Experimental characterization of NbN nanowire optical detectors with parallel stripline configuration

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Abstract. We have developed a novel geometrical configuration for NbN-based superconducting single photon optical detector (SSPD) that achieves two goals: a much lower intrinsic impedance, and a consequently greater bandwidth, and a much larger signal amplitude compared to the standard meandered configuration. This has been obtained by implementing a properly designed parallel stripline structure where a cascade switching mechanism occurs when one of the striplines is hit by an optical photon. The overall switching occurs synchronously and in a very short time, giving rise to a strong and fast voltage pulse. The SSPD have been realized using state of the art NbN deposition technology and e-beam lithography. The strips are 100 nm wide and 5 µm long and have been realized with 4 nm NbN film on sapphire and Si substrate. We report on experimental characterization of such novel devices. The performances of the proposed novel type of SSPD are compared with standard SSPD design and results in terms of signal amplitude, risetime and effective detection area.

1. Introduction

Superconducting single photon optical detectors (SSPD) are being actively developed for a wide range of applications [1-4]. In particular NbN-based SSPD have recently had large attention due to their speed, up to about 1 GHz [3], sensitivity to single photons in the near infrared region and simple cryogenic operation at T=3-4 K. In order to achieve single photon sensitivity the photon absorption should occur in a very small volume of the superconductor. Generally this kind of devices are ultra thin films that are patterned into narrow wires of about 100 nm width and arranged in a long meander configurations to increase the coverage area (see figure 1). However for very high speed operation, in the 10 GHz region, of interest for telecommunication and RSFQ circuit interfacing, the meander SSPD...
is not usable, due to their high intrinsic inductance, mostly of kinetic origin [4]. In fact the count rate of the detector is limited by the restoring time \( \tau = L_{\text{DET}}/Z \), where \( Z \) is the impedance of the signal output line typically of 50 \( \Omega \), for the bias current to return to the SSPD when its superconducting state is recovered. Moreover, due to the small cross-sectional area of the wires the critical current is very low and this limits the voltage signals generated by the meandered SSPD at a fraction of mV, which is considered too small for reliable data transmission at high speed.

Recently we investigated a new NbN SSPD which increases its operational speed and signal amplitude through the use of parallel wires [5]. The parallel SSPD represents a significant improvement in NbN SSPD design since the benefits can be obtained without loosing area coverage or filling factor and retains the excellent intrinsic dark count rate of meander SSPDs. In this paper we report on the characterization of parallel SSPD. We also report on comparative measurements of the signal amplitude, risetime and pulse count rate from both a meander SSPD and parallel SSPDs.

2. Parallel SSPD introduction

A meandered SSPD can be seen as \( N \) narrows wires in series (see Fig. 1a). If the individual wires are placed in parallel, we obtain a new configuration (see Fig. 1b) that exploits the bi-stable nature of the NbN wires by forcing a cascade switch of all the parallel wires when one of them absorbs a photon. In detail, this is possible because the parallel wires are biased with a DC current close to their critical current. When a photon impinges on one wire it is forced to change from the superconducting to the normal state through a current assisted transition. The bias current flowing in the now resistive strip is redistributed to the other parallel wires roughly until it reaches the return current. The extra current flowing into the other parallel wires will force similar phase transitions, as they are biased close to their critical current, and thus an avalanche effect is obtained. When all the wires have developed a normal region the bias current will be switched to the load and produce a signal pulse. Since the current flowing through the wires is lowered to the sum of all the return currents, the reduced dissipation allows the SSPD to cool down and restore the superconductive state again. Then the bias current will return to the SSPD and it is ready to detect another photon. Compared with a meander type SSPD the resulting signal pulse will be \( N \) times larger due to the increased amount of current flowing through the load and significantly faster due to the parallel configuration of the NbN wires.

We have made a circuit model of the parallel SSPD. Each wire is represented by an inductor, \( L_W \), in series with a parallel combination of a resistor and a current-controlled switch (see figure 1c), as is usual for meander SSPDs [4]. We use a switch since the superconducting to normal state transition is very fast in NbN, implicitly assuming that the surrounding circuit is significantly slower than the phase transition time in NbN. The bi-stable nature of a wire was incorporated into the model by the

![Figure 1.](image-url)

(a) Scanning electron microscope image of a meander SSPD. (b) Scanning electron microscope image of a three wire parallel SSPD. (c) Circuit model of used for the three wire parallel SSPD simulation.
use of a hysteretic threshold for the current controlled switch. Using a circuit simulator we can make the cascade switch of the parallel SSPD work and make it generate fast and large voltage pulses. We have found that the simulated parallel SSPD works well when an inductance, $L_S$, is inserted in series with the parallel SSPD wires as it suppresses unstable switches and oscillations. From the simulations we found that a good value is $L_S = L_W$. This makes the total inductance of the parallel SSPD $L_{SW} = (1+1/N)L_W$, which is about N times smaller than that of a meandered SSPD. Furthermore we found a current bias threshold, $I_{THR}$, below which the switch cascade does not work because the generated extra current is not large enough to induce the switching cascade. The exact value of the threshold depends on the relative value of the load and $L_S$ impedance compared to the impedance of the wires. It can be calculated to be in the range:

$$\frac{(N-1)I_C + I_R}{N} < I_{THR} < \frac{NI_C + I_R}{N+1}$$

Here $I_C$ is the parallel SSPD critical current and $I_R$ is the parallel SSPD return current. The lower limit is calculated for a high load impedance and the higher limit is calculated for low load impedance. For a low return current this implies for $N=3$ that the current bias, $I_B$, should be roughly between 67-75% of $I_C$ whereas for $N=5$ it should be between 80-83% of $I_C$. It is interesting to note that the range of bias current values in which the parallel SSPD works, from $I_{THR}$ to $I_C$, is roughly the same as for the meander SSPD. It has essentially been offset to start at higher current. We also note that using small inductances in the parallel SSPD, the signal pulse width approaches the NbN intrinsic speed of about 30 ps [2].

3. Experimental set up

We have fabricated ultra-thin films of NbN by DC magnetron sputtering deposition on sapphire substrates [6]. Using electron beam lithography we define the areas of NbN film which are not used for photon absorption and cover them with a 60 nm Ti/Au bilayer [7]. Subsequently we define structure of the NbN film, in particular the nano-wires, again using electron beam lithography. On each chip we fabricate six devices, in the following called devices A-F, all using 5 μm long and 130 nm wide NbN wires in various configurations. Devices A and B are meandered SSPDs with 21 wires, covering a 5x5 μm² area with a filling factor of 50%. Devices C and D are parallel SSPDs with 5 wires, covering a 5x4 μm² area with a filling factor of 15%. Device E is a parallel SSPD with 3 wires,

![Figure 2](image-url)
covering a 5x2 µm² area with a filling factor of 18%. Device F is a single wire SSPD. In figure 1 we show pictures of a meander SSPD and a three wire parallel SSPD.

In order to increase the speed of the characterization measurements and reduce the probability of damaging an SSPD, we designed a low cost compact chip carrier that ensures good thermal contact during optical measurements, see figure 2. It is composed of a connector, a small printed circuit board and a copper plate. We chose a standard double spacing connector because the space requirements are very small when mounted on the side of the cold finger, which makes it easy to install in a cryostat with optical access. The printed circuit board is glued onto the copper plate and the double spacing connector is soldered onto it, so that no soldering is done with the chip on the chip carrier. The chip is then glued onto the copper plate base of the chip carrier and wire bonded to the printed circuit board. To ensure high bandwidth connection we designed the transmission lines on the printed circuit board to have 50 Ω impedance. During measurements the copper plate is pressed onto the cold finger with screws to insure good thermal contact.

In figure 2 we show a box diagram of the essential parts in the experimental setup. The cryostat with optical access is a liquid helium flow cryostat which has high bandwidth coaxial cables and low bandwidth twisted pair cables. The cables have been carefully thermalized. The low bandwidth connections were used to DC current bias the SSPDs using cold RC filters to act as a bias tee. Battery powered low noise electronics was used to DC current bias the devices and measure the bias current and the device voltage through two-wire or four-wire measurements. Two cascaded 1 GHz bandwidth amplifiers (ZFL-1000 from mini-circuits) with a combined voltage gain of roughly 400 amplified the SSPD signal pulses. The amplified signal pulses were subsequently visualized and recorded using a 1 Gs/s oscilloscope, while the signal pulses were counted using a general purpose counter (HP 5316B). The optical system is moveable in all three dimensions, has a CCD camera to facilitate movements and focusing, and uses an optical fiber connector for the source of illumination. We have adjusted the system so that the focus plane of the illumination coincides with the focus plane of the camera and the image is amplified 10 times. A diffusive light source is used to visualize the device, as the interference of the coherent laser light distorts the image. However, this interference is very useful for regulation of the angle of the chip plane so that it is illuminated orthogonally, a procedure that must be repeated at least each time the chip is changed. The optical system permits the manipulation of the polarization through a polarizer, the intensity through inclined neutral density filters, the spectral distribution through laser line filters, and the spot size through focusing.

4. Measurements
We have measured the DC IVC of all the devices on 14 chips. From these measurements we selected the chips to measure under optical illumination. In figure 3 we show the IVC for four of the devices on

Figure 3. DC IVC of SSPDs measured at 4.2 K: (a) 5 wires (crosses), 3 wires (open circles) and 1 wire (solid squares) parallel SSPDs and (b) meander SSPDs with 21 strips.
a representative selected chip measured at temperature of 4.2 K. The measured I\textsubscript{C}, I\textsubscript{R} and R\textsubscript{N} are reported in table 1 and they scale as expected with the number of wires.

From the measurements on all the 14 chips at 4.2 K we have observed a probability of 25% that a meander SSPD is malfunctioning. If the cause of these malfunctioning devices is related exclusively to the failure probability of a single wire it can be estimated from this measurement as 1.4%. This estimate in turn can be used to roughly predict how many wires can be used given a specific acceptable failure rate, in our case we estimate that 50 wires can be used if the failure rate is allowed to increase to 50%. The measured failure rate for the parallel SSPDs is 17% for N=5, 21% for N=3, and 15% for the single strip. Taking into account the number of wires present in the parallel SSPDs the yield is worse, but this should be expected since this is the first production of these devices.

We have characterized the chip, from which the IVCs are reported in figure 3, under 850 nm laser light illumination at an estimated temperature of 6 K. The parallel SSPD signal pulse duration was below 1 ps which was too fast for our 1 GHz limited electronics so we inserted 500 nH surface mounted inductors in series with the SSPD on the chip carrier as seen in figure 1 to artificially increase the signal pulse duration to 12 ns which allows us to both count and record them accurately. We used a laser spot size of about 20 \(\mu\text{m}\) to ensure homogenous light intensity across the area of the SSPD. The light pulses were 6 ns long with 2.5 ns rise and fall time at a repetition rate of 10 MHz. We recorded the signal pulses from the N=5, N=3 and N=1 parallel SSPDs and found that the signal amplitude scales proportionally to the number of wires in parallel, see figure 4. The signal amplitudes were also in good agreement with the expected value, \((I\textsubscript{B}-I\textsubscript{R})Z\), and the signal pulses from the single wire were similar to the signal pulses from the meander. The rise time of the pulses observed was about 2 ns due to the artificial high inductance. We also observe no increase in the signal voltage noise level while increasing the number of wires leading to an increase in the signal to noise ratio for the parallel SSPDs.

We have performed measurements of the SSPD count rate as a function of bias current both with

|       | 5 parallel wires | 3 parallel wires | 1 wire | 21 Meandered wire |
|-------|------------------|------------------|-------|-------------------|
| R\textsubscript{N} | 7.02 kΩ | 11.4 kΩ | 34.7 kΩ | 411 kΩ |
| I\textsubscript{C} | 75 µA | 52 µA | 15 µA | 19 µA |
| I\textsubscript{R} | 26 µA | 17 µA | 5 µA | 6.15 µA |

Table 1. Values of the critical current, return current and normal state resistance relative to the characterized devices having the DC IV curves shown in the figure 3.

Figure 4. (a) Non-averaged signal pulses from the parallel SSPDs measured at 6 K under optical illumination. The signal was artificially prolonged to a 12 ns falltime as explained in the text. From bottom to top is the 1 wire, the 3 wire, and the 5 wire SSPD signal respectively. The signal pulses has been offset for clarity. (b) Measured SSPD count rates for a 5 strip parallel SSPD (closed circles) and a meander SSPD (crosses) as a function of the normalized bias current at 6 K. For both devices the upper trace is with laser illumination and the lower trace is without laser illumination.
laser illumination and without. To perform these measurements we first positioned the laser spot on
the detector and then adjusted $I_B$ to obtain signal pulses on the oscilloscope. We then measured the
count rate as a function of the trigger level of the counter. This allowed us to fix the trigger level at the
most stable position. We then measure the signal count rate as a function of laser position and
maximize it. The count rate measured for 5 wire parallel SSPDs as a function of bias current, see
figure 4, had a sharp increase around $I_B=0.8I_C$ as expected from the threshold of the cascade switch.
Furthermore the dependence is found to be exponentially dependent on the bias current and changes
about 1.5 orders of magnitude in the bias range from 0.8 $I_C$ to $I_C$. The meander SSPD showed roughly
the same behavior with bias current. In the measurements with the laser turned off, we observe a knee
in the curve at $I_B=0.9I_C$. This is most likely due to the presence of background photons in the
laboratory as the tail is highly suppressed after sunset as seen in the trace from the meander SSPD.

The presence of both meander SSPDs and parallel SSPDs on each chip is necessary for good
comparative measurements as it increases the correlation of the SSPD performances determined by the
fabrication. Furthermore, since the only action we must perform to change the device under
measurement is a XY translation of the optical system our system makes comparative measurements
easy to perform. Our procedure for determining the position of the laser spot have shown count rate
deviations of roughly a factor 1.5 for laser spot sizes of about 20 $\mu$m when we repeated the positioning
onto the same device, so it is possible to correlate the two count rate measurements shown in figure 4.
We find that the difference in count rates is roughly similar to the difference in the number of wires,
both when illuminated and when measuring the dark counts not due to laboratory photons as expected
since the transition to the normal state of the NbN wire occurs equally in both types of SSPDs,
independently of whether it was due to photon absorption or a dark count.

5. Conclusions
In conclusion we have fabricated and characterized both meander and parallel SSPDs. We have found
that the parallel SSPD signal pulse amplitude scales with the number of wires and the signal pulse
duration was found to be below 1 ns. Comparative measurements with meander SSPDs present on the
same chips showed that the count rate scaled with the number of light sensitive wires both when
illuminated and when measuring dark counts.

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