Photon Number-Resolved Detection With Sequentially Connected Nanowires

M. Bell, A. Antipov, B. Karasik, A. Sergeev, V. Mitin, and A. Verevkin

***Abstract*—Sequentially connected superconducting nanowires, such as nanopatterned meanders, are very promising candidates for single-photon detectors capable to resolve a number of photons in the pulse. In such devices, the Photon Number-Resolved (PNR) mode is possible due to independent detection of electromagnetic quanta by different regions of the meander. Every photon creates a resistive region in the superconductive meander and the total resistance is expected to be proportional to the number of photons absorbed. While the PNR mode can be realized with available single-photon detectors based on NbN nanowires, up to now it has not been observed experimentally. Here we show that the PNR mode in NbN requires the proper impedance matching between readout circuitry and nanowire-based detector. We discuss possible design of the readout circuitry for PNR detection. Results of modeling show that a high impedance amplifier placed in close proximity to the superconducting nanostructure can provide effective readout for the NbN nanowire-based detector operating in PNR mode.**

***Index Terms*—Impedance, photon number resolving, sequentially connected nanowires, single photon detector, superconducting.**

I. Introduction

NOVEL technologies based on single photons operating as carriers of quantum information surpass traditional classical approaches in the efficiency of information processing and offer the ultimate security for communications. Advanced quantum optics technologies, such as quantum communication, cryptography, quantum imaging, optical quantum computing, nanobiophotonics, and quantum metrology require ultrafast processing of individual and entangled photons.

The most advanced optical quantum information strategies are based on processing of maximally entangled photon multiplets. The ability to perform fast and efficient photon-number state detection is critically important for many modern technologies, including quantum cryptography, and quantum computing. For instance, the Quantum Key Distribution (QKD) scheme is considered to be a very promising candidate for future secure quantum communications. Although the Bennett-Brassard 1984 (BB84) protocol with a pseudo-single-photon source is a popular method, but alternatively, entanglement-based QKD has also been investigated. For example, one of the most secure QKD scheme utilizes one mode of spontaneous parametric down-conversion, gated by a Photon Number Resolving (PNR) detector [1], [2]. By post-selection, the multiphoton probability in this scheme can be reduced to lower than that of a scheme using attenuated coherent light resulting in the improvement of security.

TABLE I
PERFORMANCE OF SINGLE-PHOTON DETECTORS OPERATING AT $\lambda = 1.55$ mm

Detector Model	Max Count. Rate Hz	QE (%)	Timing jitter ps	Dark Counts Hz	NEP, $W/Hz^{1/2}$	Operat. Temp. K	Comments
W-TES [4]	$\sim 10^4$	>80	N/A (high)	<0.001	$<10^{-19}$	0.1	Slow, High QE PNR
Al-STJ [5]	$\sim 10^3$	60	N/A	N/A	N/A	0.3	Very slow, PNR
NbN Counter [6]	$>10^8$	>10	~30	<0.01	$\sim 10^{-19}$	4-10	Very Fast, No PNR yet

In the past five years we have also seen the emergence of single photon technologies as a realistic way of achieving universal quantum computation. This started with the pioneering work of Knill, Laflamme, and Milburn (KLM) [3] who showed that with single photon sources, PNR detectors, and linear elements, all basic gates for quantum computing could be created. In the KLM protocol, probabilistic two-photon gates are teleported into a quantum circuit with high probability. Subsequent error correction in the quantum circuit is used to bring the error rate down to fault-tolerant levels. Up until now, several significant improvements of the protocol were proposed, leading to a decreasing overhead cost on computation [4].

Non-classical features of measured biological luminescence signals highlight the limitations of classical molecular biology. This emerging field would require non-gated ultrafast counters with PNR as an available mode of operation.

Ultrafast PNR detectors could also result in revolutionary advances in the area of photonic technology related to analog-to-digital converters. These converters will provide an essential link between the analog optical sensor systems and the digital electronic signal processing systems.

II. PNR Superconducting Detectors

The main operating parameters of modern superconducting single photon detectors capable of working in PNR mode are shown in Table I. Our comparison is done for 1.5-μm photons, which is the most popular wavelength for applications dealing with single-mode optical fiber.

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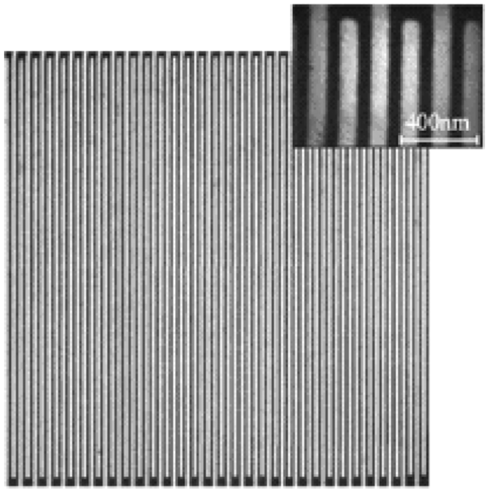

Fig. 1. SEM image of meander-type NbN counter.

The tungsten-based transition-edge sensor (TES) has already demonstrated a capability to operate in PNR mode [5]. However, superconducting TES exhibits a counting rate which is four orders of magnitude slower compared with that in NbN nanowire-based devices. The inefficient counting speed of TES is a result of slow electron relaxation at ultra-low temperatures, which are required for single-photon sensitivity in these devices.

The superconducting tunnel junctions (STJs) have the same drawbacks, such as ultra-low operating temperature and very slow counting rate. For these reasons, both of the above devices are not very prospective for future high-speed quantum information technologies. Nevertheless, TES and STJ sensors have attracted much attention from the quantum information community solely due to their ability to work in PNR mode. Already, this feature has made them extremely attractive for characterization of light statistics.

Besides single photon sensitivity, the mentioned above PNR detectors require a sensitive readout capable of distinguishing between multiple photon detections. The SQUID readout coupled with low-impedance TES naturally help to achieve PNR mode in this devices, but creates additional technical difficulties and further reduces counting speed. Also, such detectors operate at ultra-low temperatures and require He-3 refrigerators or adiabatic demagnetization systems, which are not only very expensive, but have to be periodically recharged.

NbN counters composed of sequentially connected nanowires have already demonstrated their unique ability for fast and effective single-quanta detection [8]–[10]. Nanopattering is the key technology in preparing specific structures, which allow us both to obtain single-photon detection in a nanoscale volume and to effectively couple the nanostructure to the fiber. In this nanodevice (Fig. 1), a single photon is absorbed in a narrow (about 100 nm width) ultrathin (several nm thickness) NbN superconducting dc-biased stripe. Local heating of quasiparticles results in the resistive state formation, and, finally, the resistivity change is measured by an external readout [10]. The fast rise time of the photoinduced resistivity is determined by the disorder-enhanced quasiparticle multiplication [11]. Finally, the superconducting state is restored within a nanosecond time frame. Picosecond timing resolution and gigahertz counting rates have already been already demonstrated with NbN detectors.

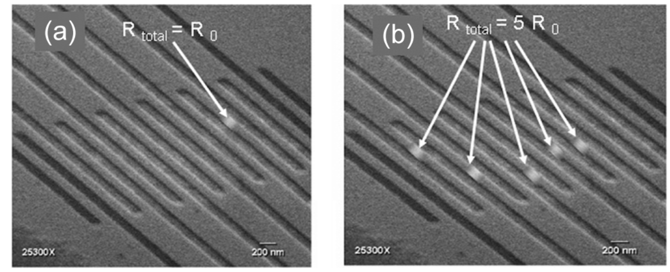

Fig. 2. PNR mode in the meander-type device is possible due to geometrical separation effect. Schematically, the total resistance of the normal areas is proportional to their total length, which, in turn, is proportional to the number of photons absorbed in the nanowire, in a simplified representation shown in this figure. For example, a) one photon absorbed; b) 5 photons absorbed.

III. PNR Mode in NbN Meander

As shown in Table I, ultrafast counting speed, very low jitter, low dark counts, and very good NEP are already achieved in superconducting detectors based on NbN nanowires, but PNR mode has not yet been demonstrated, in contrary to TES and STJ detectors [5]. In the suggested approach below, the realization of PNR mode is expected due to the independent detection of electromagnetic quanta by different parts of the superconducting meander (Fig. 2). The standard $10 \times 10\ \mu\mathrm{m}^2$ area nanowire meander device can be coupled easily with a standard single-mode fiber of 9 micron core diameter [12]. In such a situation, we can expect the incident photons to be absorbed in different parts of the meander during ultrafast (sub-picosecond to picosecond range) weak pulse laser excitation, then with very high probability, the total resistance of the device would be simply proportional to number of photons absorbed. However, the realization of PNR mode in devices with sequentially connected nanowires would require specific high-impedance readout. Below we study this and other related issues in more details.

IV. Circuit Modeling

We have simulated the dynamics of switching in NbN detectors using a circuit simulation package PSPICE. The equivalent circuit used is shown in Fig. 3. The device is biased with a DC voltage source; switches are used to represent the fast switching between the resistive and the superconducting state [13]. The parameters E_b and Z are the source voltage and the input impedance of the amplifier, respectively. The bias tee consists of an inductor L_1, resistor R_1, and capacitor C through which the signal propagates to an amplifier. The actual device is simulated as a set of switches and a kinetic inductance L_2. The resistance of the device in the resistive state is R_2. Kinetic inductance is an inherent limitation in superconducting electronics and has been analysed rigorously for NbN meander-type devices to determine their ultimate counting speed limitations [14], [15]. In general, the total inductance of a micro-strip consists of the magnetic (geometrical) inductance and the kinetic inductance. The geometric inductance of the meander is significantly smaller then the kinetic inductance. The kinetic inductance is described by the imaginary part σ_2 of the complex conductivity in the superconducting state. At low temperatures, $\mathrm{T} \ll \mathrm{T_c}$, it is given by [16]

$$\sigma_2 = \frac{\pi\Delta}{\hbar\omega}\sigma_n, \tag{1}$$

$$\Delta \approx \Delta(0) = 1.76kT_C, \tag{2}$$

where σ_n is the conductivity in the normal state, and Δ is the energy gap at $T = 0$. Thus, the kinetic inductance may be presented as

$$L_2 = \frac{1}{\omega\sigma_2}\frac{l}{wd}, \tag{3}$$

where l is the length, d is the thickness, and w is the width of the nanowire. For our standard meander-type superconducting single photon detector (SSPD) geometry (10 × 10 $\mu\mathrm{m}^2$ area, 4 nm-thick, 120 nm-wide stripes, 60% fill factor, $\rho = 1/(\sigma \mathrm{d}) = 500 \div 600\ \Omega$, $\mathrm{T_c} = 11$ K) we expect the value of L_2 to be about 260 nH.

Recently, Hadfield *et al.* have presented evidence of a phase locking phenomenon in a meander-type SSPD [13]. The voltage pulses generated were fit using a model that took into account the inductance of the SSPD. These experimental results show a kinetic inductance of about 500 nH in a similar 10 μm × 10 μm NbN meander-based device.

The switches in our equivalent circuit (Fig. 3) are used to simulate switching from the superconducting to the resistive state. According to this simple model, after a photon is absorbed, the current through the device drops with a fall time of L_2/R_2, resulting in the same photoresponse signal rise time. Once the current drops below the return super-current I_r, defined as the current necessary for superconductivity to be restored [13], the current begins to rise again.

The circuit model without transmission lines $\mathrm{T_1}$ and $\mathrm{T_2}$ is described by the system of equations:

$$\begin{aligned} E_b - L_1 * i_1' &= R_1 * i_1 + Z * i_3 + q_3/C \\ -L_2 * i_2' &= R_2 * i_2 - Z * i_3 - q_3/C \\ i_1 &= i_2 + i_3 \\ i_3 &= q_3' \end{aligned} \tag{4}$$

In addition, the PSPICE package allows us to take into account the transmission lines (see Fig. 3), which are ever present in a realistic setup.

First, we verify the above concept using our model to fit our measured photoresponse pulse generated from a 10 μm × 10 μm meander. The photoresponse of the NbN device under 1.55 micron wavelength single-photon level illuminations, taken with a 50 GHz bandwidth sampling oscilloscope, is shown in Fig. 4. We then calculate the rise time of the photoresponse signal using $L_2 = 273$ nH, $Z = 50\ \Omega$, $R2 = 500\ \Omega$, and $I_r = 0.60 I_c$, where I_c and I_r are the direct and return supercurrents [13]. The model fits very well the measured photoresponse rise time of 200 ps

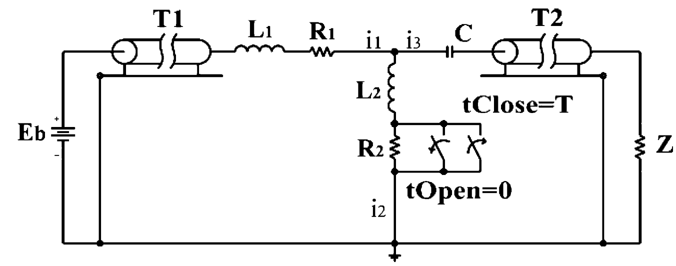

Fig. 3. Equivalent circuit used for simulation of switching dynamics in NbN PNR detector.

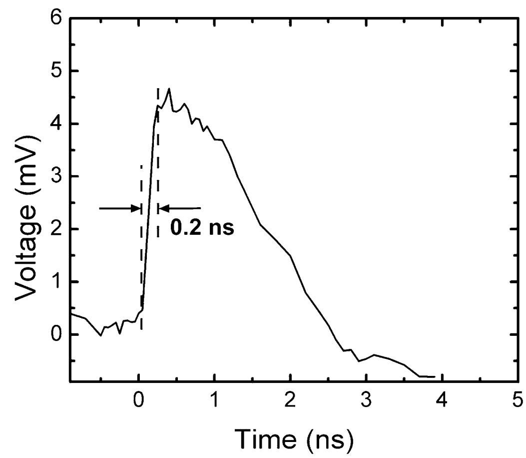

Fig. 4. Measured photoresponse temporal dynamics of NbN detector (see text).

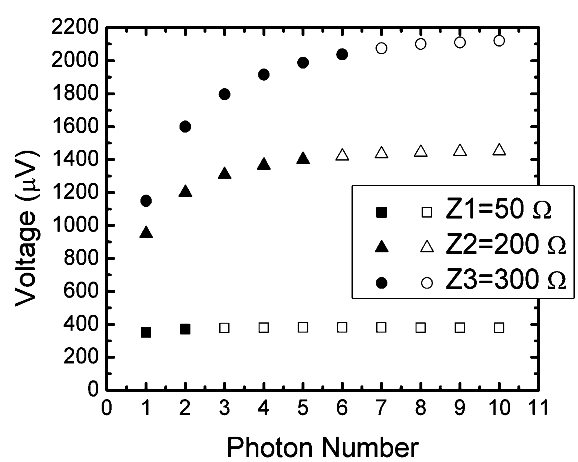

Fig. 5. Dependence of the signal amplitude vs. number of photons absorbed in the nanowire for amplifiers with a input impedance of $\mathrm{Z} = 50\ \Omega$, 200 Ω, and 300 Ω.

(Fig. 4). The normal resistance of the hotspot is $\sim 500\ \Omega$ and agrees quite well with the value of 800 Ω used in [13] for estimation of the photoresponse rise time.

Having been obtained from simulations, the dependencies of signal amplitude vs. number of photons absorbed in the nanowire for various values of input amplifier impedances are represented in Fig. 5. As we can see in Fig. 5, no substantial difference in the amplitude of the output signal is expected with a 50 Ω input impedance amplifier even in case when one or two photons are absorbed. To qualitatively estimate our limitations for PNR mode, we should take into account the amplifier input noise. In the ideal case it is given by

$$\delta U = \sqrt{4k_B T Z \Delta\omega}, \tag{5}$$

where k_B is the Boltzmann constant, T is the amplifier noise temperature, ω is the amplifier bandwidth. We assume $T = 30$ K, $\omega = 1$ GHz, $Z = 50 \div 300\ \Omega$, and evaluate $\delta U = 9 \div 22\ \mu$V. The solid and open symbols in Fig. 5 show the number of photons that can be distinguished or undistinguished by the readout system respectively.

Amplifiers with higher input impedances (or transimpedance amplifiers) will significantly improve our capabilities for realization of PNR mode. In Fig. 5 we show that with a 300 Ω amplifier it is possible to distinguish the absorption of up to six photons in already available NbN nanowire-based device.

We should emphasize that the ability to distinguish between the number of photons absorbed with 50 Ω-impedance transmission lines placed in between the detector and readout circuit is very limited. Therefore, a high-impedance amplifier should be placed in close proximity to the detector to eliminate the effects of standard 50 Ω coaxial transmission lines.

V. Conclusion

Sequentially connected superconducting NbN nanowires are very promising candidates for Photon Number Resolving (PNR) mode. The total resistance of the normal area in the superconducting stripe within an individual excitation event should be proportional to the total energy of photons absorbed during fast weak laser pulse excitation. In NbN nanowire-based detector, every photon absorbed produces a certain resistance of the order of 500 Ω, and a finite number of photons can be resolved. While the PNR mode can be realized with already available single-photon detectors based on NbN nanowires, it has not been observed experimentally yet. The realization of PNR mode in NbN requires the proper impedance matching between readout circuitry and nanowire-based detector. The results of modeling show that a high input impedance amplifier placed in close proximity to the superconducting nanostructure can provide effective readout for the NbN nanowire-based detector operating in PNR mode. Our modeling shows that it is possible to resolve a significant number of photons using a high input impedance amplifier placed in close proximity to the detector.

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