# Towards Linear Optical Detection with Single Photon Sensitivity at Telecommunication Wavelengths

S. Jahanmirinejad, and A. Fiore

COBRA Research Institute, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, the Netherlands

*The conventional optical detectors operate in a linear mode, but their sensitivity is limited due to the noise in the readout electronics. Single photon detectors, on the other hand, have the highest sensitivity, but are strongly nonlinear. Photon number resolving detectors, which can precisely determine the number of photons in weak optical pulses, are potential candidates to fill the gap between these two detection modes. We present the design of photon number resolving detectors with large dynamic range, based on spatial multiplexing of superconducting single photon detectors, with excellent timing resolution and very high sensitivity at the telecommunication wavelength range.*

## Introduction

Photon number resolving (PNR) detectors which have the capability to determine the exact number of photons in a weak optical pulse are required in many applications including linear optics quantum computing [1] and ultra-long distance optical communications. However, a mature technology for fast and sensitive PNR detection, with large dynamic range does not exist, particularly in the telecom wavelength range.

In this paper we propose a PNR detector with large dynamic range based on the series connection of N nanowire superconducting single photon detectors (SSPDs), called hereafter Series Nanowire Detector (SND). The SSPD [2], in brief, is an ultrathin, and narrow superconducting nanowire, arranged in a meander-like geometry to cover a large active area. It is cooled down typically to 2-4 K to operate in the superconducting state and is biased slightly below its critical current. The photon detection process is based on the formation of a resistive region in the nanowire upon absorption of an incoming photon, which results in a measurable voltage pulse. SSPDs offer broad spectral response from ultraviolet to infrared wavelengths, high count rate, low dark count rate and small timing jitter. SNDs preserve all the advantages of SSPDs in terms of simplicity, sensitivity, timing resolution and speed.

## The SND structure

The SND structure consists of the series connection of N superconducting nanowires, each connected in parallel to a resistor $R_p$. It is operated in a circuit as depicted in Fig.1. The bias current of the SND is provided by the DC arm of a bias-T, while its voltage response is read-out through a cryogenic high impedance load $R_L$ (e.g. cryogenic preamplifier with large input impedance) that can be further amplified using room temperature amplifiers. The superconducting nanowire is modelled as an inductor $L_k$ (the kinetic inductance of the nanowire) in series with a resistor $R_n(t)$ which is zero when the nanowire is in the superconducting state and manifests as a time-dependent resistance upon absorption of a photon. All the detecting sections are equally biased (in series) with a bias current $I_b$ very close to the critical current of the superconducting wire (ideally the same for all branches).

Absorption of a photon in a superconducting nanowire creates a hotspot in the wire, where the temperature of the electrons is elevated. After the initial thermalization, the hotspot starts to grow, making a resistive slab across the wire. This resistive region is a source of Joule heating which raises the wire temperature. Accordingly, the critical current, which is strongly temperature-dependent, also drops off to a value lower than $I_b$, giving rise to further perturbation of the superconductivity and expansion of the resistive region. The generated heat is dissipated along the nanowire and through the substrate, increasing the total resistance of the nanowire. In the meanwhile, the growing resistance of the wire repels the bias current of the wire to its parallel resistor, therefore creating a negative feedback loop that self-resets the nanowire to the superconducting state after each photon absorption event. The value of $R_p$ should be smaller than the photon-induced normal resistance of the nanowire and is chosen so that it does not cause the wire to latch into the permanent resistive state. When the bias current switches to $R_p$, a voltage pulse is formed across the branch. When more photons hit the distinct detection sections of the SND, the voltages produced across all the sections are added up to generate an output voltage which is proportional to the number of firing detectors. In the case of the traditional 50Ω readout via a coaxial cable, after one section absorbs the photon, the bias current is partially redistributed to the load, temporarily decreasing the bias in the unfiring branches, and therefore introducing a dead time and reducing the output voltage, which makes it not suitable for large dynamic range.

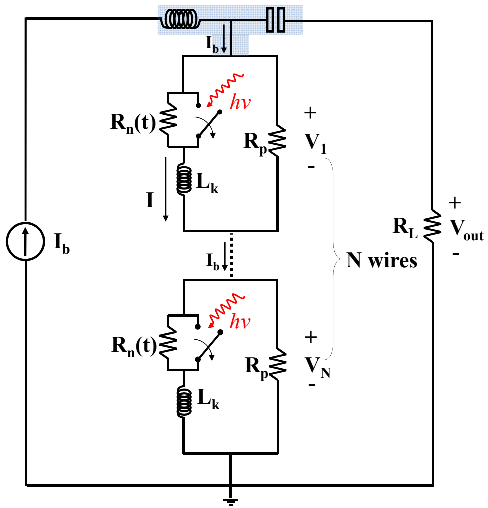


Fig.1. Electrical circuit for the implementation of the SND structure. N superconducting nanowires, each with a resistor in parallel, are connected in series. The voltages produced by photon absorption in different sections are summed up in the high impedance output.

## Electrothermal Simulation Results and Discussions

The electrothermal model that describes the detection principle of the SNDs is simulated to study the dynamics of the transient response. To do so, the heat equation, relating the heat generation and dissipation to the rate of change of total energy in the nanowire, coupled with the electrical equations governing the circuit are solved simultaneously. The details about the thermal equation and the related coefficients are explained in [3].We consider SND structures made of d=4.1nm thick, w=100nm wide NbN nanowires on a GaAs substrate, folded in a meander with f=50% filling factor. A total of N=100 detection sections are put in series, covering the area of 40x40μm$^2$.

Based on the experimental current-voltage characteristics of a typical NbN SSPD on GaAs [4], the macroscopic thermal properties of NbN nanowire required for solving the thermal equation are extracted. All the wires are assumed identical with critical temperature $T_c$=10.5K, and critical current $I_c$=22μA at the ambient temperature of $T_{sub}$=2K, with the kinetic inductance $L_k$=90pH/□. The value of the parallel resistor to each detection section is chosen to be $R_p$=80Ω, and the load impedance is $R_L$=1MΩ.
The simulation starts at time t=0 when the photon absorption at the center (x=0) of a firing wire has formed a small resistive segment across it (in the range of 20nm). The subsequent Joule heating leads to the growth of the temperature along the length of the wire (Fig.2a), expanding the hot resistive regions (Fig.2b) and forming a time-variable resistor (Fig.2c). The growth of the temperature is counteracted by the diversion of the bias current to $R_p$, which results in the reduction of the source of Joule heating and finally cooling down of the wire within ~110ps to the base temperature. By this time the normal region extends to ~150nm, making the maximum resistance of ~1.1kΩ.

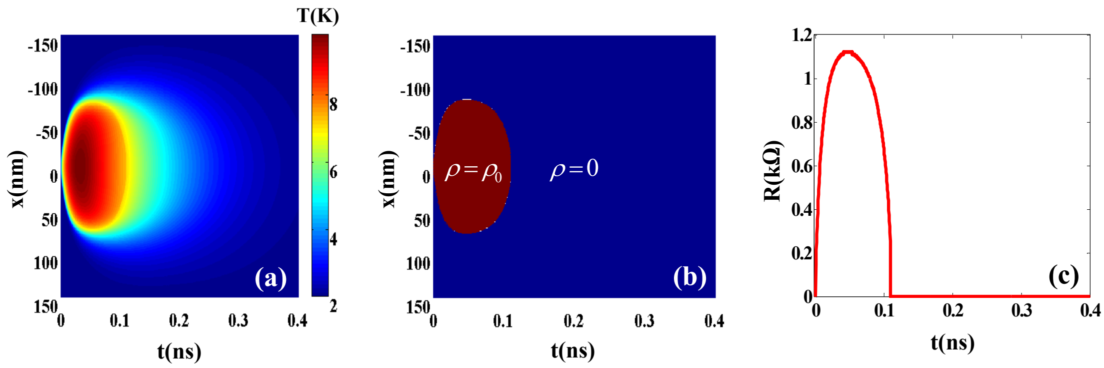


Fig.2. Electro-thermal simulation for a firing section in the proposed SND, biased with $I_b$=0.99$I_c$, and read-out with $R_L$=1MΩ. (a) Temperature map vs. time along the switching wire after photon detection (b) The temporal evolution of the resistive region along the wire. (c) Time-dependent resistance of the wire.

Having the high impedance read-out ensures that all the bias current of each firing wire is diverted to its parallel resistor, therefore the voltage produced across $R_p$ can be accurately measured at the output. This implies that the different detection sections of the SND are decoupled from each other and photon absorption in one section does not affect the bias of the other sections, which is highly favourable for a PNR detector. Fig.3a shows the output voltage transient of the SND for n=10-100 number of firing branches (i.e., number of photons incident on distinct wires). Fig.3b shows the peak of output voltages as a function of n, as the evidence of the perfectly linear response.

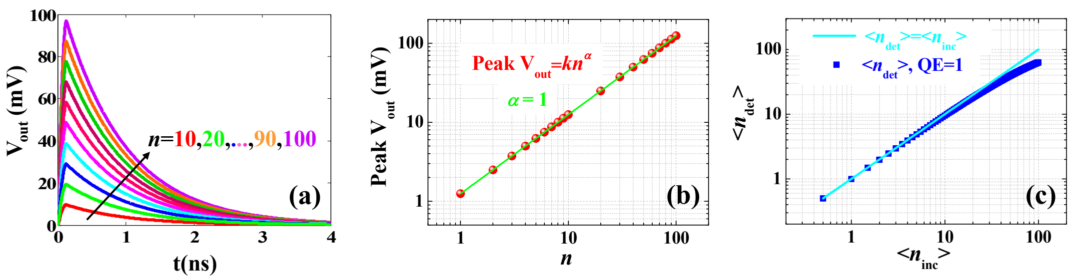


Fig.3. (a) Transient response of the proposed SND, biased with $I_b$=0.99$I_c$ and read-out with $R_L$=1MΩ for the case where n=10, 20,.., 100 photons are absorbed. (b) Peak output voltages vs. of the number of absorbed photons together with a power-law fit (solid lines) plotted in log-log scale as $V_{out}=An^{\alpha}$. (c) Calculated average number of detected photons $<n_{det}>$ as a function of the average number of incident photons $<n_{inc}>$, evenly distributed to N=100 detecting sections of the SND with unity QE (blue circles), compared with ideal response, the light blue line with slope=1.

The linearity shown in Fig.3b only concerns the output voltage as a function of the number of firing sections. However, we note that in a spatially-multiplexed detector, such as the SND, the finite number of the detection sections and the imperfect QE of each section can further limit an accurate measurement of the photon number. In the applications where a nsitive linear optical detector for determining the average number of photons in a weak coherent optical source is required, the non-unity QE does not affect the SND performance, apart from a reduction in the sensitivity, since the average detected photon number scales as the QE. In Fig.3c we show the effect of the finite probability that more than one photon are absorbed in the same wire as described in [5]. We consider the case where n=1-100 photons hit the SND with N=100 elements, each having QE=1. The symbols in Fig.3c show the average number of detected photons $\langle n_{det} \rangle$ as a function of the average number of incident photons per pulse $\langle n_{inc} \rangle$ assuming a Poissonian source. The comparison of the results with the ideal case of unity-slope line (in light blue) reveals that the linearity is conserved in the limit $n \ll N$, with increasing saturation as n approaches N. However, the deviation from a linear slope is quite acceptable even for n~ 50.

## Conclusion

In conclusion, we have proposed a photon number resolving detector based on superconducting nanowire single photon detectors.  which is a promising candidate to fill the existing gap between the single photon and the linear detection regimes at telecom wavelengths. The combination of spatial multiplexing over a large number of nanowires in series and current discharging on the parallel resistors allows accurate and easy voltage readout. Using a high impedance load (e.g. a high input impedance cryogenic preamplifier stage mounted close to the device), a large array of series nanowires may allow photon number measurements in the range of few to few tens of photons with high fidelity and repetition rates in the hundreds of MHz range.

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