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An Interleaved Two element superconducting nanowire single photon detector with series resistors method for better reduction in inactive period

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Abstract

The photon-counting detectors in an optical communication receiver can provide several advantages including excellent receiver sensitivity However, the sensitivity and data rate of photon-counting optical communication systems can be limited by photon counting detectors with low detection efficiency or long reset times. Recently, error-free photon-counting optical communication has been demonstrated at a data rate of 781 Mbit/s using a superconducting nanowire single photon detector (SNSPD). The sensitivity of a photon-counting optical communication system is reduced by any source of optical loss in the receiver, which will include losses in the photon counter due to both non-unity detection efficiency and blocking. These blocking losses can be reduced by improving the detector performance in either of two ways: (1) by reducing the duration of the inactive period or (2) by increasing the number of detectors. In this paper we focused on both ways to obtain the maximum detection efficiency and reduction in inactive period. The proposed series resistor method with two element superconducting nanowire single photon detectors was found to be due primarily to the faster reset time of the individual elements relative to a single-element SNSPD with the same active area.

Keywords: Photon-counting, superconducting nanowire single photon detector, inactive period, thermal model, series resistor method.

Classification numbers: 2.02, 6.05

1. Introduction

Single photon generation, manipulation and detection technologies are important for several areas in quantum optics [9]. Recent drives to develop technologies using single photon generation and single photon detection are quantum computation, where photons are used as quantum bits. Single photon detection itself has many applications in diverse fields in which high timing resolution and high sensitivity to low photon levels are required. Infrared single-photon detectors are a key enabling technology for a host of scientific applications. The Advances in photon-counting applications place stringent demands on detector performance and new detector technology are rapidly being developed, evaluated, and deployed. Superconducting nanowire single-photon detectors offer wide spectral range (from visible to infrared wavelengths) with free-running operation, low dark counts, short reset times, and low timing jitter. SNSPDs have begun to have a significant impact on applications, such as quantum key distribution, time-of-flight ranging, high bit-rate ground-to-space communications and optical quantum information processing. Recent work on SNSPDs has concentrated on increasing detection efficiency (DE) through improved materials, device layout, and optical architecture [3].

1.1 SNSPD operating principle and Why thin nanowires.

The device operation of the superconducting nanowire single-photon detector, the NbN nanowire is well maintained below its critical temperature T_c and direct current biased just below its critical current as shown in figure1.the hotspot itself is not large enough to span the width of the 100nm nanowire. The hotspot region forces the super current to flow around the resistive region [5]. The local current density increases beyond the critical current density [10] and thus forms a barrier across the width of the nanowire. The sudden increase in resistance from zero to finite value generates an output pulse across the nanowire.

The resulting voltage signal across the contacts of the device can then be amplified for use with conventional time–correlated single photon electronics. As the nanowire strip cools, the electrons lose energy through electron-photon scattering and the hot spot rapidly shrinks, breaking the barrier and restoring the superconductivity. Early designs suffered from low detection efficiencies as they were based on long, straight wires meaning that the incident photon had to strike the relatively thin 100 nm width of the wire to be detected. The obvious way of increasing the detection efficiency is to increase the area of wire. However, the actual width of the wire cannot be increased due to the small width of the hot spot formed; hence the thin wires are used in order to prevent an effective area more consistent with the focusing of visible and infrared light.

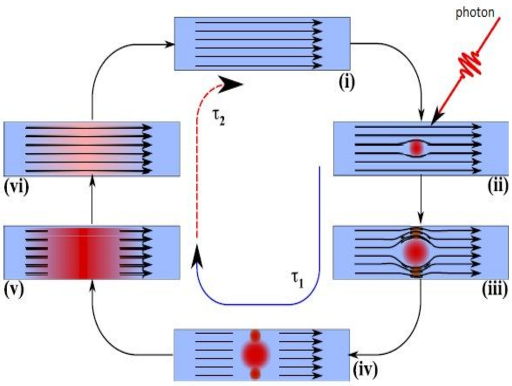

Figure1. Detection cycle in SNSPD. (i) The superconducting nanowire maintained well below the critical temperature is direct current (DC) biased just below the critical current. (ii) When a photon is asbsorbed by the nanowire a small resistive hotspot is created. (iii) The super current is forced to flow along the periphery of the hotspot. Since the NbN nanowires are narrow, the local current density around the hotspot increases, exceeding the superconducting critical current density. (iv) This in turn leads to the formation of a resistive barrier across the width of the nanowire.(v) Joule heating (via the DC bias) aids the growth of resistive region along the axis of the nanowire until the current flow is blocked and the bias current is shunted by the external circuit. (vi) This allows the resistive region to subside and the wire becomes fully superconducting again. The bias current through the nanowire returns to the original value (i).

1.2 Detection Efficiency

An important characteristic of a detector is its efficiency. For SNSPD it is a measure of the probability that an input photon results in an electrical output pulse. In this probability (DE) different sub processes can be recognized.

$$DE = \eta d \cdot \eta A \cdot \eta c$$

Where ηd is the probability of electrical pulse generation due to an absorbed photon, ηA the photon absorption efficiency of the superconducting nanowire and ηc the optical coupling efficiency between the incident light and the active area of the detector. The first factor is the intrinsic quantum efficiency of the nanowire and it is the probability that a voltage pulse will be generated given that a photon is absorbed. Coupling losses are represented by ηc. Coupling losses occur when the photon is coupled to the detector. This is usually done with an optical fiber or a microscope objective. As for the ’end-user’ of the detector the coupling loss is not of interest, often the system detection efficiency (SDE) is defined.

1.3 Dead time

The primary limitation to the maximum counting rate of an SNSPD is the reset time

[4] since it determines when a second photon can be detected. The detection response time is set by electrical and thermal properties of the SNSPD. Reset will only occur if the resistive state in the wire is unstable, for this to happen the thermal time constants has to be sufficiently fast compared to the electric time constants (i.e. the time it takes for the current to decrease and return in the SNSPD).This means that the electrical time constant cannot be lowered indefinitely. The recovery time τ is mainly determined by the kinetic inductance *Lk* of the nanowire and the load impedance *RL* to which it is connected $\tau = Lk/RL$. The kinetic inductance is proportional to the length of the nanowire divided by the cross-sectional area of the nanowire [6]. For example :The kinetic inductance of a 5 nm thick, 100 nm wide, 500 μm long NbN wire is approximately 500 nH and *RL* is typically the input impedance of an RF amplifier (i.e. 50 Ω), implying that τ = 10 ns. Shorter wires will have lower inductance resulting in faster reset times, though they imply smaller active areas, thus there is a tradeoff between maximum counting rates and overall efficiencies. An alternative way to decrease the kinetic inductance is to put more detectors in parallel. The total kinetic inductance is then $1/Lk,total = 1/Lk,1 + 1/Lk,2$.... A third option to decrease τ is to increase the impedance as seen by the detector (R*L*).It is possible to reduce the electrical time constants, however the thermal constants, dictated by material properties, place a lower limit on the reset time.

2. Series resistor method

Electrically, the SNSPD was modeled as an inductor in series with a resistor as shown in Figure 2. The inductor L_K represented the kinetic inductance of the superconducting nanowire superconducting detector. The resistance R_n in series with the inductor was the total resistance formed from a contiguous number of segments that switch into the normal state. For experiments, the authors bias their devices using a bias tee and a low-noise current source. The DC port of the bias tee was modeled as a constant current source and a capacitor Cbt was included to represent the AC port. The impedance of the transmission line connecting the probe to RF amplifiers was modeled as a 50-Ω load. The authors solved for the current I through the nanowire using the following equation.

$$C_{bt}(d^2 L_k I / dt^2 + d(I\,Rn)/dt + Z_O\, di/dt) = I_{bias} - I$$

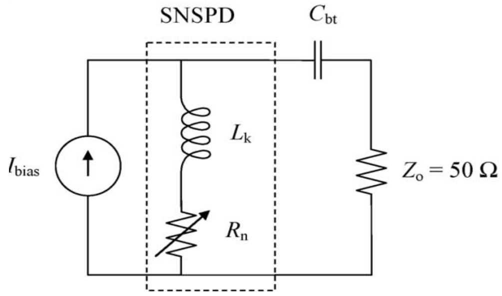

Figure: 2 A simplified electrical model of the SNSPD connected in a typical testing configuration.

The R_n is coupled to the thermal model [5] and is not a constant value. The thermal model (where the series resistor is not present) determines the length of the normal region which is proportional to R_n.

The proposed series resistor method (electrical model) by adding a resistor in series with the SNSPD is shown in the figure 3. The series resistor method

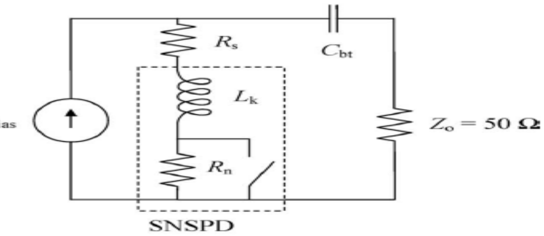

Figure.3 Schematic of Modified Electrical Model after Adding a Resistor Rs in Series with the SNSPD (The added series resistance will reduce the reset time of the detectors by lowering the time constant.)

With the two elements SNSPD is simulated and experimented to increase the detector speed and to reduce the in active area has been achieved. By comparing the results of both simulation and experimental work, where the results are of high yield when compared with the performance of the device.

3. Two Element SNSPD design

Efficient SNSPDs could be made using 4 nm thick (300-600Ω) NbN patterned into 100 nm wires. The films had a nominal thickness of 4nm, typical room temperature resistivities of 300-400Ω/k and critical temperatures between 10k and 11k. The films were diced into square chips 7 mm on a side with a layer of photo resist protecting the NbN surface, which was face down on the dic tape. After dicing, the chips were removed from the dicing tape in acetone and subsequently cleaned using a clean room swab to rub the surface first with acetone, followed by drying with nitrogen, and finally the surface was rubbed a second time using a clean room swab with deionized water. Contact pads were added using the standard photolithography. Finally, the NbN was etched using CF4 gas for two minutes to remove the Niobium – nitride superconducting nanowire not protected by the hydrogen silsesuioxane. After etching, the device is ready for testing. The proposed interleaved pattern of the SNSPD nanowire after the process of fabrication is as shown in the figure 4.

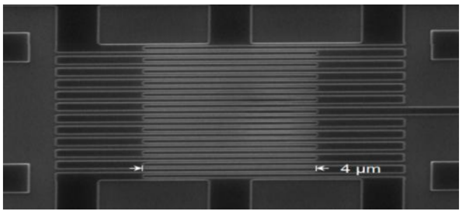

Figure.4 An interleaved SNSPD nano wire pattern after the process of fabrication.

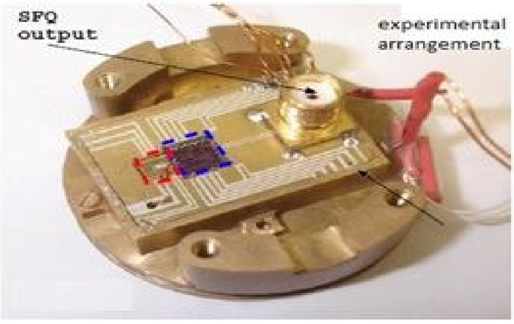

Figure.5 the arrangement and the detection lay out in SNSPDs.

3.1 Measurement Setup And Detector Circuit

The electrical connections to the two – element SNSPD were made through two independent, but identical circuits as show in the figure 5&6. Each device connected to a 50 ohms transmission line through a RF probe. The end transmission line was connected to a bias "T" with a DC port connected to a current source and the AC port connected to amplifier chain and data collection electronics.

The DCE unit consists of the two wide band, low noise amplifiers and finally a DC block in order to limit noise due to a ground loop when the amplifier chain from each of the detector elements were connected to separate channels of an oscilloscope and a frequency counter[7].

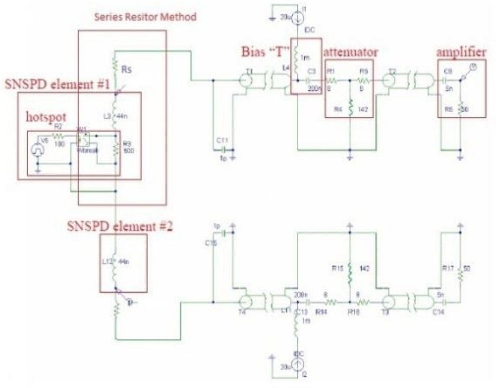

Figure 6. The detailed electrical model, only SNSPD element #1 had a periodically forming hotspot, while SNSPD element #2 was always superconducting.

4. Results and discussion

Spreading an optical beam across a two-element SNSPD could provide a higher maximum counting rate for a detector with a given active area [3]. This increased counting rate come from two sources, the faster reset time of the shorter elements relative to a single element covering the same active area and due to the elements counting in parallel. The reset time of an SNSPD is limited by the time it takes for the bias current to again flow as a super current in the nanowire following a detection event. After current is diverted out of the nanowire, the resistive region must collapse so as the nanowire can return to the superconducting state. The process of expansion and contraction of the resistive state, and the corresponding amount of current flowing in the nanowire, requires considering both the electrical and thermal properties of the detector structure as discussed in the series resistor method.

The recovery of the detection efficiency following detection event was also calculated using the measured inductance and detection efficiency versus current. The detector efficiency recovery for the two- element detector (black line in Figure.7) was calculated assuming the second detector remains active 87% of the time. The recovery of each independent element was also calculated and shown in Figure.5 (red curve in Figure.7). Finally the detection efficiency recovery time [6] of a device with same active area as the two-element device was calculated by assuming its inductance was the sum of the two individual elements inductances (blue curve in Figure.6), because the kinetic inductance dominated and was proportional to the length of the nanowire [6].these curves in Figure.7 clearly shows that the counting rate of the two-element SNSPD is increased relative to a single SNSPD with the same active area.

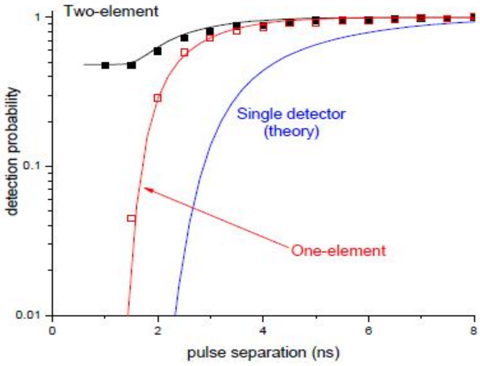

Figure 7. Data marked with red open squares were for one of the individual elements while the data marked with black closed square was for the 2- element SNSPD.

5. Conclusion

A two-element SNSPD was proposed as an approach that could reduce the reset time with the series resistor method .The detector efficiency recovery for the two- element detector is increased relatively to a single detector with the same active area. The two-element detector results suggested that using more elements would have provided additional benefits, particularly for measuring the number of simultaneously incident photons also. Although the two-element measurement demonstrated the potential of multi-element concept, there remain a number of issues that have not been fully resolved. It was certainly possible, particulary given that all of the two-element devices tested were from a single chip, that the superconducting film or fabrication differed in some way from those that yielded the best demonstrated devices. Our model accurately predicts the speed-up in device performance due to series resistance along with the two-element SNSPDs as show in the figure 6.In our model calculations on device latching, we used L_K = 70 nH and we also see that for values of R_S >200 **Ω**, latching occurs and the device does not reset, i.e. the current does not increase to original value. Finally, we observed, both experimentally and through simulations, an upper limit to speeding up the devices and in turn reducing the inactive time using the series-resistor method with two SNSPDs has been successfully achieved by the interleaved pattern.

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