IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 6, October 2008
(ASC Preprint 3EPD04 conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)

The published version of this manuscript appeared in *IEEE Transactions on Applied Superconductivity* **19**, No. 3, Part 1, 367 - 370 (2009)

Superconductive three-terminal amplifier / discriminator

Orlando Quaranta, Stefania Marchetti, Nadia Martucciello, Sergio Pagano, Mikkel Ejrnaes, Roberto Cristiano, Ciro Nappi

***Abstract*— We describe a new superconductive three-terminal device that acts as a fast pulse amplifier and discriminator. The device is based on a parallel nano-wire configuration. The nano-wires are properly biased near their critical current. When a current pulse of sufficient amplitude is injected into one of the wires, a transition to the normal state of all the wires occurs, thus generating a large output current pulse. This device could be used as a pulse amplifier for signals generated by nano-wire detectors or by RSFQ circuits. The parallel nano-wire structure can be realized with the same fabrication process used for NbN Superconducting Single Photon Detector (SSPD), so its integration into the existing technology is straightforward. Here we present numerical simulations of the device, with special attention to circuit requirement for the correct operation.**

***Index Terms*— Fast Pulse, Parallel SSPD, Pulse Discriminator, Superconductive Amplifier, Three-terminal Device.**

I. INTRODUCTION

IN this work we describe an innovative superconductive three-terminal device that acts as a fast pulse amplifier and discriminator. The principle of operation is similar to that of nano-wire single photon detectors. In this case, however, the role of the photon is taken by the input current pulse.

The proposed device is able to generate large current/voltage pulses when the input signal overcomes a given threshold, determined by the DC current bias. In this work we study the properties of this device trough the realization of various numerical simulation of an electrical model of the device.

The nano-wire structure can be realized using the same fabrication process used for nano-wire Single Photon Detector (SSPD), so its integration into the existing superconductive electronics technology is straightforward.

Possible applications are: on-chip pulse amplifier of the signals generated by nano-wire detectors and output interface of RSFQ circuits.

II. SIMPLE NANOWIRE SWITCHING MODE

The proposed device is based on the induced superconductive to normal state transition of a nano-wire biased near its critical current. In single photon detectors the photon absorption triggers the transition. In our case, is the input current injected into the wire to trigger the transition to the normal state.

A simplified electrical model of the nano-wire is widely used to describe the operation of SSPDs [1]. Within such model a superconducting nano-wire is represented by a series connection of an inductor and a resistor, shunted by a current controlled switch. The inductor represents the wire inductance, mostly kinetic. The resistor represents the resistance of the wire section that goes into the normal state. When the current through the inductor exceeds a given value (the nano-wire critical current) the switch opens and the current is forced to flow through the resistor. When the current reduces below another value (the nano-wire return current) the switch closes, thereby recovering the superconductive state.

In Fig.1 is shown the simple electrical model of a nano-wire: L_W is the wire inductance, R_W the normal state resistance of the wire section undergoing the transition, Z is the high frequency load (typically 50 Ω), V_B and R_S constitute the current bias network (R_S>>Z).

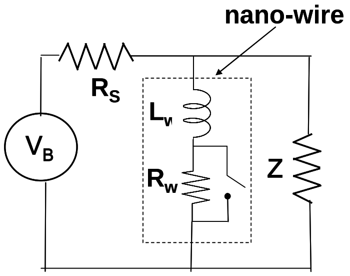

Fig. 1. Electrical model of a nano-wire (SSPD) with the bias and high frequency load circuits

In Fig. 2 is shown a typical experimental DC I-V characteristic of a nano-wire array (having a meander geometry in this case), where the critical current I_C and the return current I_R are indicated by the arrows.

Using this simple electrical model it is possible to compute the pulse response of the nano-wire device to an external stimulus (a photon in the case of SSPD detectors).

For example for an N wires meander with a total inductance:

Manuscript received 17 August 2008. This work was performed in the framework of the EU project "SINPHONIA" NMP4-CT-2005-016433.

O. Quaranta S. Marchetti and S. Pagano are with Dipartimento di Fisica "E.R. Caianiello", Università di Salerno, Baronissi (SA), 84081 Italy (S. Pagano phone: +39-089-965327; fax: +39-089-965275; e-mail: serpa@sa.infn.it).

O. Quaranta and S. Pagano are with CNR-INFM "Coherentia", Naples, 80126 Italy.

N. Martucciello is with CNR-INFM "Supermat", Baronissi (SA), 84081 Italy.

M. Ejrnaes R. Cristiano and C. Nappi are with CNR Istituto di Cibernetica "E. Caianiello", Pozzuoli (NA), 80078 Italy.

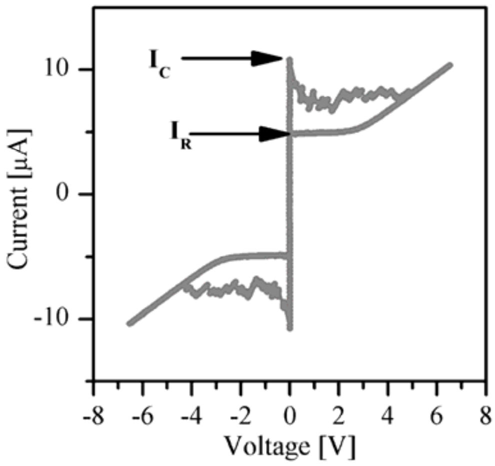

Fig. 2. Experimental I-V curve for a nano-wire (with a meander geometry). I_C and I_R are respectively del critical current and the returning current.

$$L_M = N * L_W \tag{1}$$

is possible to obtain a pulse with rise time, fall time and amplitude respectively:

$$\begin{aligned} \tau_R &= \frac{L_M}{(R_W + Z)}; \\ \tau_F &= \frac{L_M}{Z} >> \tau_R; \\ V_S &= (I_C - I_R) * Z. \end{aligned} \tag{2}$$

The resulting signal is shown in Fig. 3 and compared with experimental data. The excellent agreement demonstrates the validity of this simple electrical model.

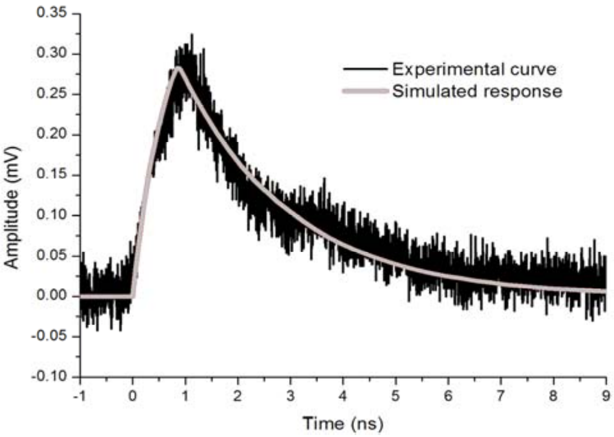

Fig. 3. Pulse response of a meander nano-wire device. Comparison between experimental data (black) and numerical simulation (grey).

III. PARALLEL NANO-WIRE STRUCTURE

The superconducting nano-wires are normally patterned in a meander shape with sub-micron width [2]. The meander geometry is used to enhance the filling factor of the detection area and hence the detection efficiency of the device. However the meander geometry implies a large total device inductance, which negatively affects the timing of the generated pulses [3].

Recently [4] an alternative geometrical nano-wire configuration (a parallel array instead of a meander shape) has been proposed to enhance both speed and signal amplitude of single photon detectors.

Under proper bias conditions, the photon induced transition of one of the wires in the parallel array induces a transition of all the other wires with a cascade mechanism. When all the wires are in the normal state, the detector becomes highly resistive and the total bias current redistributes to the external load.

In Fig. 4 is shown the electrical model of the parallel nano-wire detector, in which each single wire is represented by an inductor L_W in series with a parallel connection of a current controlled switch and a resistor.

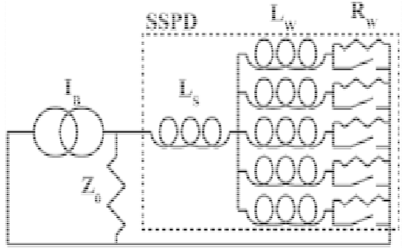

Fig. 4. Electrical model of parallel nano-wire detector.

To achieve a synchronous switching an additional inductor L_S, with $L_S \geq L_W$, has to be inserted in series to the nano-wires [5].

Compared with a meander structure having the same number N of nano-wires, the parallel nano-wire configuration has a much lower total inductance and therefore generates N times faster signals:

$$\begin{aligned} L_{TOT} &= L_S + \frac{L_W}{N} \approx L_W \approx \frac{L_M}{N}; \\ \tau_R &= \frac{L_{TOT}}{(R + Z)} \approx \frac{\tau_{R,meander}}{N}; \\ \tau_F &= \frac{L_S}{Z} \approx \frac{\tau_{F,meander}}{N}. \end{aligned} \tag{3}$$

Moreover, due to the much larger current sent to the load, the generated signal amplitude is N times larger.

$$V_S = N * (I_C - I_R) * Z \approx N * V_{S,meander}. \tag{4}$$

IV. MODEL OF 3-TERMINAL DEVICE

The detection mechanism in the SSPD is based on the fact that the absorption of a photon in a nano-wire biased near its critical current can induce the overcoming of the critical current density in a portion of the wire [1]. The same effects can be obtained by the injection of a current pulse. Starting from this concept we have developed a superconductive three-terminal device that, by employing a parallel wire configuration, is able to generate a large output pulse.

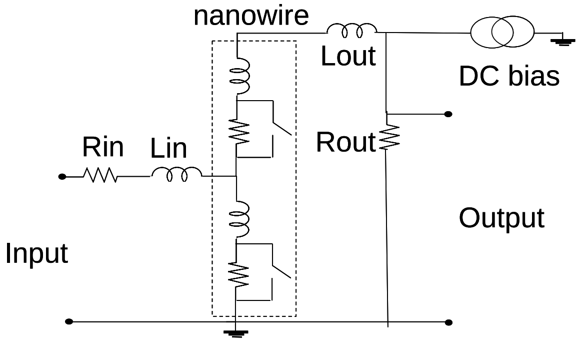

Fig. 5. Electrical model of the basic element of the amplifier.

In Fig. 5 it is shown an electrical model of the basic element of the pulse amplifier. In this figure is represented a single nano-wire. An input connection is added along the nano-wire, to allow an input pulse to be injected in the lower part of the wire. To the right, connected by an output inductor, there is the DC current generator, that biases the nano-wire near its critical current, and the high frequency load (usually 50 Ω). When a current pulse reaches the nano-wire through the input port, and if the wire is biased near its critical current, a switch to the normal state occurs in the lower wire portion. This device acts as a pulse amplitude discriminator: for a given bias value only pulses above a certain amplitude can generate an output pulse.

When the nano-wire goes in the resistive state the current that is flowing trough it will be redistributed to the output and input ports. Because the input and the output resistance has the same value (typically 50 Ω) the redistribution is essentially determined by the inductance L_{IN} and L_{OUT}. Therefore the voltage pulse on R_{OUT} will be approximately given by:

$$V_{OUT} \approx R_{OUT}\left(I_C - I_R\right)\frac{L_{IN}}{\left(L_{OUT} + L_{IN}\right)}. \tag{5}$$

Where I_C-I_R is the amount of current that a nano-wire can redirect toward an external load.

Ideally one would like to have $L_{IN} \gg L_{OUT}$, to maximize the output pulse amplitude. However, L_{IN} determines the operational bandwidth of the device: $B = R_{IN}/(2\pi L_{IN})$, and should not be too large. L_{OUT} has a minimum value due to the wires connecting the device to the output port. Moreover, and will be discussed in the following in the case of integration with parallel nano-wires, L_{OUT} should also be larger than L_W to allow the synchronous switching of the parallel nano-wires configuration [5].

V. SIMULATION RESULTS

To study the properties of the proposed device we have realized various numerical simulations of the proposed circuital model.

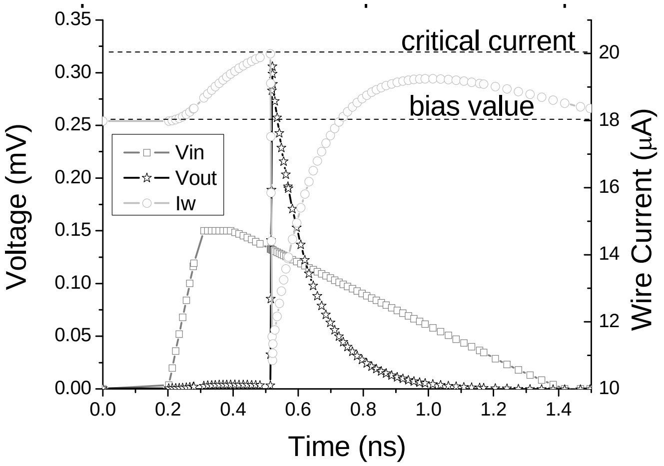

Fig. 6. Response from a 3-terminal device to an input pulse. The input (squares) and output (stars) voltage signals and the wire current (circles) are shown.

In Fig. 6 is shown a typical response of the 3-terminal device (stars) to a 0.15 mV input pulse with 100 ps rise-time and 1 ns fall-time (squares). The output pulse has 0.3 mV amplitude (“gain” = 2) and much shorter rise and fall times. The time evolution of the nano-wire current is also shown (circles). The circuit parameters are: I_C=20μA, I_R=10μA, I_B=18μA, R_{IN}=R_{OUT}=50Ω, L_{IN}=10nH, L_{OUT}=5nH, R_W = 500 Ω, L_W=(0.5+4.5) nH. The input portion of the wire is 10% of the total length.

To further amplify the signal a parallel configuration can be employed, as shown in Fig. 7. In such case the arrival of the input pulse triggers a cascade switching of all the parallel nano-wires, so the output voltage is roughly multiplied by the number of wires. In Fig. 8 is shown the output pulse obtained from a 3-terminal device realized with 5 nano-wires in parallel. The input signal is injected in the lower (10%) portion of the first nano-wire. The input signal amplitude is 0.15 mV, the rise-time 100 ps and the fall-time 1 ns. The circuit parameters used in that simulations are: N_{WIRES}=5, I_C=20μA, I_R=10μA, I_B=18.5μA, R_{IN}=R_{OUT}=50Ω, R_W = 500 Ω, L_{IN}=20nH, L_{OUT}=5nH, L_W=(0.5+4.5) nH. The output pulse has 2 mV amplitude (“gain” = 13) and much shorter rise and fall times. The time evolution of the currents in the nano-wires is also shown.

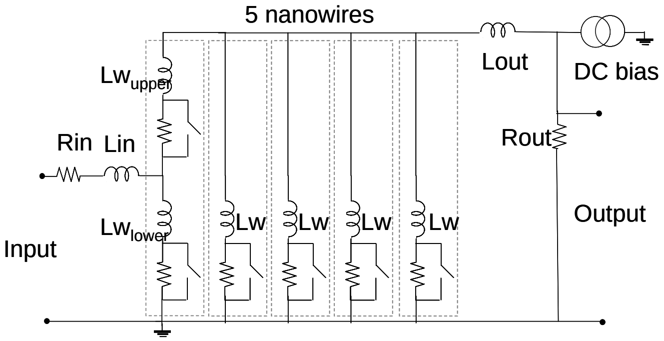

Fig. 7. Example of nano-wire amplifier made with 5 parallel strips.

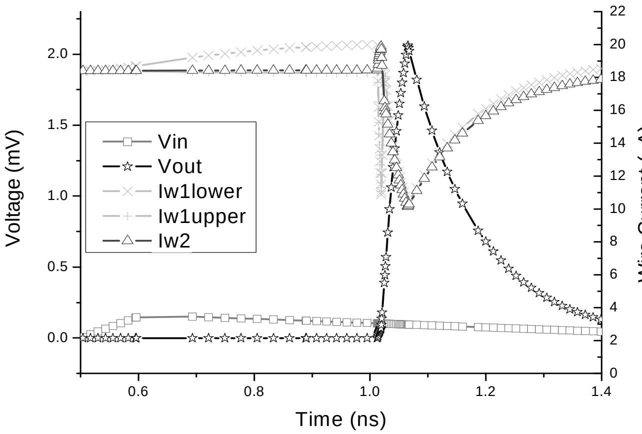

Fig. 8. Response of 3-terminal device realized with a 5 parallel nano-wires. The input pulse (squares) is the same as in Fig. 6. The output pulse (stars) and the current flowing in the upper (+) and lower (x) portion of the input nanowire, as well as the current flowing into one of the parallel nano-wires are also shown.

The number of parallel nano-wires cannot be arbitrarily increased because the more they are less is the bias range in which the cascade switching could work [3]. Is it possible to increase the output signal amplitude by using nano-wires with a higher critical current. An easy way to accomplish this is by fabricating wider nano-wires.

Using this principle it is possible to realize multiple stage devices, where each successive stage has larger critical currents, and obtain very large amplitude pulses. In Fig. 9 is shown an example of a two stage device.

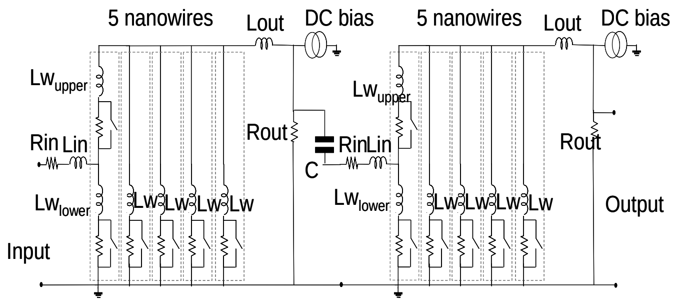

Fig. 9. Example of a series of a two stage 3-terminal device. The second stage has a tenfold increase of the critical current.

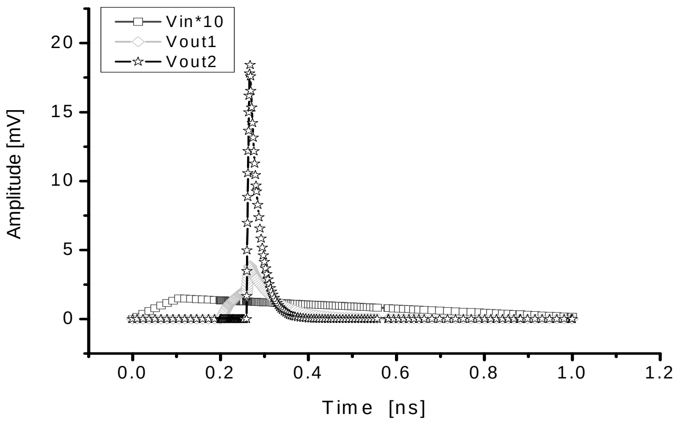

Fig. 10. Signal pulses from a 2-stage amplifier. The output signals from the first (diamond) and second (stars) stage are shown. The input pulse (squares) has been scaled up ten times. The overall amplitude ratio is 120.

In this way can be easily obtained a “gain” up to 120. These results are shown in Fig. 10, where the (scaled) input pulse (squares), the output of the first stage (diamonds) and the output at the end of the amplifier chain (stars) are shown. The value of the parameter for the first amplifier stage are the same as before, while for the second stage the critical and bias currents have been increased tenfold and the inductances decreased by the same amount.

VI. APPLICATION AS SSPD PULSE AMPLIFIER

A possible application of the nano-wire three terminal device can be the amplification of the pulses generated by SSPDs. Standard SSPDs having meander geometry, do generate small amplitude signals as response to a single photon detection. Typical values are: amplitude 0.3 mV, rise-time < 1 ns, fall-time 3-4 ns.

By cascading an SSPD with the proposed three-terminal device (Fig. 11), it will be possible to boost the signal amplitude in the mV range while preserving the signal timing.

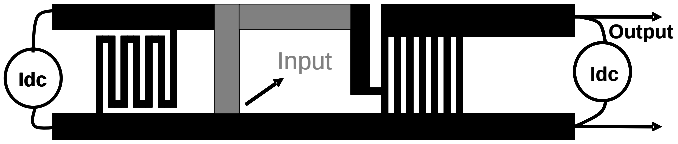

Fig. 11. Possible configuration of an SSPD integrated with a pulse amplifier. The black lines represent superconducting wires, the gray ones resistive wires.

Moreover, being the basic structure of the 3-terminal device similar to that of a nano-wire SSPD, its integration in the existent SSPD technology is also straightforward.

VII. CONCLUSIONS

In this work we have proposed an innovative superconductive three terminal device that can act as amplitude pulse discriminator and/or pulse amplifier.

A circuital model of the device has used to study its properties through extensive numerical simulation. The simulations, concerning the behavior of a single wire 3-terminal device, a parallel 3-terminal device and a series of two parallel 3-terminal devices, demonstrate the validity of the proposed device. A possible application as SSPD pulse amplifier has also been proposed.

REFERENCES

[1] G. N. Gol’tsman et al, “Picosecond superconducting single-photon optical detector”, *Appl. Phys. Lett.*, vol 79 num 6, Aug 2001, pp.705-707.

[2] A. Verevkin, J. Zhang, R. Sobolewski, “Detection efficiency of large-active-area NbN single-photon superconducting detectors in the ultraviolet to near-infrared range”, *Appl. Phys. Lett.*, vol 80 num 25, June 2002, pp.4687-4689.

[3] A. J. Kerman et al, “Kinetic-inductance-limited reset time of superconducting nanowire photon counters”, *Appl. Phys. Lett.*, vol 88, 2006, pp. 111116.

[4] E. Ejrnaes et al, “A cascade switching superconducting single photon detector”, *Appl. Phys. Lett.*, vol 91, Dec 2007, pp. 262509.

[5] O. Quaranta et al, “NbN nanowire optical detectors for high speed applications”, *Journ. of Phys.: Conf. Series*, vol 97, 2008, pp. 012264.