NbN nanowire optical detectors for high speed applications

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Abstract. We have developed a novel geometry for single photon optical detectors (SSPD) based on NbN nanowires. Traditionally the SSPD are realized in a meander structure in order to realize a reasonable (few square microns) collecting area. This has the disadvantage of generating a large detector inductance, mostly of kinetic origin, that strongly limits the detector operation in high speed applications, such as telecommunication. Moreover the extreme aspect ratio of the detector (a nanowire a fraction of mm long and 100 nm wide) puts strong requirements on the nanofabrication processes, with negative effects on the production yield. Our novel proposed geometry is based on a parallel stripes configuration designed in such a way that the light induced switching of a single stripe generates the switching of all the other through a cascade mechanism. The net result is an SSPD device that has a much lower intrinsic inductance, and consequently a much wider bandwidth (up to 10 GHz range). Moreover the signal amplitude generated is much larger than that of traditional SSPD, due to the contribution of all the parallel stripe. We present here the design and results of numerical simulation of the response of this novel type of SSPD. In particular we discuss of the design solutions that allow the cascade operation of the detector, by realizing a very fast and synchronous switching of all the parallel lines. Key issues, such as the optimal number of parallel lines, with respect to fabrication and operation constraints of the detectors are also discussed.

1. Introduction
The development of the superconducting single photon detector (SSPD) has recently gone through an intensive activity. These detectors had application in quantum optics, quantum cryptography, circuit defect analysis, etc. In particular, due to their intrinsic high speed, low dark count rate and single photon sensitivity in the infrared spectral region, SSPD are very interesting for application to the telecommunication, were great sensitivity and fast response are fundamental. Actually the most

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common version of this device is based on a NbN ultra-thin film patterned in form of a long nanowire (~ 5 nm thickness and 100 nm width) [1]. In order to cover a large sensible area the nanowire is arranged in a meander structure, with size from 5 x 5 to 10 x 10 \(\mu\text{m}^2\). This solution has two big disadvantages: low signal to noise ratio and limited count rate. In this work we introduce a new design for the SSPD that improves both the signal to noise ratio and count rate, maintaining the high sensitivity and the single photon response.

2. Parallel SSPD

To obtain the single photon sensitivity all the SSPDs use the same basic structure: a long nanowire of superconducting materials, biased with a DC current \(I_b\) close to the wire critical current \(I_C\). The nanowire is narrow enough so that the absorption of a photon can induce a transition to the normal state, due to the local overcoming of the critical current [1]. The nanowire is typically connected, through high bandwidth line, to a fast signal amplifier with an input impedance \(R_L=50 \Omega\). In the case of NbN the normal state resistance \(R_W\) of the nanowire is considerably higher that the load resistance \(R_L\), so after the transition the current once flowing into the nanowire redistributes into the load producing an output signal. The rise time is given by \(\tau_{RM}=L_M/(R_W+R_L)\), where \(L_M\) is the meander inductance (mainly of kinetic origin). After the effect of the photon dies away, the nanowire returns to the superconductive state, so the bias current, which by now has reduced to \(I_b<I_b\), refloows into the meander with a characteristic time \(\tau_{FM}=L_M/R_L>>\tau_{RM}\). Typically \(\tau_{RM} \approx \tau_{FM}\) are of order of few ns. The results voltage signal across the load \(R_L\) has an amplitude \(V_S=\left(I_c-I_b\right)/R_L\), and a duration determined by \(\tau_{RM}\).

In order to increase the output signal amplitude and to reduce its duration we propose a new design were the nanowires are linked in a parallel geometry. The total length of the nanowire is divided into \(N\) stripes, all connected in parallel. In this way the overall critical current is increased by a factor \(N\) and the inductance reduced by a factor \(1/N^2\). The detection mechanism is unvaried. When a photon is adsorbed in one of the stripes, it induces a phase transition and the current flowing through the stripe redistributes to the surrounding circuit. As the remaining stripes are biased near their critical, the excess current will induce in them a transition to the normal state, with a cascade effect. Once all the stripes go to the normal state, the overall bias current is redistributed to the load resistance, giving rise to an output voltage signal that is \(N\) times, larger of the signal from a single nanowire. Moreover the time duration of the pulse is much shorter of that of the meander. In fact, being the total inductance \(L_o<<L_M\), the characteristic times will now be \(\tau_{RM}=L_M/(R_W+R_L)\) and \(\tau_{PS}<\tau_{RM}\) where \(\tau_{PS} \approx 70\) ps represent the time necessary to the formation of the phase slip centers [2] in the stripes due to the cascade effect. To work properly the device must be biased near \(I_C\), in order that the transition of one stripe induces the cascade mechanism. This implies that the larger the number of stripes, the smaller is the range of possible bias value. Moreover increase the number of stripes involves a reduction of the total resistance of the device, that become no longer larger than \(R_L\). These conditions limits the practical maximum number of parallel nanostripes to 10-20.

3. Circuit simulations

To investigate the properties of the new design, and to compare with that of the meander SSPD, we have realized some simulation using a circuits equation solver [3]. We have modeled a nanowire as a series connection of an inductor \((L_W)\) with the parallel of a current controlled switch and a resistance \((R_W)\), as also reported by other authors [4]. In order to mimic the real behavior of a superconducting nanowire the switch has two threshold value: high and low. When the current flowing into it is below the lower limit \(I_b\) the switch is closed and the resistance \(R_W\) is short-circuit, this represent the superconductive state of the nanowire. When the current is above the high limit \(I_C\) the switch is open, the current flows through the resistance and the nanowire is in the resistive state. For currents in between \(I_b\) and \(I_C\) the switch retain its previous state (hysteric behavior). \(L_W\) represents the kinetic inductance of the nanowire and \(R_W\) its resistance in the normal state.
In Figure 1 are shown two circuits representing, respectively, (a) a meander and (b) a parallel SSPD. In both is present a DC current source ($I_B$) to bias the device near its critical current and a load resistance $R_L=50 \, \Omega$, which represents the fast readout electronics. Moreover, is present a current pulse generator (Ph) that generates a small (2 $\mu$A) current pulse, to overdrive the switch above the threshold and mimic the absorption of the photon. To minimize its influence on the circuit time evolution the “photon” pulse duration is set to be very short (few ps). In the circuit of the parallel device is also present another inductance ($L_C$) in series with the parallel of the stripes, whose role is very important for the synchronization of the various switches.

In Figure 2 an experimentally measured output to a single photon absorption by a meander SSPD is shown [5], together with the results from the simulated circuit in Figure 1 (a). The experimental curve concern a 21 stripes meander. The circuit parameters used are $I_C=11$ $\mu$A, $I_R=5$ $\mu$A, $I_B=10.8$ $\mu$A, $R_W=120$ $\Omega$, $L_M=105$ nH, and have been chosen close to experimentally measured values. The good agreement between experimental and simulated signals is a confirmation that the proposed circuit model can capture the essence of the SSPD dynamic.
In Figure 3 is shown the simulated current flow of 5 stripes in parallel, respectively, (a) with $L_C = 0$ and (c) $L_C \neq 0$. The circuital parameter values used are $I_C = 20 \, \mu A$, $I_R = 10 \, \mu A$, $I_B = 19 \, \mu A$, $L_W = 5 \, nH$, $R_W = 500 \, \Omega$.

**Figure 3.** Current flow and output voltage pulse in a 5 stripes parallel device with (a) $L_C = 0$ and (c) $L_C \neq 0$. In (b) an example of the after-pulses generated in the case (a).

In Figure 3 is shown the simulated current flow of 5 stripes in parallel, respectively, (a) with $L_C = 0$ and (c) $L_C \neq 0$. The circuital parameter values used are $I_C = 20 \, \mu A$, $I_R = 10 \, \mu A$, $I_B = 19 \, \mu A$, $L_W = 5 \, nH$, $R_W = 500 \, \Omega$. 
The arrival of the “photon” current pulse on the Stripe 1 generates a very fast initial increase of the current that flow through it until it reaches $I_C$, at this point the switch opens and the current starts to decrease. After the open of the switch 1 the current starts to redistribute to the other stripes and to the load. While the current in the Stripe 1 decreases towards $I_R$, the current in the other stripes increases with a characteristic time of the order of $L_W/R_L$. When their currents reach $I_C$, the stripes become resistive and the bias current redistributes mainly to the load $R_L$, producing an output voltage signal.

Meanwhile, Stripe 1 is again in the superconducting state and an increasing current starts to flow into it. This produces, at a later time, another switch to the normal state in Stripe 1, that induce again a switch to the normal state of the other stripes. The overall process repeats again with the result of generating a number of after-pulses from the device, as it is show in Figure 3 (b).

To avoid this behavior it is important to have a series inductance $L_C$ in the circuit, that forces the current from the Stripe 1 to quickly flow into the other stripes. In Figure 3 (c) is shown the simulated current flow of 5 stripes SSPD with $L_C \neq 0$. It is immediately evident that the currents flowing in the various stripes are synchronized, giving rise to a clear voltage peak across $R_L$. After extensive simulations we found that the minimum value of $L_C$ for the synchronization mechanism to work is $L_C \approx L_W$.

In Figure 4 is shown a comparison between the signal obtained from a meander, a parallel of 3 stripes and a parallel of 5 stripes. It’s easy to see from the figure that the signal generated by the parallels SSPD is larger in amplitude and faster in time than that of the meander SSPD and proportional to the number of parallel stripes involved. In order to obtain the same area coverage of a meander SSPD, it is possible to connect several parallel stripes in a series. To obtain a good sensible area the various devices could be arranged in a meander structure. Also shown in Figure 4 is the signal generated by the series of 5 parallel block, each made of 5 stripes. As can be clearly seen, the signal generated is essentially the same of that of the single parallel of 5 stripes. Each block of parallel stripes react to the absorption of a photon with the cascade mechanism described before, while the other blocks only contribute to the overall device inductance. If enough blocks are used $L_C$ can even be avoided.

![Figure 4](image)

**Figure 4.** Comparison of the output voltage pulse generated by a meander, a 3 stripes parallel, a 5 stripes parallel and a series of parallels device.
4. Conclusions
We have performed simulation of superconductive circuits representing nanowire SSPD. We have introduced new SSPD design solutions, based on a parallel architecture, that have clear advantages respect to a meander SSPD, as increased signal to noise ratio and increased count rate. The other characteristics of meander SSPD, like single photon response and good area coverage, are preserved in the proposed device.

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