduce the detector length and therefore leads to a small foot-print device that can be efficiently combined with established integrated optical circuits. Our detectors are realized on commercial silicon-on-insulator substrates and thus allow for realizing densely integrated photonic circuitry.

To demonstrate the time-domain performance of our detectors we resolve the delay of ballistic photon transport in on-chip optical ring resonators.

Traditional superconducting nanowire SPDs (SSPDs) absorb incoming photons under normal incidence. Therefore the detector absorption length is determined by the thickness of the superconducting thin film. This implies that only a fraction of the photon flux is absorbed because the film is normally only several nanometers thick. Resonant cavities can be employed to enhance the absorption by virtually prolonging the interaction length\textsuperscript{29}. However, this approach inevitably reduces the detector optical bandwidth and the obtainable quantum efficiency is eventually limited by the quality of the deposited end mirrors and the coupling conditions to the cavity.

Here, in contrast, we employ the travelling wave geometry shown schematically in Fig.1a) in order to maximize the waveguide-detector interaction length and thus obtain strong photon absorption. Photons propagate along silicon waveguides in an on-chip photonic network towards the detector region. In the detection area the silicon layer is covered with a superconducting Niobium Nitride (NbN) thin film of 3.5nm thickness, which couples evanescently to the guided optical mode. To achieve hot-spot formation upon photon absorption, the NbN thin film is patterned into two narrow wires, with a wire width of 100nm and a wire spacing of 120nm. Light
from an external pulsed laser source is coupled into the chip using focusing grating couplers (Fig. 1b, pink triangles), guided along low-loss photonic waveguides, and further split into two paths: one path leads towards the detector and the other path is directed to a calibration port. After passing through the detector, any residual light is collected into an additional output port (labeled residual light port in Fig.1b)). Thus, for the purpose of detector calibration, the photonic circuit allows us to estimate absorption losses from the NbN wires. In the scanning electron micrograph (Fig. 1b, inset), the NbN structures are discernable as the light regions, located on top of the silicon photonic circuitry. In addition to the optical ports, metal RF-contact pads are used to extract the detector signal from the chip, as shown in the upper half of Fig.1b).

The absorption properties of the detector are first analyzed with three-dimensional finite-difference time-domain (FDTD) simulations as shown in Fig.1c). The fundamental optical mode of a 750x110nm² silicon waveguide is launched from the left towards the NbN detector region (light structure in the center of the image). The waveguide supports one single optical mode in TE polarization (Fig.1d)). In the presence of the NbN thin film the evanescent tail of the guided optical mode is coupled strongly to the superconducting wires. In this case the optical fields are more tightly confined to the metallic regions, as shown in the inset of Fig.1e), with significant field enhancement at the NbN sides. This coupling leads to strong absorption of the incoming wave, as presented in the log-plot of the modal intensity in Fig.1c). From the optical simulation we obtain 10.1dB attenuation within a10μm long waveguide with NbN wires on top, i.e.1.01dB attenuation per μm of detector length.

The simulation results are verified experimentally by measuring photon absorption for detectors of varying length. We characterize the optical attenuation of the device shown in Fig. 1b) using a low-temperature cryostat setup configured with a RF probe and a fiber array. A photonic chip containing 60 devices is mounted on a movable three-axis stage (by Attocube) that is hanging under a 1K pot inside a Helium-4 Cryostat. After device cool down, we use a tunable laser source (New Focus 6428) to scan the transmission properties of the optical circuits with continuous-wave light (CW). The light at the control port and the residual light port are detected simultaneously with two external low noise photoreceivers. After establishing electrical contact with the chip, the fiber-array is separated from the sample surface by a gap on the order of 100μm. The input grating coupler have 13dB±0.5dB insertion loss across the wafer. Despite of the coupler variations from chip to chip, the power extracted from the two output ports on the same device are identical within 0.2dB (5%) in the absence of detectors. By varying the period of the coupler grating we are able to cover operation wavelengths in the telecoms L and C bands. In Fig.1f) we show the measured absorption spectra for a range of devices with total detector length varying from 5μm to 40μm. Each detector comprises two wires in series; therefore the length of the NbN wires on top of the waveguide is roughly twice the length of the detector. The absorption spectra are measured over the bandwidth of the grating couplers from 1520 nm to 1555nm. An almost flat absorption profile (Fig.1f)) shows that the detector is wavelength insensitive over the measured coupler bandwidth. The attenuation increases exponentially with increasing detector length, as predicted from the numerical simulations in Fig.1c). The absorption of the detector film can be extracted from the attenuation-length dependence as shown in Fig.1g), revealing an attenuation of 0.98±0.1dB per micrometer detector length. The measured results are in good agreement with the simulated absorption rate (blue triangles in Fig.1g)). From the linear fit of the attenuation we find that a detector with a length of 20μm provides 99%±2% absorption of the incoming light.
The performance of our single-photon detectors is assessed in terms of detection efficiency, dark count rate, and timing jitter\textsuperscript{6,23}. We analyze the on-chip detection efficiency (DE) by measuring the rate of the detected photons propagating inside the waveguide. We fabricate several different detector structures with varying length in order to evaluate the dependence of the on-chip DE on the detector length. The detector counting rates are measured at 2.0K. The integrated circuit is optically excited using a pulsed laser source with a pulse-width of 1ns and a period of 20ns (50MHz repetition rate, see Methods section). The optical power fed into the photonic circuit is measured with a calibrated power meter prior to adding controllable attenuation. We fixed the average input power at 100\(\mu\)W. Subsequently, calibrated optical attenuation up to 90dB is added. Taking into account the input loss occurring at the input grating coupler as well as the loss due to the on-chip 50/50 splitter, the resulting total photon flux travelling along the waveguide leading to the on-chip detector is on the order of \(10^6\) photons/second, which is less than one photon per pulse on average, but significantly higher than the dark count rate. At 2K, the critical current \(I_c\) is measured to be 28\(\mu\)A for typical devices. The detectors are current-biased with a low-noise battery powered current source close to the critical current. Two cascaded high-bandwidth electrical amplifiers are used to raise the electrical signal for use with a PicoHarp300 Time-Correlated Single Photon Counting (TCSPC) system (by PicoQuant).

Fig.2 illustrates the measured dependence of the on-chip DE as a function of detector length and bias current. The bias current is scanned between 60\% and 99\% of the critical current value for devices with detector length of 20\(\mu\)m and 30\(\mu\)m. The best detection efficiency out of all the examined devices on the chip is obtained for a 20\(\mu\)m long device. In this case we measure a maximum on-chip DE of 94\(\pm\)5\% at a bias current of 99\% \(I_c\), which is close to the expected value for an absorption value of 20dB. On the measured chip we do not find improved DE for detectors with increased length, which is most likely due to a higher probability of fabrication imperfections for longer wires. For the sake of comparison we also present the detection efficiency measured for an alternative, more conventional meander wire detector design (purple markers) where the detector wires are laid out in a traditional meander structure (see Supplementary Materials) with a total meander length of 600\(\mu\)m. In this case we encounter increased scattering loss and thus reduced detection efficiency of 3\% at the highest bias current. Results for the dark count rate as a function of detection efficiency are presented in Fig.2b). At a detection efficiency of 10\% we measure dark count rates below 0.1Hz for a typical detector with optical attenuation above 20dB. Due to the low dark count rate and high detection efficiency we are able to deduce low Noise Equivalent Power (NEP) as presented in the inset of Fig.2b). The NEP is calculated as 

\[
NEP = \frac{h\nu\sqrt{2R_d}}{DE},
\]

where \(h\nu\) is the energy of photon and \(R_d\) is the dark count rate. Shown are results for the two detectors at 4.2K and 2K. For a bias current of 82\% \(I_c\) we find a best NEP of \(4\times10^{-19}\)W/Hz\(^{1/2}\) for the 20\(\mu\)m long detector. Higher detection efficiency at increased bias current is accompanied by an increased number of dark counts, which is comparable to previously reported SSPDs\textsuperscript{30}. However, we note that included in the unwanted detection events are also counts due to unshielded ambient background light which is leaking through the fiber cladding. Utilizing light-tight fiber jackets can alleviate this in a future improved measurement setup.

The electrical pulse profiles for four detectors of different lengths are shown in Fig.3a). The decay time extracted from these profiles increases linearly with detector length as shown in Fig.3b), which is expected due to the increase in kinetic inductance. Due to the smaller kinetic
inductance of shorter detectors, the relaxation time of the detector is significantly reduced\cite{31}. For the shortest detector of 10μm length we measure a decay time of 455ps and a FWHM of 505ps. For the longest detector the decay time increases to 1392ps, paired with a FWHM of 1226ps. Sub-nanosecond pulse width implies that detection rates in excess of 2GHz can be achieved with our detectors.

We also determine the timing jitter of the signal from the NbN wires in order to evaluate the detector performance for optical buffering and time-domain multiplexing. We excite the optical circuit with a sub-picosecond pulsed laser source (0.6ps pulse width), tunable over the telecom C-Band. We determine the timing jitter of the detectors using both a high-speed sampling oscilloscope (Agilent Infinium with 20GHz sampling rate) and the PicoHarp300 Time-Correlated Single Photon Counting (TCSPC) system. We first determine the intrinsic instrument jitter by employing an electrical self-referencing method (splitting the same electrical pulse in two using a T-connector) and extract the jitter from the Gaussian fit to the measured data. For the sampling oscilloscope we obtain intrinsic jitter of less than 1ps, while the PicoHarp300 yields significantly higher instrument jitter of $\tau_{ph} = 19$ps. The sampling oscilloscope is then employed in start-stop configuration. The attenuated laser output is split with a fiber 50/50 splitter before being fed into the on-chip devices. The light from one arm of the splitter is fed into a high-speed photodetector with 20GHz bandwidth to provide a stable trigger (start) signal. The light from the second arm is fed into the on-chip detector devices and their electrical output is used as a “stop” signal for the jitter analysis. The oscilloscope is run in histogram mode with a time-window size of 200ps, providing high temporal resolution at a sampling rate of 20GHz. The oscilloscope provides an interpolation function in between sampling intervals and allows for true picosecond histogram resolution. The measured value is the jitter between consecutive pulses and is shown in Fig.3c) by the blue squares. Fitting the data with a Gaussian function yields a jitter value of 18.4ps. For comparison we also show the jitter measurement obtained with the PicoHarp300 (green circles in Fig.3c)). In this case fitting the measured time-resolved coincidence counting rate with a Gaussian function yields a jitter value of $\tau_m = 50$ps. However, the real detector jitter is shadowed by the PicoHarp’s instrument timing jitter. Therefore the estimated SSPD jitter extracted from the PicoHarp300 amounts to $\tau_{SSPD} = \sqrt{\tau_m^2 - \tau_{ph}^2} = 46$ps\cite{31}. Contributions to the rather high jitter value result from variation in the discriminator value of the PicoHarp300 as well as the relatively high noise value of the fused broadband inverting amplifiers used by the PicoHarp. Furthermore, the PicoHarp300 cannot be used in TTR mode in our case due to the high repetition rate of the pulsed-laser source, which also contributes to increased jitter values.

To further verify that the jitter signal is not limited by the bandwidth of the electrical amplifiers, we measure the jitter in dependence of the analog bandwidth of the amplifier set as shown in Fig.3d). Even for low bandwidth of 1.4GHz, the oscilloscope yields a reduced jitter value of 30ps. Increasing the amplifier bandwidth above 10GHz leads to a converged jitter estimate of 18.4ps. Beyond 10GHz, the electrical bandwidth is limited by our cryogenic cables and the detector’s impedance mismatch to 50Ω circuits.

The high quantum efficiency and fast detector response of our detector enable time-domain multiplexing in integrated photonic circuits\cite{32}. This opens a way for high-fidelity manipulation of multiple optical qubits on chip. In order to demonstrate the applicability of the SSPDs to fast on-chip single-photon measurements we examine variable photon-delay from a micro-ring resonator. The device used in the experiments is shown in Fig.4a). Two sets of input grating couplers are used to provide measurement capabilities of the micro-ring in both through and drop
port configuration. The optical output from one of the drop lines is split with an on-chip 50/50 splitter and fed into a grating output port and an integrated SSPD (shown in the inset of Fig.4a)). The input waveguides are coupled to a ring resonator of 5.8mm in length. The optical resonator is laid out in a meander form with a radius of 25μm at the bends in order to reduce the covered chip area. The bending loss induced at the turning points is small and does not compromise the optical quality factor because we are employing silicon waveguides with a high refractive index contrast. The width of the waveguides is fixed at 750nm, which provides measured propagation loss of 4.3dB/cm.

The ring resonator can be used in the overcoupled or undercoupled regime by varying the gap between the coupling waveguide and the ring. When the gap is small, the resonator is strongly coupled to the feeding waveguide and thus a significant portion of the input light is transferred into the ring. The light circulating within the ring is, in turn, coupled out efficiently as well. Thus the circulating intensity drops quickly over time, as illustrated in the schematic in Fig.4b). This strong coupling reduces optical quality factors because the cavity is overloaded. We measure the transmission spectrum in the through port with a tunable laser source in order to assess the quality factor of the ring. Results for an overcoupled device with an input gap of 100nm are shown by the purple curve in Fig.4b). Because of the large circumference of the ring resonator the free spectral range (FSR) is small, leading to dense transmission dips at the optical resonances in the spectrum. Fitting the dips with a Lorentzian function yields a quality factor of 14,000 in the overcoupled case (orange curve in Fig.4b)). When the coupling gap g is increased, less light is coupled into and out of the ring resonator. Therefore, light circulating inside the ring decays slower and produces elongated pulse trains when the ring is excited with a pulsed laser source (Fig.4c)). We measure improved optical quality factors around 24,000, as shown in Fig.4c) with the blue markers (the red line denotes the Lorentzian fit to the resonance curve) for a device with increased coupling gap of 200nm.

We then analyze the ring parameters in the time-domain with our low jitter single photon detectors. The optical circuit is excited with attenuated picosecond laser pulses and photon detection events are registered with the on-chip SSPD. The detector is biased far enough from the critical current (86% I/Ic) to yield good detection efficiency (~15%) at low dark count rates (<1Hz). The traces are recorded in the drop port (through port traces are also recorded, see Supplementary Materials). For the overcoupled ring resonator we measure the time-domain trace shown in Fig.4d). The photons circulating inside the ring resonator quickly decay from the cavity, so that only 2 peaks are discernable in the linear plot of the arrival time histogram. A third peak is barely visible above the detector count background in the log-plot shown in the inset of Fig.4d). We can obtain the decay time of the ring resonator from the position and height of the peak amplitudes, which amounts to 19.3ps in an exponential fit to the data. Converted into the spectral domain, the decay time corresponds to an optical quality factor of 11,900 which is in good agreement with the measured spectral value. The decay from the cavity is slowed down when we consider an undercoupled device with a coupling gap of 200nm. In this case we are able to observe four consecutive pulse fronts in the time-domain trace. Fitting peak positions with an exponential function reveals a decay time of 37.1ps corresponding to a spectral width of 67pm or equivalently an optical quality factor of 22,900. The positions of the pulse peaks are separated by a delay time of 72.7ps, which is determined by the length of the ring resonator and the group index of the waveguide profile. The group index value measured from the spectrum is 3.58, close to the simulated value of 3.6. The corresponding delay time of 69ps is likewise in good agreement with the measured value.
The demonstrated performance of our fast and high-efficiency superconducting single-photon detector opens a road for integrating tens and hundreds of such devices on a single chip. It will allow for the realization of densely packed integrated photonic circuits for quantum information processing and quantum communication applications. The unique combination of near-unity detection efficiency with increased detector bandwidth and time resolution makes the device invaluable for high-fidelity manipulation and evaluation of quantum states of light on a chip, in both spatial and temporal domains. The use of silicon for device manufacture offers additional advantages in comparison with integrated photonic circuits realized on silica-based substrates because of its large refractive index contrast. Therefore the overall size of quantum photonic circuits can be drastically reduced and combined with other electronic components that are already developed on silicon substrates. While the detectors demonstrated here were analyzed in the telecom band, the detection wavelength range can in principle be extended towards the band-edge limited transmission window of silicon down to 1100nm with adjusted grating couplers. Furthermore, by moving to an alternative material system such as Silicon Nitride we anticipate that our detectors can also be used at visible wavelengths.

We also expect exciting applications by exploiting integrated SSPDs for photon buffering using silicon based photonic circuits. With 4dB/cm loss waveguides, we were already able to resolve 4 round trips of photons in a 5.8mm ring. Recent progress in CMOS level nanofabrication has enabled fabrication of ultra low loss waveguides with propagation loss on the order of 0.1dB/m. Although there are technical challenges to interface such waveguides with our detectors, in principle, it is possible to delay photons for many round trips without experiencing loss in rings of similar dimensions as the devices demonstrated here. Such a low loss delay line also brings photon number resolving detectors within reach, which ideally complement recently demonstrated transition edge detectors, yet with the benefit of much higher quantum efficiency and speed.

To address the ultimate desires of the quantum communication community the detection speed of our travelling wave detectors can be increased further into the tens of GHz by reducing the length of the NbN covered waveguide, at the cost of somewhat lower detection efficiency. This will eventually allow for bringing quantum cryptography close to the speed of conventional telecommunication equipment.

**Additional information**

Our detectors and integrated optical components are realized on commercially available silicon-on-insulator wafers with a buried oxide thickness of 3μm and a top silicon layer of 220nm thickness. The silicon top layer is thinned down to 110nm by oxidation and subsequent wet etch in buffered Oxide etch (BOE). Niobium nitride thin films of 3.5nm thickness are deposited by dc reactive magnetron sputtering in an Ar and N\textsubscript{2} atmosphere. The as-deposited films were characterized by the surface resistance $R_S = 500\Omega/$sq, critical temperature $T_c = 10$ to $11K$, superconducting transition width $\Delta T_c \sim 0.3$ K, and critical current density $j_c = 6 \times 10^6A/cm^2$ measured at 4.2K. Optical photo-lithography using a double-layer lift-off resist (Shipley 1805 + LOR5A) is utilized to define contact pads and alignment marks. E-Beam evaporation of 5nm Cr and 200nm Au is performed and the contact pads are formed by lift-off in NMP. A first Electron-beam lithography step is carried out on an EBPG 5000+ 100kV system using HSQ e-Beam resist to define the detector structures. A timed etching step in ICP RIE using CF\textsubscript{4} chemistry is performed to etch through the NbN layer. Subsequently, a second e-Beam lithography is...
employed to define optical circuitry. The sample is then etched by ICP RIE in Cl₂ plasma to define the waveguiding structures in the top silicon film.

Coherent pump light is launched into the chip from a swept wavelength diode laser (New Focus 6428) combined with two optical attenuators (Tektronix OA5002), which provide up to 60dB of optical signal reduction each. The transmitted light from the device is recorded with a low-noise, high frequency photodetector (New Focus 1554-B) for wavelengths around 1550nm. Optical pulses are generated using a lithium niobate high-speed electro-optical modulator (Lucent 2623NA) combined with a pulse generator (HP8133a). For the ring-down measurements a Pritel fiber laser with a pulse width < 1ps and a period of 12.5ns is employed. The central pulse wavelength can be tuned over the telecom C-Band from 1532nm to 1565nm, which is used to match the input wavelength to the central wavelength of the on-chip grating couplers. The SSPDs are current-biased with a battery powered current source (LakeShore101) and a bias-T. Two electrical amplifiers with varying analog bandwidth (by RF-Bay and Picosecond Labs) are used to elevate the electrical signal by up to 47dB. For use with the PicoHarp300 an inverting 15GHz amplifier (Picosecond Labs 5828) is used. The time-domain signal is recorded on an oscilloscope (Agilent Infiniium 54855A).

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**Figure 1**: Design of the travelling wave SSPD. a) Principle of the travelling wave SSPD: a sub-wavelength absorbing NbN nanowire is patterned atop a silicon waveguide to detect single photons; b) Optical micrograph of a fabricated device showing the optical input circuitry, RF contact pads and the SSPD; Inset: zoom into the detector region with an SEM image showing the detector regime. The control and residual ports are used for calibration purposes. c) Finite-difference time-domain simulation of the absorption characteristics of the detector. The propagating intensity is displayed in a logarithmic scale. d) The simulated field distribution of the optical mode in the silicon portion of the waveguide; e) The modal pattern with NbN wires on top. The inset shows the optical field concentration around the NbN wires; f) measured absorption spectra of detectors with lengths varying from 5μm to 40 μm. g) The detector attenuation in dependence of length, measured as the ratio of power between the residual port and the control port, exhibits a slope of 0.98dB/μm.
Figure 2: SSPD detection performance. a) Shown is the detection efficiency of fabricated devices as a function of detector length and normalized biasing current. The best detection efficiency of 94% is obtained for a 20μm long detector at 99% of the critical current. For comparison, a meander-type detector (MMI) is also measured with a peak detection efficiency of 3%; b) The detector dark count rate measured at 2K as a function of detection efficiency. Shown are data for two different detectors with lengths of 20μm and 30μm. Inset: The resulting Noise-Equivalent Power in dependence of bias current measured at 2K and 4.2K. The best value is $4\times10^{-19}$ W/Hz$^{1/2}$, obtained at 82% $I_c$. 
Figure 3: Single-photon detector characterization in time domain. 

a) Measurement of the pulse shape for SSPDs with lengths varying from 10μm to 40μm. Discrete symbols indicate experimental data, the solid lines are exponential fits to the decay of the detector. A decay time of 455ps is obtained for the shortest detector. 
b) The extracted detector decay time as a function of the detector length. The decay time increases linearly with increasing detector length due to increased kinetic inductance. 
c) The timing jitter measured for a representative detector. Green symbols denote the jitter measured with the PicoHarp300, with an intrinsic instrument jitter of 19ps. Blue symbols denote results obtained with a high-speed oscilloscope with an instrument timing jitter of less than 1ps. 
d) The timing jitter measured in dependence of amplifier bandwidth. Results converge towards 18.4ps for an amplifier analog bandwidth of 10GHz or more.
Figure 4: Time-domain ring-down measurements. a) An integrated photonic circuit with input grating couplers, a long micro-ring resonator and integrated SSPD. Inset: zoom into the detector region. b) Schematic of the time-domain response of an over-coupled ring resonator. Measured results in the spectral domain reveal an optical quality factor of 14,000. c) Schematic of the time-domain response of a weakly coupled ring resonator in the drop port. The measured optical Q in the frequency domain is 24,000. d) The measured time-domain response for the overcoupled ring resonator. The length of the ring introduces a round-trip delay of 72.7ps, while the circulating pulse amplitude decays with a time constant of 19.3ps when travelling along the ring. e) The measured time-response of the undercoupled ring resonator. The device shows a decay time of 37.1ps. Due to the slower decay four consecutive pulses are discernable in the log-plot (inset).
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