

SUPERCONDUCTIVE MICROWAVE SINGLE-FLUX-QUANTUM DIGITAL CIRCUITS AND CORRESPONDING OPTO-ELECTRONIC INTERFACES: ON-GOING STUDIES AND FIRST EXPERIMENTAL RESULTS

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RESUME : Les circuits numériques supraconducteurs micro-ondes, basés sur la logique à quantum de flux (logique RSFQ), offrent la possibilité de traiter les signaux de manière numérique à des fréquences de plusieurs dizaines de GHz. Un exemple d'application bénéficiant des avantages de cette technologie concerne les SQUIDs numériques. Ces SQUIDs peuvent être utilisés pour la magnétométrie avec une très grande dynamique, résultant de la possibilité d'avoir un "slew-rate" associé à des fréquences de l'ordre du GHz. Des résultats expérimentaux récents de SQUIDs numériques, basés sur une technologie de jonctions Josephson shuntées en Nb/Al-Al₂O₃/Nb, sont présentés dans cet article. De manière à obtenir les meilleures performances des circuits RSFQ, en particulier en ce qui concerne les fréquences ultimes de fonctionnement, un diagnostic précis de tels circuits est nécessaire. Nous développons actuellement un système de diagnostic résolu en temps, basé sur l'utilisation de photocommutateurs rapides, afin d'échantillonner à température cryogénique les faibles signaux sortant des circuits RSFQ. Ce banc de mesure comporte deux types d'interfaces opto-RSFQ, basées sur des matériaux semiconducteurs et supraconducteurs, respectivement. Des résultats de simulations hyperfréquences, ainsi que des mesures donnant une idée des potentialités des photocommutateurs étudiés sont présentés ici.

ABSTRACT : *Superconductive microwave rapid single-flux-quantum (RSFQ) digital circuits offer the possibility to digitally process signals in the frequency range of tens of GHz. An example of application to bring the advantages of this technology deals with digital SQUIDs, used for sensitive magnetometry with a broadband dynamics connected to a slew-rate in the GHz range. First recently obtained results of digital SQUID operation, based on Nb/Al-Al₂O₃/Nb shunted Josephson junctions, are presented in this article. In order to obtain the best performance of RSFQ circuits, and especially to push their speed at its limits, a precise diagnostic of such circuits is needed. We are developing a time-resolved diagnostic system based on sensitive photoconductive switches to sample the weak signals coming out of RSFQ circuits at cryogenic temperature. This system includes two different sorts of opto-RSFQ interfaces, based on superconducting and semiconducting materials, respectively. Some simulation results in the microwave range, along with measurements giving the potentialities of different photoswitches are presented.*

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1 - RSFQ ELECTRONICS AND DIGITAL SQUIDS

1.1 - INTRODUCTION

With their high intrinsic speed of several tens of GHz and very low dissipation, superconductive circuits open the way to high-speed digital electronics. In Rapid Single Flux Quantum (RSFQ) digital circuits based on shunted Josephson junctions [1], digital data are transmitted through picosecond voltage pulses with quantized area of 2.07 mV-ps, corresponding to one magnetic flux quantum. Hence, the pulse voltage is weak, of the order of 1 mV or less, it corresponds to pulses of about 2 ps duration. It is possible to use such a technology to develop digital Superconducting Quantum Interferometer Devices (SQUIDS). These devices can count quanta of magnetic flux under the form of picosecond voltage pulses. The pulses are processed by RSFQ transmission lines and flip-flop cells which transform the SFQ pulses in Non-Return-to-Zero (NRZ) signals, compatible with classical semiconductor electronics. The main advantage of digital SQUIDS, compared to their analog counterparts, is their theoretically infinite dynamics, which should permit to measure absolute magnetic fields with a very high accuracy. The other advantage is connected to their intrinsic very high slew-rate, of the order of $10^9 \Phi_0/\text{sec}$, corresponding to the digital clock rate of the SFQ circuits.

1.2 - PRINCIPLE OF OPERATION AND RESULTS

The principle of operation of the digital SQUID is presented in [2-3]. Figure 1 shows the circuit diagram of the SQUID.

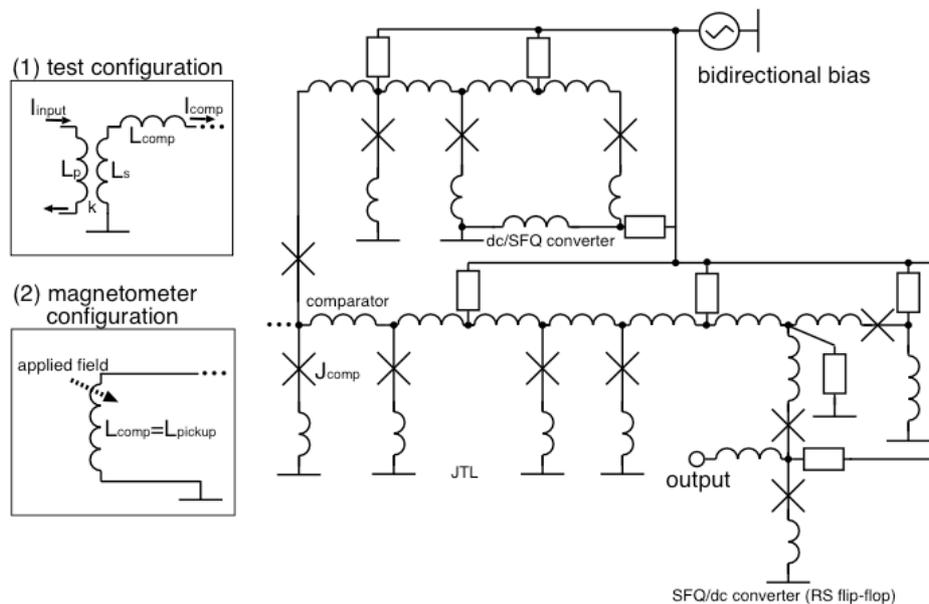


Figure 1 - Lumped circuit diagram of the digital SQUID device. Test configuration (1) is used to test the SFQ part of the SQUID device, while the magnetometer configuration (2) is the configuration to be used for regular operation.

A new interesting feature about such SQUIDS deals with its bidirectional bias which consists of a train of alternate negative and positive SFQ pulses, generated by the clocked dc/SFQ converter. It allows to "follow" the signal to measure with only one digital output. Indeed, the output signal consists of negative or positive SFQ pulses, depending respectively whether the signal to measure increases or decreases. The key part of this device is the ac SQUID defined by the comparator

junction J_{comp} in parallel with inductance L_{comp} (see figure 1). This junction switches, generating an SFQ pulse which is processed by the JTL and the SFQ/dc converter, in two cases: a) when the additional current produced by an increase of the magnetic field to detect adds up in the comparator junction with the current associated to a positive SFQ pulse: a positive SFQ pulse is getting out of the ac SQUID loop; b) when the current negative variation produced by a decrease of the magnetic field to detect adds up with the current associated to a negative SFQ pulse: a negative SFQ pulse is getting out of the ac SQUID loop. In other cases, for each negative or positive clock pulse coming on J_{comp} junction, there is no generated output pulse. A picture of such a digital SQUID is shown in Figure 2. It has been fabricated in a certified ISO9001 foundry at IPHT Jena [4]. The shunted Josephson junctions, based on a Nb/Al-Al₂O₃/Nb trilayer, have a current density of 1 kA/cm² and an $R_N I_C$ product of 256 μ V.

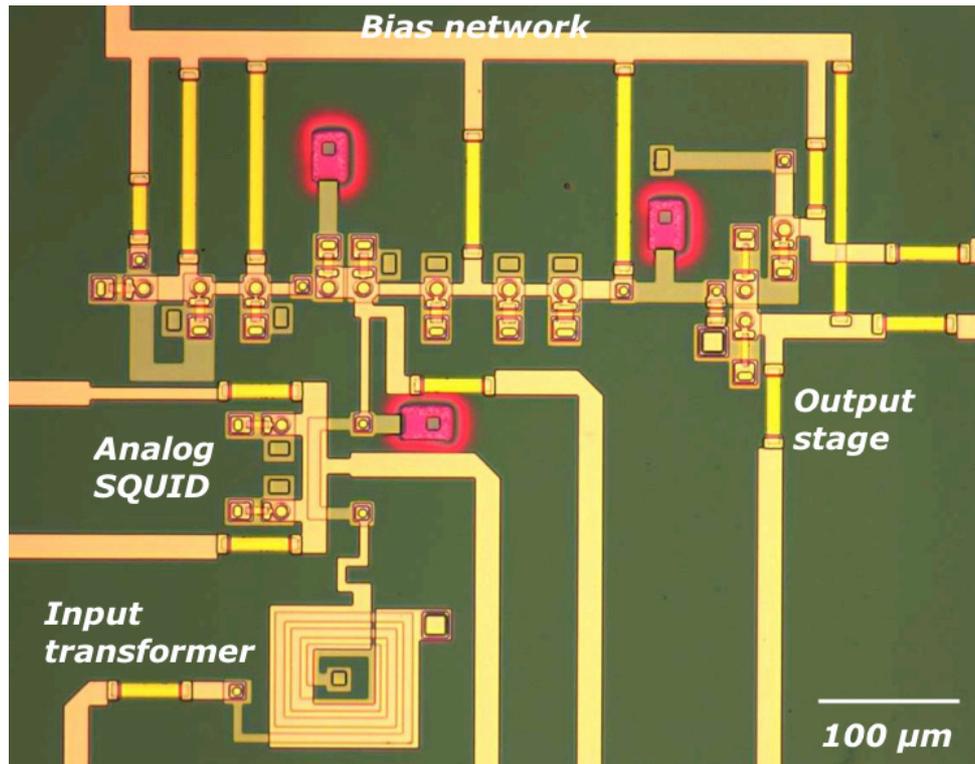


Figure 2 - Picture of the digital SQUID made of 11 shunted Nb/Al-Al₂O₃/Nb Josephson junctions. Junctions have a current density of 1 kA/cm². Fabrication has been performed at IPHT Jena in Germany. The analog SQUID on the left is not part of the overall circuit described in figure 1. It has been added there for additional functionalities, not described in this article.

Figure 3 shows the output signal measured with a low-frequency 1 kHz digital clock. The signal to be measured is a 5 Hz sinusoidal pattern.

1.3 - PROSPECTIVES

Such digital SQUIDs have been qualified at low frequencies and still need to be diagnosed at higher frequencies. Nevertheless, a very good agreement has been found between simulation results and measurements, in terms of technological parameters and bias margins for correct operation [3]. Moreover, the design based on bidirectional bias presents some clear interest in terms of high slew-rate, which is directly connected to the clock frequency. Also, the high intrinsic speed of the RSFQ processing circuits should allow the measurements with a high sensitivity of magnetic fields presenting relatively fast time variations. Besides, the low complexity of such SQUIDs opens the way to develop high-T_c counterparts that can work at liquid nitrogen temperature and present additional interest for magnetometry in space scientific applications.

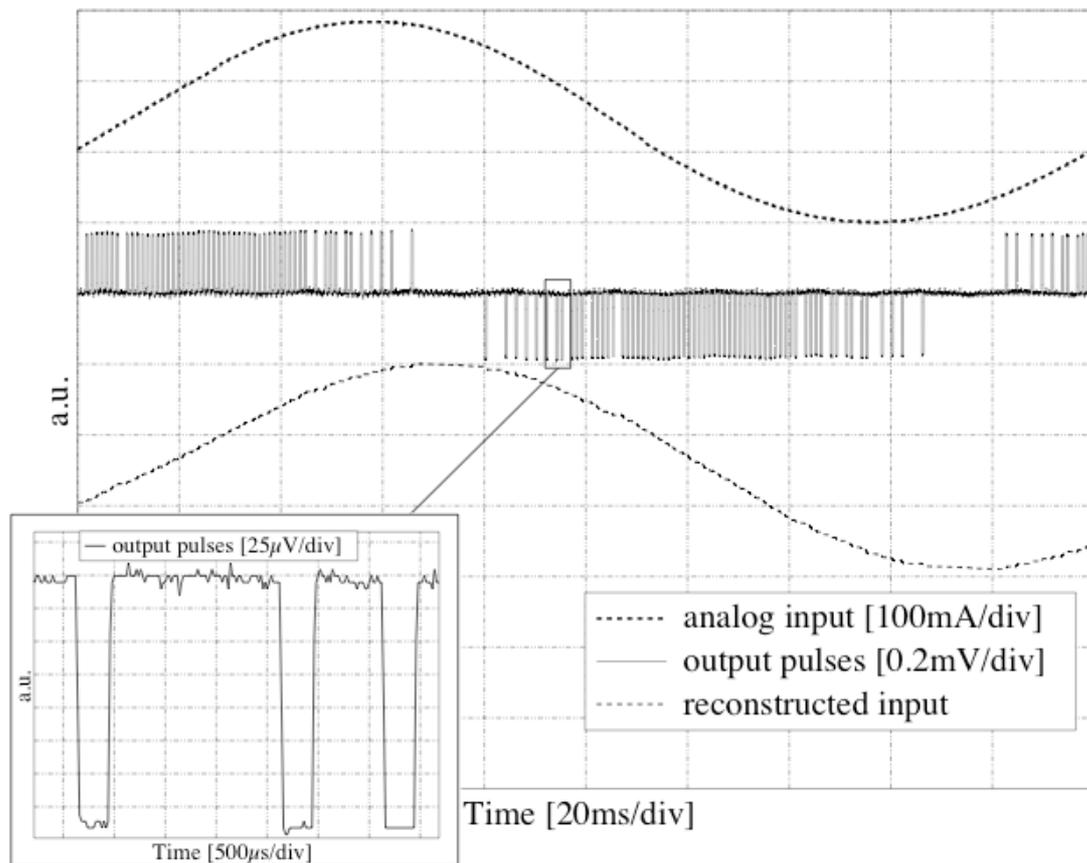


Figure 3 - Measurement of a sinusoidal input signal corresponding to a magnetic field variation (top curve). The central curve shows the measured signal at the digital SQUID output. The bottom curve shows the input signal reconstructed from the digital measurements.

2 - OPTO-RSFQ INTERFACES

2.1 - INTRODUCTION

Since RSFQ technology exhibits some unparallel performances for miscellaneous digital high-speed applications at several tens of GHz, it becomes valuable to be able to measure in a time-resolved manner the patterns of digital signals coming out of RSFQ circuits, for diagnosis and for studying in detail their behaviour close to their speed limits, of the orders of a few tens or hundreds of GHz, depending on the technology and parameters of the shunted Josephson junctions. To do so, ultrafast optoelectronics interfaces, triggered by a pulsed femtosecond Ti-Sa laser, are studied as readout of RSFQ signals [5], but also to feed signals in the RSFQ circuits.

2.2 - TEST SETUP

A block diagram of the general test setup is shown in figure 4. Measurements are based on the sampling of the signal to measure with ultrashort optical laser pulses having a duration of the order of 100 fs. This allows to reach a time-resolution of the order of 0.5 ps. The input interface has mainly, in a first step, a role of synchronisation and triggering between the laser pulses and the signals coming out of the RSFQ circuit under test. Different technologies are currently being investigated: 1°) superconducting photoswitches present the advantage of being compatible with the

RSFQ technological process. Also, in a next step, it is planned to use superconducting ultrafast nanodevices to replace the current interfaces, in order to open digital processing to the detection of weak optical signals in the visible and IR frequency ranges; 2°) semiconducting photoswitches offer the advantage to work at room-temperature and to generate powerful signals which can be used to characterize some parts of the test bench setup.

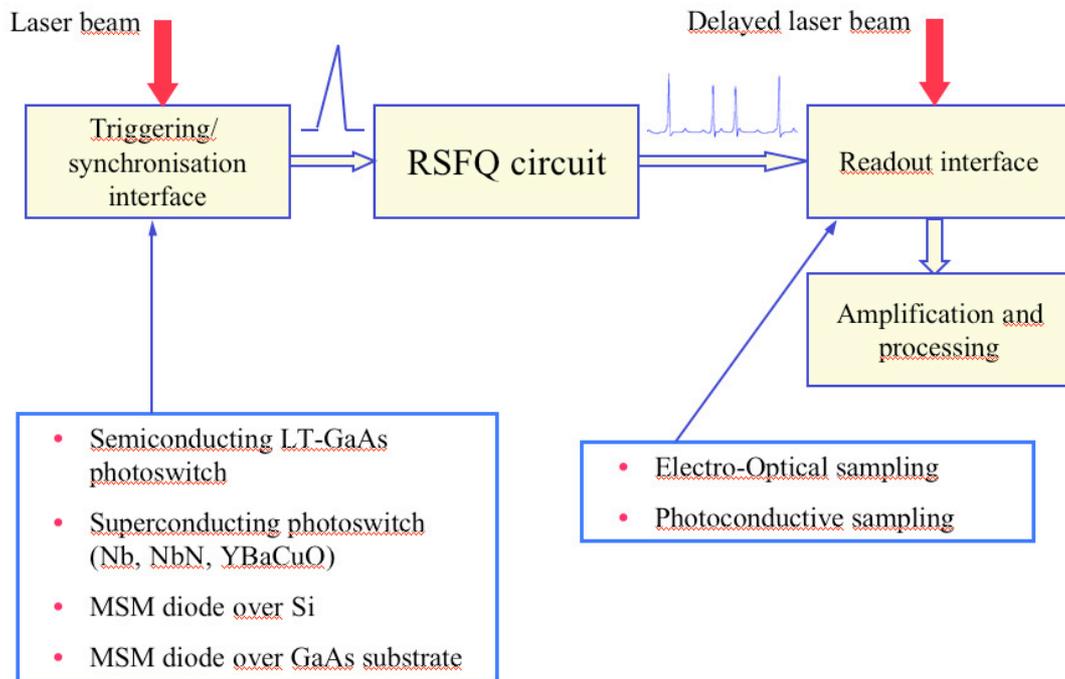


Figure 4 - Block diagram of the test setup used to diagnose RSFQ circuit waveforms with a high sensitivity (of the order of $100\mu\text{V}$) and high time resolution (lower than 0.5 ps). Different configurations are under development, depending on the circuit to be measured and needed performance. The laser beam is a pulsed femtosecond signal (around 100 fs) at a 800 nm wavelength, with a repetition rate close to 80 MHz.

The output opto-RSFQ interfaces make use of two different and complementary techniques: 1°) electro-optical sampling which has the advantage of being sensitive and has been used in the past to make the first direct measurements of RSFQ pulses [6]. It can use either a bulk crystal (this method is currently used in our laboratory at room-temperature but is not convenient for cryogenic measurements), or a thin film of electro-optic material deposited on the circuit to be measured; 2°) photoconductive sampling based on ultrafast low-temperature-grown GaAs photoswitches. This last method does not require additional steps in the RSFQ process to deposit a thin film of electro-optic material. It is also easier to handle for cryogenic measurements. As a disadvantage, measurements can only be made at certain locations (outputs) of the RSFQ circuits to test.

2.3 - DESIGN OF SUPERCONDUCTING PHOTOSWITCHES AS TRIGGERING INTERFACES

Some superconductor photoswitches have been designed and integrated with RSFQ circuits for processing. They have been fabricated at Jena ISO9001-certified IPHT foundry. A picture is shown in figure 5. So far, as shown in figure 6, DC measurements have been successfully performed to verify separately the correct operation of RSFQ circuits and superconducting photoswitches. Microwave measurements still remain to be done.

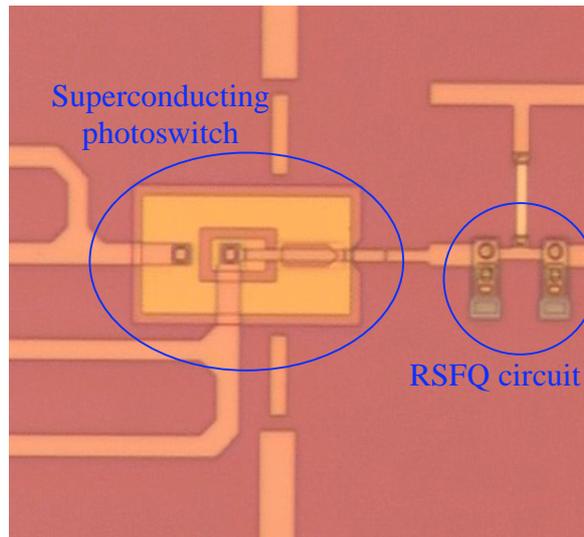


Figure 5 - Superconducting niobium bridge used as a triggering interface to feed an RSFQ circuit using 1 kA/cm^2 Nb/Al-Al₂O₃/Nb -based shunted Josephson junctions.

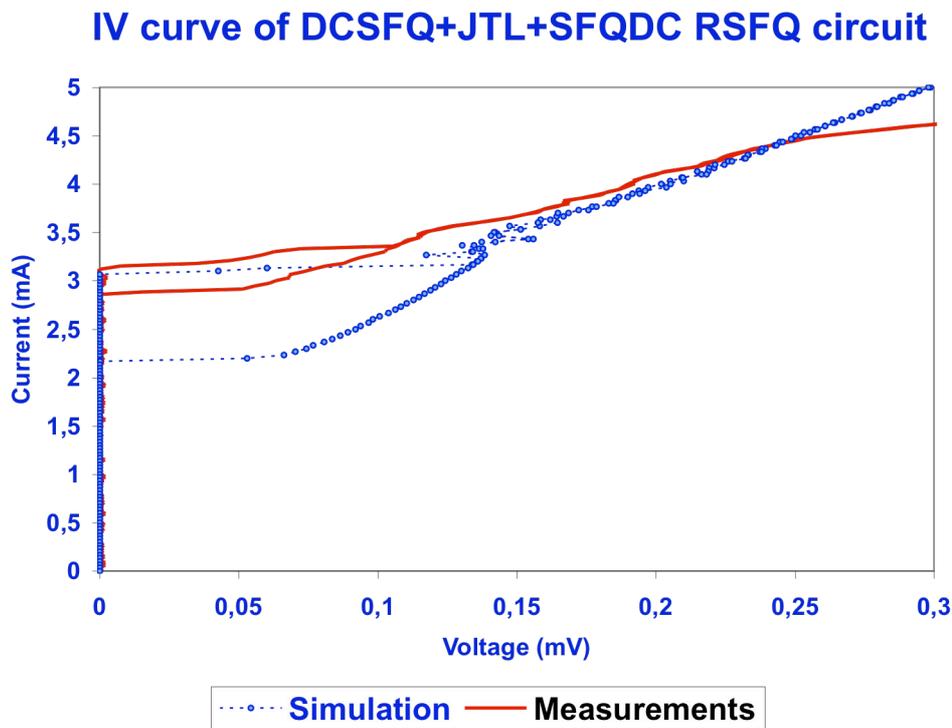


Figure 6 - Simulations and dc measurements of the RSFQ circuit part of the integrated device shown in figure 5.

2.4 - MICROWAVE SIMULATIONS OF LT-GaAs PHOTOSWITCHES AS READOUT INTERFACES

In this part, the attention has been focused on determining the microwave response of photodetectors and optimising the MSM photodetector sensitivity accordingly, to be suitable to detect weak pulsed signals. First the microwave model of the photoswitch has been described under (ON mode) and without (OFF mode) optical illumination. In a second step, the scattering parameters for different photodetector geometries have been determined. In a last step, the reflected and transmitted waves and associated voltages in the ON and OFF modes have been computed. Figure 7 shows the low-temperature-grown GaAs photoswitch geometries, along with the associated microwave model.

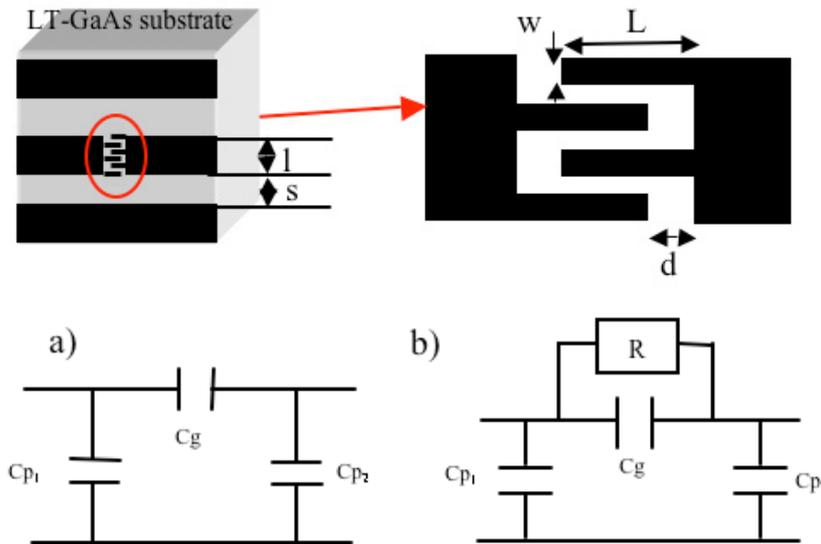


Figure 7 - On top: MSM photodetector configuration: gold electrodes are deposited on the LT-GaAs substrate. Parameters l , s , L and w can be adjusted. Bottom: Pi-model of MSM photodetector a) without illumination and, b) under illumination.

S-parameters of a photoswitch consisting of 4 interdigitated fingers have been calculated under and without illumination. This photoswitch is integrated in a coplanar line with a 50-ohm characteristic impedance. Figure 8 shows the S-parameters in the ON mode (photoswitch not illuminated). Figure 9 shows the incoming RSFQ signal applied to the photoswitch, along with the output signal. It shows that the photoswitch correctly transmits (and detects) the signal, under the assumption that it is illuminated during the whole duration of the RSFQ pulse.

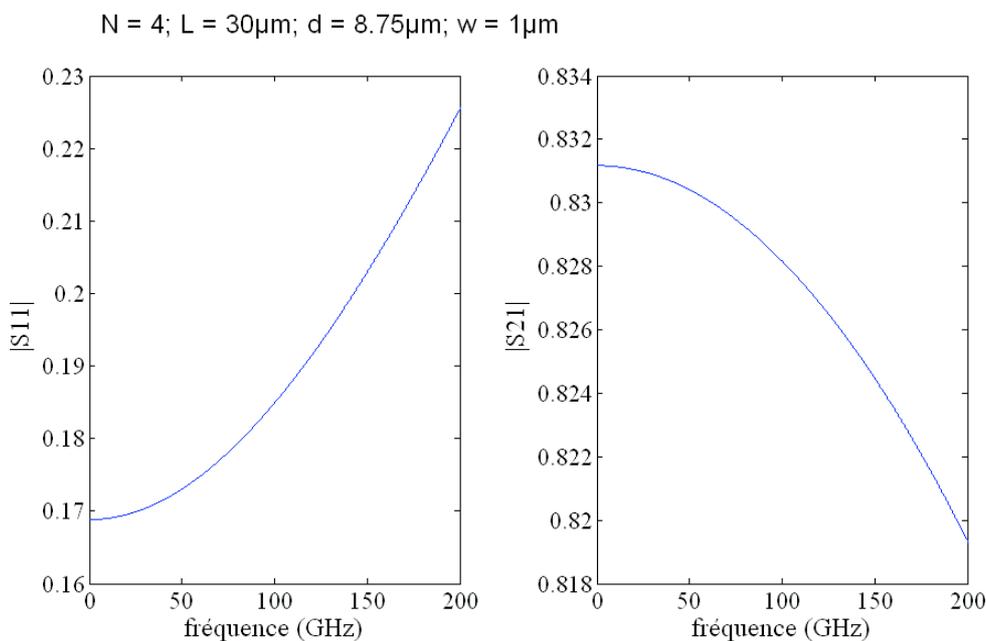


Figure 8 - Reflection and transmission scattering parameters of a LT-GaAs photoswitch consisting of 4 interdigitated fingers. The switch is illuminated. One can see that the transmission of the signal is quite good over a 200 GHz bandwidth.

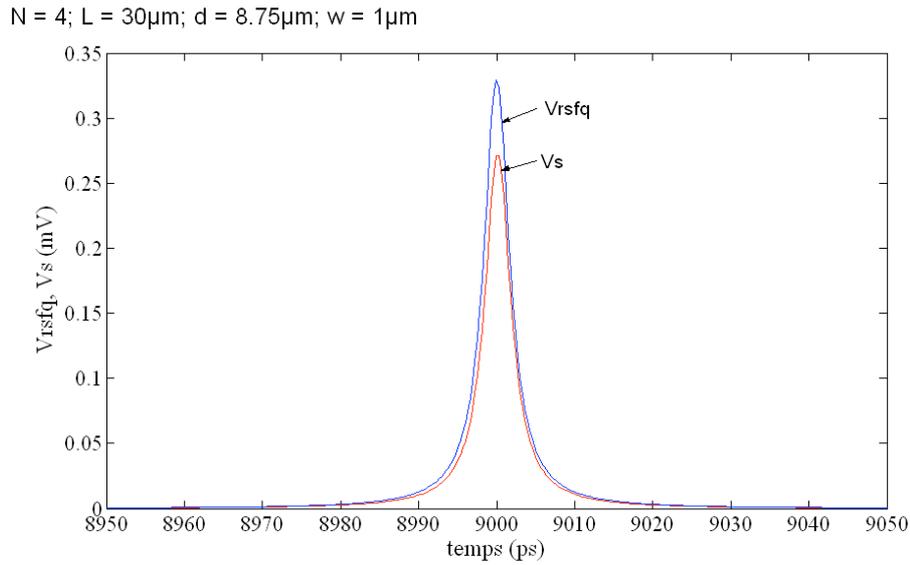


Figure 9 - Input (blue curve) and output (red curve) signal associated to the photoswitch under study in the ON mode. One can notice that RSFQ signal is correctly transmitted through the photoswitch.

At last, Figure 10 shows the same signals when the photoswitch is not illuminated. One can clearly see that the RSFQ pulse is mostly reflected at the input. This corresponds to a good contrast between the two extreme modes of operation (ON and OFF) of the photoswitch. As a consequence, one expects a good sensitivity for time-resolved measurements, still remaining to be done.

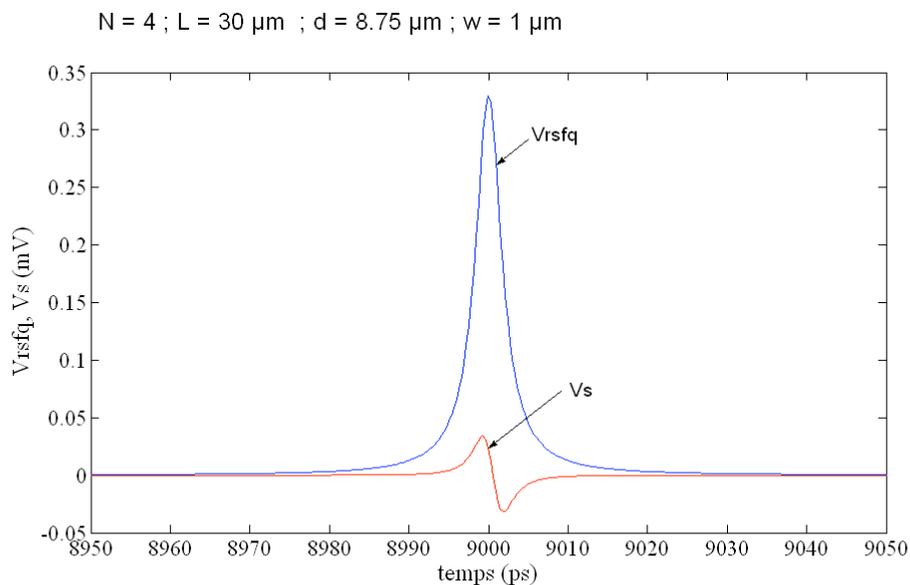


Figure 10 - Input (blue curve) and output (red curve) signal associated to the photoswitch under study in the OFF mode. One can notice that RSFQ signal is mostly reflected through the photoswitch, allowing a good contrast with the case under illumination.

3 - CONCLUSION

The first successful measurements of RSFQ circuits for digital SQUIDs have been performed, along with preliminary DC measurements of several types of opto-RSFQ interfaces. These interfaces are needed to trigger RSFQ pulses and measure them in a time-resolved manner. Some microwave simulations have also been done to optimize the design of the opto-RSFQ detection interfaces in a 200 GHz bandwidth. All these technologies present some interest for very high-speed processing of ultrafast signals, that can be fed from and transmitted to the "room-temperature world", and sensitive detection of magnetic and electro-magnetic signals. To that regards, space applications have always been a powerful engine to pull disruptive technologies. Connected to that particular point, we foresee different fields for which such technologies are so far unbyassable.

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