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Photon-counting and analog operation of a 24-pixel photon number resolving detector based on superconducting nanowires

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Abstract: We investigate the transition from the photon-counting to the linear operation mode in a large-dynamic range photon-number-resolving-detector (PNRD). A 24-pixel photon-number-resolving-detector, based on superconducting nanowires in a series configuration, has been fabricated and characterized. The voltage pulses, generated by the pixels, are summed up into a single readout pulse whose height is proportional to the detected photon number. The device can resolve up to twenty-five distinct output levels corresponding to the detection of n = 0-24 photons. Due to its large dynamic range, high sensitivity, high speed and wide wavelength range, this device has potential for linear detection in the few tens of photons range. We show its application in the detection of analog optical signals at frequencies up to few hundred MHz and investigate the limits related to the finite number of pixels and to the pixel's dead time.

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References and links


1. Introduction

Several applications from linear optical quantum computing [1] to near-infrared spectroscopy, optical communication [2] and quantum communication [3] need a linear detector in the single- to hundred-photon regime. This is particularly challenging in the near-infrared spectral region of interest for fiber transmission, where silicon detectors are not sensitive. Conventional linear detectors, such as InGaAs photodiodes, are not sensitive below few hundred photons, due to the noise in the electronic read-out circuit. On the other hand, most single-photon detectors provide an output signal independent of the photon number ≥1 due to a very nonlinear internal amplification. Transition-edge-sensors provide a linear response to the photon number up to 10–20 photons, and information on higher photon numbers can be deduced by the analysis of the time traces [4]. However, they are severely limited in terms of maximum frequency (typically well below 1 MHz) and operating temperature (~100 mK). The combination of upconversion and a silicon photomultiplier has enabled PNR operation up to ~20 photons at telecom wavelengths [5], but it requires a complex set-up and it is limited to...
frequencies of few MHz. Photon-number-resolving detectors (PNRDs), based on a spatially multiplexed array of nanowire superconducting-single-photon-detectors (SSPDs), have been demonstrated [6,7]. In order to scale up the photon number, a series connection (series-nanowire detector, SND), was proposed [8] and experimentally demonstrated for 4 pixels [9] and 12 pixels [10]. The voltage signals coming from all the pixels are summed up into a single readout pulse, whose height is hence proportional to the detected photon number. This configuration was theoretically shown to be suitable for scaling to even larger photon numbers [8]. SSPDs [11] have been taken as a starting point for PNRD implementation because of their excellent performances in single-photon detection at telecommunication wavelengths. Indeed, they provide high quantum efficiency (QE) [12], short response time, low timing jitter and low dark count rate (DCR) [13]. Since the detection mechanism of a standard SSPD is intrinsically nonlinear, spatially-multiplexed arrays are needed to obtain the PNRD functionality. Here we report and investigate a PNRD capable of resolving up to 24 photons at telecommunication wavelengths. Due to its large dynamic range, high sensitivity, high speed and wide wavelength range, this device shows great potential for linear detection in the few tens of photons range, where a gap in detection technologies exists. Taking advantage of this large dynamic range, we investigate the application of the PNRD in the measurement of analog optical signals and analyze the limitations related to the dynamic range and bandwidth. The detector's response to modulated signals at frequencies up to few hundred MHz is measured and well reproduced on the basis of a simple model of a multi-pixel detector.

2. 24-pixel PNRD

The electrical equivalent circuit of the 24-pixel PNRD is shown in Fig. 1(a)): each nanowire section (folded as a meander) is connected to a parallel resistor (R_p), which is integrated on the chip together with the nanowires. All the 24 pixels are connected in series so that they are equally biased with the same bias current I_b that is close to the critical current. When the detector is not illuminated, each nanowire section is in the superconducting state and the I_b flows through the nanowire. The absorption of a photon in one pixel, temporarily perturbs the superconductivity, and a resistive section across the whole width of the wire is created (the formation of the normal region is presently understood as the consequence of vortex crossing [14–21]).

As the value of R_p is much smaller than the photon-induced normal resistance of the nanowire R_n(t), the bias current of that pixel is diverted into the parallel resistor, generating in this way a voltage pulse across the whole detector. If more pixels absorb a photon the bias current flows into the corresponding parallel resistors and the voltages produced across each of them add up at the output: the pulse is in this way proportional to the number of firing pixels and hence to the number of absorbed photons. The parallel resistance R_p also plays the key role of discharging each meander pixel after a resistive transition, avoiding latching.

2.1 Fabrication process

The fabrication process uses the high resolution and the realignment capability of four direct-writing electron beam lithography (EBL) steps. A 4-5 nm thin NbN superconducting layer is deposited by DC-magnetron sputtering at 750°C on a thermally grown silicon oxide layer/4 optical cavity on silicon (for λ = 1510 nm), in order to maximize absorption under top illumination [22]. NbN has been chosen because of its high critical current and fast photoresponsive properties [11,23]. The transition temperature is of the order of 10 K and with a transition width < 1 K. The four steps, described in detail elsewhere [24], are used to define the different parts of the structure: a) 10 nm/60 nm Ti/Au pads designed as a 50Ω coplanar waveguide for the fast signals of the output voltage pulse together with alignment markers. b) 10 nm/20 nm Ti/Au thin gold pads needed to contact the NbN layer.
Fig. 1. a) Electrical equivalent circuit of a series photon number resolving detector and its bias circuit. Each superconducting nanowire section is connected in parallel with a resistance $R_p$ fabricated on chip. The meander section (orange box) is schematized as a superconducting switch in parallel with its normal resistance and in series with the kinetic inductance $L_k$. When a photon is absorbed (red lower section in the scheme) the bias current $I_b$ is diverted into the parallel resistance. b) Scanning electron microscopy image of a 24-pixel-PNRD fabricated on Silicon oxide on Si. Each pixel in the optical active area of the detector has been colored for clarity. The nanowire width is 100 nm with a filling factor of 40%. Au–Pd parallel resistors are in blue in the image.

c) The nanowire geometry, is defined by means of a hydrogen silsesquioxane layer (a positive tone e-resist HSQ XR-1541) exposed and developed in MF322. The NbN film areas not covered either by the HSQ or by the Ti/Au pads are etched with a reactive ion etching, based on a CHF$_3$/SF$_6$ gas mixture. The geometry and the exposure procedure have been optimized to control the linewidth and the critical current uniformity [25,26]. d) In the forth step, 50 nm thick Au/Pd alloy resistances are defined.

2.2 Electrical and optical characterization

The electrical and optical characterization is performed in a pulsed tube system equipped with an additional Joule-Thomson cycle with a base temperature of 1.6 K, equipped with a X-Y-Z cryogenic piezo-stage that allows moving a polarization-maintaining lensed fiber with respect to the sample surface, along all the three axes.

For the IV characterization, the signal from a dc source, either in the voltage bias or the current bias mode, is fed to the detector through a 10-$\Omega$ bias resistor and the DC arm of a bias-T. Figure 2 shows the I-V curve of the device, showing a superconducting branch, an ohmic branch corresponding to the parallel resistors, and the hot-spot plateau, as observed before on series-nanowire detectors [10]. The critical current measured at 1.6 K is 20.5 $\mu$A, about 50% larger than our previous devices on GaAs [10] allowing in this way a higher signal to noise ratio (SNR), crucial for the distinction of many output levels. The small ramp that connects the superconducting to the ohmic branch was not observed previously and may be related to a non-uniform critical current among the wires. From the ohmic branch fit (dash-dot line of Fig. 2) $24 \times R_p$=1695 $\Omega$, the resistance of each parallel resistance can be inferred ($R_p$=70.6 $\Omega$).

During the optical measurements, the position of the spot with respect to the detector and the fiber-sample distance are characterized by measuring the spatial map and the spectrum of the reflection of a broadband LED source (center wavelength $\lambda_c$ = 1525 nm) [24]: in this way the fiber distance can be arranged so that the whole detector area with a lateral size of 12 $\mu$m

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is nearly uniformly illuminated, as required for the optimal operation of the PNRD. The spot size in this condition is estimated as ∼16 μm full-width half-maximum. A 1310 nm gain-switched pulsed diode laser is used to probe the detector response. A fiber-based beam-splitter (BS) and a fiber-based variable attenuator are used to attenuate and monitor the optical power down to the single-photon level. The optical response signal of the device is collected through the RF arm of the bias-T at room temperature and amplified by a room-temperature (RT) low-noise amplifier in the mV to few V range. Either a 40-GHz sampling oscilloscope or a 350-MHz fast counter are used to analyze the signal. A pulse width of 100 ps and a repetition rate of 2.1 MHz, was used to perform the optical characterization of the detector. The light polarization was aligned along the direction parallel to the nanowires. The light power was changed in the range 0-15 nW and the sampling oscilloscope was used to acquire histograms of the output signals.

For the measurements shown in Fig. 3, a low-pass filter (DC-80 MHz) has been added to the amplification chain in order to remove the high-frequency noise of the signal and to improve the visibility of the voltage peaks. The histograms of the output signals obtained at device current bias $I_B = 19.0 \, \mu\text{A}$ at different light powers in the range 0-15 nW are shown as a color map in Fig. 3(a). Twenty-five distinct output levels are clearly visible: they correspond, from the left to the right in Fig. 3, to the detections of 0-24 photons. Figure 3(b) and 3(c) show two of the histograms at fixed light powers (3.26 nW and 364 pW in b and c), respectively used to obtain Fig. 3(a). Due to the fact that at higher photon numbers, the probability that two photons are absorbed in the same section must be taken into account, the average of the detected photon number distribution is linear with the input power only up to ∼11-12 photons, after which saturation occurs. Increasing the number of absorbed photons, the distance between the $n^{th}$ and the $(n + 1)^{th}$ peaks tends to decrease, as it was already observed in 12-pixel PNRDs and attributed to non-uniformities in the wire width [10]. These non-uniformities, besides Johnson noise, are also the likely cause of the increase in peak width with photon number. We note that the 1-photon signal amplitude, and thereby the possibility to discriminate n-photon peaks, can be improved [8] by employing a high impedance readout scheme based, for example, on a cryogenically operated high electron mobility transistor mounted close to the detector.
From the count rate (CR) dependence on the input light power, we have verified the PNR functionality of the 24-pixel PNRD. The trigger levels of the counter are chosen in the middle between the $n^{th}$ and the $(n + 1)^{th}$ peaks. For $n \leq 5$ and mean absorbed photons $\eta \mu < 1$, the counts were observed (not shown) to follow the expected power dependence proportional to $(\eta \mu)^n$ where $\eta$ is the quantum efficiency of the detector and $\mu$ is the mean photon number impinging on the detector itself. For larger $n$ values not enough counts were measured in the $\eta \mu < 1$ regime to measure the corresponding slope.

The detector output pulses, as measured on a 40 GHz oscilloscope (in the case of strong pumping, corresponding to 24-photon absorption), shows a jitter of 116 ps and a 1/e decay time of 13 ns, giving a kinetic inductance of one pixel $L_k = 27$ nH. The 1/e decay time corresponds well to the value of $\sim$11 ns expected from the simulation in Ref [8], considering the slightly different filling factor. The pulse decay time and jitter indicate the excellent timing and recovery performances of the PNRD based on superconducting nanowires in a series configuration. We note that the dynamic range of this detector is comparable or slightly higher than those achieved using transition-edge-sensors [4] and silicon photomultipliers with upconversion [5], but its temporal response is much faster, as also confirmed in the experiments below.

The device quantum efficiency $\eta$ was measured with the lensed fiber close to the surface of the sample so that the light was focused onto the optical active area and with the average number of absorbed photons $<< 1$: as usual, the value of $\eta$ was observed to be a strong function of $I_B$, with a maximum value of 0.5% (at $I_B = 19.0$ $\mu$A, $\lambda = 1310$ nm). This relatively low efficiency value is typical for the detectors fabricated with this technology and is not related to the PNRD structure.
2.3 PNRD as analog detector

In order to investigate the application of a large dynamic range PNRD as analog detector, and the fundamental limits in its modulation response, an experimental and theoretical investigation of its response to modulated optical signals was performed. In the experiments, the 1310 nm gain-switched diode laser under a square-wave or a sinusoidal wave modulation is used to illuminate the detector: the fiber was positioned out of focus to ensure a uniform illumination of the whole device. For the theoretical modeling, a Monte Carlo simulation based on a simple model of a 24-pixel PNRD detector was used. In the model, each pixel is illuminated equally and has a probability of switching to the normal state proportional to the instantaneous incident power \( P_i(t) \). Upon switching, it produces a voltage pulse (with a peak amplitude set to 1) with a fast rise and an exponential decay with time constant \( \tau \). After switching, it is assumed to remain inactive for a time \( 3\tau \). The total output is obtained by summing up the voltage across the 24 pixels in a given time sequence, and then averaged over 50-200 random realizations to obtain a time trace comparable to the experimental oscilloscope traces. While this model neglects some important aspects of the SND operation, such as the multieponential recovery of the bias current (and correspondingly of the efficiency) and the effect of a single wire switching on the bias current of the other wires [8], its simplicity allows investigating the transition between the PNR and the pure analog regime and makes it applicable to any PNR detector where the output pulse is formed out of many single-photon detection events. It therefore applies equally well to SNDs, photomultipliers, avalanche photodiodes operated in PNR mode [27], and even simple p-i-n detectors. In the simulations, we find that assuming \( \tau = 0.4 \) ns provides the best agreement with the experimental data. This value closely corresponds to the time constant \( L_s/R_p = 0.38 \) ns for the current recovery of a single pixel through its parallel resistance \( R_p \).

Figures 4(a) and 4(b) show the experimental and calculated output signals under a sine-wave power modulation at a relatively low frequency of 15 MHz. In the experiment, the device was biased at 18.5 \( \mu \)A and an average power of 414 nW from the fiber (corresponding to an estimated power of 161 nW on the active area) with a modulation depth of 100% were used, while in the model an average power of 161 nW, a modulation depth of 100% and an efficiency of 0.5% were assumed. Due to the continuous input signal (photons are absorbed at all times), and to the repetitive nature of the measurement/simulation, the single-photon detection peaks are averaged out and not resolved in this mode of operation - rather, the detector operates as a linear detector and provides an analog response to an analog signal. We note that for this power level about 400 photons are incident on average on the detector in a time interval of 0.4 ns corresponding to the pixel's time constant, and two are detected. In this regime the 24-pixel PNRD is below saturation (most pixels are not active), while a single-photon detector would be continuously clicking, making the reconstruction of a modulated signal impossible (this was verified numerically). This clearly shows the advantage of a large-dynamic range PNRD over a single-photon detector for the measurement of weak analog signal.

In another set of measurements we investigated the limits related to the finite dynamic range. Figure 4(c) shows the experimental output data of a 24-pixel PNRD under a square-wave modulation at 100 MHz for different powers. The total power from the fiber is increased from 32 nW (black curve) up to 3.45 \( \mu \)W (blue curve). At the higher powers, synchronous oscillations in the “on” periods are observed. This is attributed to the synchronous switching of the pixels and it is well reproduced in the simulations (Fig. 4(d)). Indeed, for high powers at the rising edge of the optical signal the detector receives a number of photons large enough that a significant fraction of the pixels switch to the normal state, after which the response is partially suppressed due to the dead time. After the dead time they recover simultaneously, resulting in a periodic oscillation. The experimental oscillations have
lower amplitudes probably because of the crude approximation of on/off detector used in the model. We also

![Image](image_url)

**Fig. 4.** a) Experimental output signal coming from the detector illuminated with a sinusoidal light modulation: the average power from the fiber is 414 nW and the modulation frequency is 15 MHz. b) Calculated output under a sine-wave power in the same conditions (average over 50 realizations). c) Experimental output data under a square wave light modulation at 100 MHz. The power from the fiber is 3.45 μW, 334 nW and 32 nW for the blue, red and black curve respectively. d) Calculated output under a square-wave power modulation with average power corresponding to the experimental condition for the three cases, averaged over 200 realizations. In the simulation, V_{out} = 1 corresponds to the peak of the pulse produced by one photon.

note that device heating may considerably affect the operation at the highest powers in the experiments. The results of Fig. 4(c) and 4(d) show that the pixel dead time is a major problem for reaching a high dynamic range in the measurement of an analog signal, as observed in both the experiment and the simulation. In fact, when a large fraction of the pixels switch, the oscillations distort the output pulse, thereby reducing the useable dynamic range well below the 24-photon range potentially available from the detector.

Finally, we explore the limit to the modulation speed. We expect the PNRD to follow the modulation of the input signal as long as the corresponding frequency is lower than \(1/3\tau\), i.e. the inverse of dead time, so that pixels can recover from a switching event before the input signal changes. A systematic numerical study (not shown) of the modulation amplitude in the “small-signal” regime, where the average number of detected photons in the \(\tau\) time window is much smaller than 24, shows that the output modulation amplitude indeed decays for frequencies above few hundred MHz, i.e. of the order of \(1/3\tau\). This confirms that the single-pixel dead time directly determines the modulation bandwidth in analog operation. We performed an experimental and theoretical study of the response to a large-signal digital modulation in the high-frequency regime, simulating the detector application in a directly-modulated optical communication system. Figures 5(a) and 5(c) show the detector output when the input power is modulated as a square wave, at frequencies of 250 MHz (a) and 700 MHz (c).
MHz (c) (average power from the fiber 5.4 μW and 47 μW respectively), while parts (b) and (d) show the corresponding simulations. In the 250 MHz trace the synchronous switching is clearly visible and reduces the visibility of the output pattern, while the modulation at 700 MHz is actually improved (as compared to e.g. 500 MHz, not shown) by the synchronous switching since this frequency approximately matches the inverse of the dead time. As expected from simulations, no clear modulation pattern was observed at frequencies above 700 MHz. We note that, with the present value of efficiency, the PNRD is not more sensitive than a standard avalanche photodiode operating in linear mode. For example, in the digital modulation experiment in Fig. 5(a) about 3x10^7 photons were incident on the detector in the “1” bit and, while the power may still be lowered, operation below the 10^6 photon level is not possible. However, by using the materials and cavity structures currently employed in high-efficiency SSPDs [12], a system quantum efficiency over 50% can easily be reached in a PNRD structure. This would bring the sensitivity to a level well below the range of conventional linear detectors. On the other hand, the dynamic range needs to be further extended. Indeed, as shown in the experiments and simulations of Fig. 4, the useable dynamic range for the measurement of analog signals is significantly lower than the maximum number of photons measurable in a short pulse. This limitation is general to all PNRDs based on an array of single-photon detectors with finite dead time. The series-nanowire configuration can in principle be extended to the 100 photons level and beyond, when combined with a high-impedance read-out [8] - however, this will require a change in the device geometry in order to accommodate the parallel resistors.
3. Conclusion

In conclusion, we have fabricated and tested a 24-pixel PNRD, based on superconducting nanowires in a series configuration. The device is able to discriminate 0-25 photon levels, and features a 1/e time of 13 ns and a jitter of 116 ps, indicating the excellent potential of this class of detectors. Its application as a linear detector of analog signals has been investigated by probing its response to square-wave and sinusoidally modulated signals. The maximum modulation frequency is in the order of 700 MHz and is related to the dead time of a single pixel. The synchronous switching of the pixels produces oscillations of the output voltage at high input powers, thereby limiting the dynamic range in the analog operation.

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