Development of superconductive parallel junction arrays for Submm-wave local oscillator applications

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***Abstract*—In order to develop Submillimiter-wave fully Integrated Superconducting Receivers (SIRs) based on parallel small SIS junction arrays (multijunction) operating as local oscillator, we investigate their performance through measurement and simulation. Multijunction may be an interesting alternative to LJJ because it allows wide LO tunability, wide impedance matching bandwidths and increase design flexibility and control of technological parameters.**

I. INTRODUCTION

Because of its low size, mass and power consumption the complete compact ultra-sensitive submm receiver system is very attractive for multi-spacecraft applications using interferometry technique for post-Herschel submm-wave spaceborne instruments or for distant monitoring of the Earth atmosphere from space. They also open the way to on-chip integration of heterodyne receivers with the digital processing unit. Khoshelets & al [1-2] developed an efficient SIR system using a Long Josephson Junction (LLJ) operated in the Flux-Flow Oscillator (FFO) regime. In this study, we propose to use SIS parallel junction arrays as local oscillators instead of a LJJ. Indeed, the latter has an impedance often < 1Ω while the multijunction can present several tens of ohms making it suitable to deliver higher output power with larger bandwidth. Moreover, non-uniform arrays can be designed to provide very wide coupling bandwidths, a property which has already been employed to optimize multijunction quasiparticle mixers [3]. The resonance shapes observed in multijunction I-V curve and their behavior versus external applied magnetic field remind strongly Zero Field Steps (ZFS) and Fiske Steps (FS) usually seen in LLJ suggesting travelling fluxons [4]. A fundamental issue to use this kind of circuit as local oscillator is their ability to produce usable submillimeter signals. In this paper, we report the first measurement results of multijunction-generated radiation in the submm-wave range by using the heterodyne technique. We will also briefly present the modelling work of this kind of circuits.

II. CIRCUITS

The non-uniform parallel junction arrays investigated here were initially designed for broadband submillimeter-wave heterodyne quasiparticle SIS mixers [3] (see figure 1). The circuits are made up of 5 identical junctions of l_jxw_j=1x1 µm² embedded in superconductive Nb/SiO/Nb stripline of width w=5 µm and length l=80 µm. The spacings between junctions, allowing to tune out the tunnel barrier capacitance at desired frequencies, were optimized for best RF coupling in 480-640 GHz frequency range, and are summarized in the following table:

TABLE XI
DIMENSIONS OF THE SIS JUNCTION ARRAYS (µM)

N x junction	l_1	l_2	l_3	l_4
5	20	42	12	6

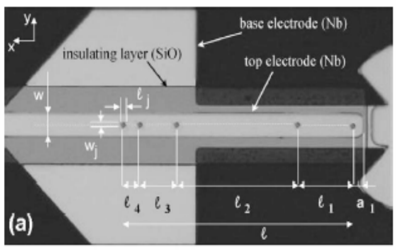

Fig. 1 Photograph of multijunction circuit. The 1 µm² junctions are made out of Nb/Al-AlO$_x$/Nb.

The multijunction is integrated with a bowtie antenna and RF choke filters, on a 50 µm thickness quartz substrate, mounted across a 100×400 µm half-height rectangular waveguide followed by a corrugated horn. In this particular configuration, the source impedance at the bowtie is real (~50 Ω) over 480-640 GHz [5] [7], allowing an optimized detection, but potentially also emission, of submillimeter-wave signals in that range. The multijunction circuits were made at Paris Observatory facility using standard Selective Niobium Etching Process [6] [12].

III. EXPERIMENT

The aim is to study the radiation generated by a 5-junction array circuit with current density of ~ 10 kA/cm², in a Josephson resonant mode, by using the heterodyne technique as shown in figure 2. Two identical mixers blocks optimized for the 480-640 GHz band were employed, each in its own liquid helium cryostat, respectively hosting the multijunction used as a submm-wave source, and a twin-junction fabricated by the KOSMA group as the SIS mixer [13]. The mixer output signal at intermediate frequency (IF) is fed through an isolator and a cryogenic HEMT preamplifier at 4-8 GHz, then measured using a power-meter and spectrum analyzer. The Josephson currents are entirely suppressed in the twin-junction and must be finely controlled in the multijunction by a magnetic field generated by NbTi superconductive wire coiled around a cryoperm core. On its quasioptical path, the RF signals from the multijunction must pass through a 13-µm mylar beam splitter, and twice across a 25-µm mylar window at room temperature, a 250-µm Zitex infrared filter at 77K, and a pair of cold elliptical mirrors at 4.2K. A 385-550 GHz solid-state local oscillator (LO), combining a Gunn source and a Schottky frequency-multiplier, was used to pump the SIS mixer's twin-junction.

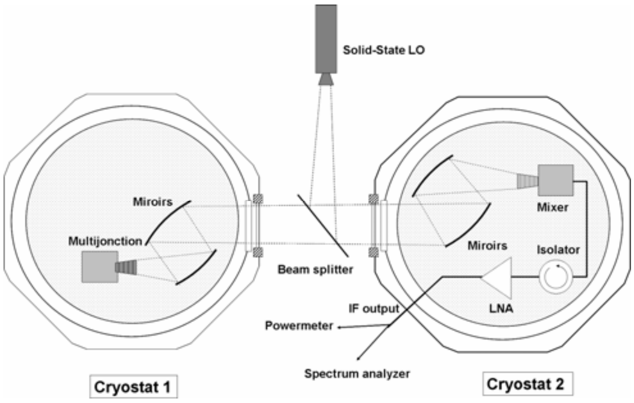

Fig. 2 Schematic diagram of the setup bench to characterize resonances observed in multijunction IV curve. Cryostat 1 and cryostat 2 contain respectively multijunction operating as LO and twin-junction as mixer.

A. Preliminary measurements

Figure 3 shows typical resonances appearing in the I-V curve of the multijunction. Three resonances emerged at V_{Res} ~ 0.5 mV, 0.84 mV and 1.02 mV for different values of the magnetic field. The corresponding fundamental frequencies ($f_{Res}= 2eV_{Res} / h$) are ~ 242, 406.5 and 493.6 GHz.

To determine which Josephson resonances in the multijunction, i.e which frequencies, could be observed with our setup, we measured the RF coupling bandwidths of both the emitter (multijunction) and the detector (twin-junction), by Fourier Transform Spectrometry technique (FTS), as shown in figure 4.

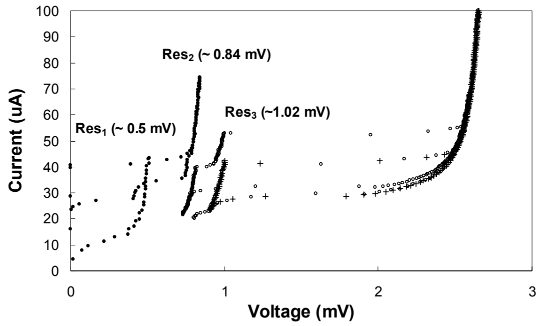

Fig. 3 I-V curve of multijunction. Resonances obtained for different values of applied magnetic field.

Note that in this characterization we operate the multijunction as a detector, and assume the equation between input and output coupling responses. We find a low-frequency cutoff at 400 GHz for the twin-junction and at 435 GHz for the multijunction. We conclude that the first two resonances at 242 and 406 GHz are out-of-band and that consequently their associated fundamental Josephson frequencies cannot be detected. The heterodyne measurement was therefore carried out mainly with the third resonance (f_{Res3} = 493.6 GHz).

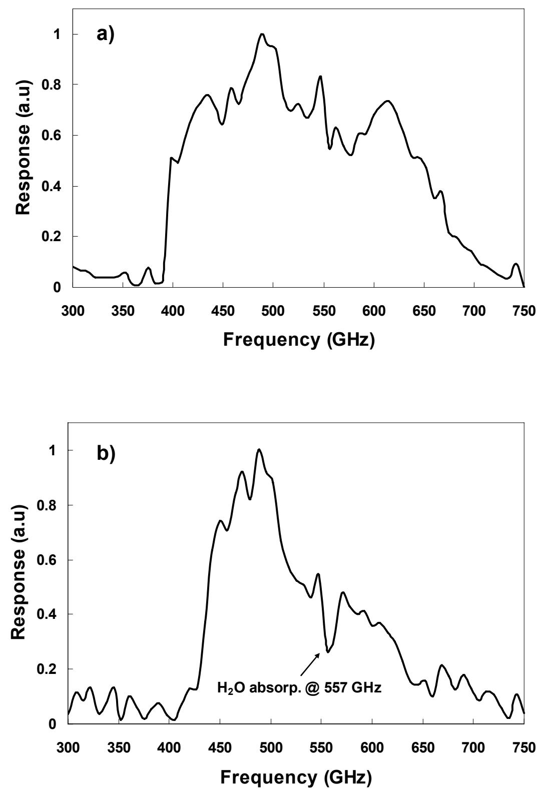

Fig. 4 Instantaneous frequency response measured by Fourier Transform Spectroscopy (FTS) of a) the twin-junction (mixer) and b) the multijunction circuit (emitter).

Figure 5 shows the I-V curve of the SIS mixer pumped by a LO at 494 GHz and the corresponding output IF power, integrated over the 4 GHz bandwidth, obtained at two bias voltages, respectively in the presence (ON) and in the absence (OFF) of the resonance. Absence of resonance means that the multijunction is biased either at V=0, V_{res}< V< V_{gap} or V> V_{gap} for each measurement. Those three bias voltages give the same IF output response at the mixer. However, when the multijunction is biased at V_{Res3} = 1.02 ± 0.01 mV, the mixer IF power increases over the quasi-particle step as is shown in figure 5. From the curve, the mixer twin-junction is expected to be most sensitive in the 1.6-2.3 mV bias voltage range.

B. Heterodyne measurement

In the ON position the multijunction was biased on the resonance at 1.02 ± 0.01 mV (493 ± 4.84 GHz), whereas the solid-state LO was tuned at 495 GHz. The twin-junction mixer is biased at 1.9 mV (for maximum sensitivity). The IF power spectrum measured across the 4-8 GHz frequency range is shown in figure 6. Several reproducible spectral structures probably corresponding to the beat signal were observed, *only* in the presence of the resonance (ON).

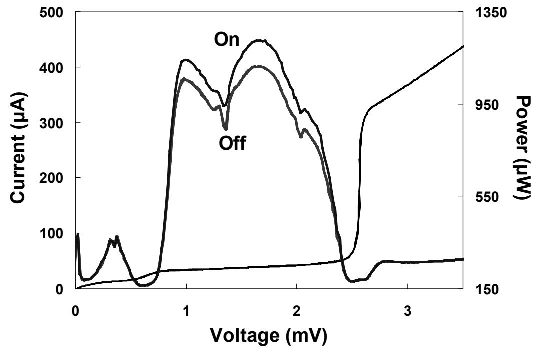

Fig. 5 Twin-junction mixer Pumped IV curve at 495 GHz and the output power FI obtained in the presence (On) and absence (Off) of the resonance Res_3.

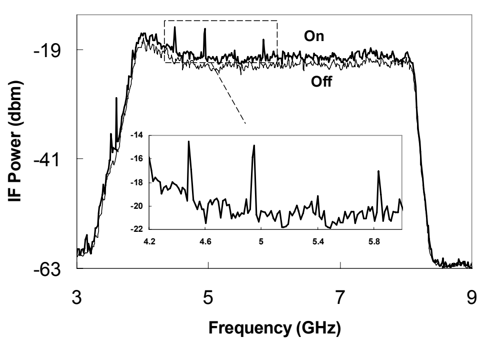

Fig. 6 IF power spectrum measured across the IF band of 4-8 GHz.

The measured linewidth is $\Delta f \approx 50$ MHz for all spectral lines. Nevertheless, we have not yet clearly identified the source of noise in these structures even though we strongly suspect the instability due to the multijunction bias voltage, since the Josephson resonance was not phase-locked. More measurements with very stable bias are needed to confirm these results.

IV. SIMULATIONS

To understand the complex Josephson behaviour of non-evenly distributed, parallel junctions, we developed a new model based on sine-Gordon equation, suitable for any small junction arrays embedded in superconductive stripline. The mean difficulty to model this kind of circuits lies in the inhomogeneous distribution of the junctions, unlike the cases treated by [8-9]. In our case, the junctions are considered as a sum of Dirac distribution δ [10-11] within the stripline. This original approach allowed us to analyze finely the Josephson static regime of any non-uniform arrays, which is also a non-uniform SQUID array or grating (SQUIG). Figure 7 shows the experimental and theoretical curves of critical current I_{max} at V=0 versus an externally applied magnetic field H_{ext}. The excellent agreement between simulations and measurements confirms the validity of this model. The shape of the curves indicates that the static magnetic field penetrates in the multijunction as flux quanta. Further details are given by [12].

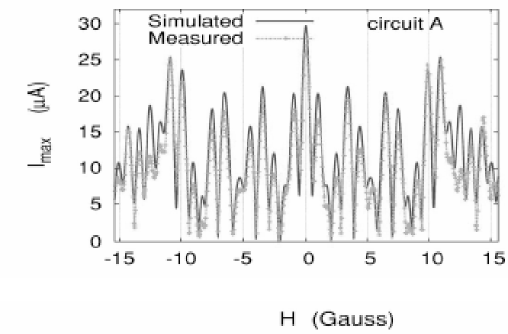

Fig. 7 Measured and simulated $I_{max}(H_{ext})$ at V=0 of our multijunction circuit.

This static model constitutes the first step toward the global electrodynamic model to describe the exact operating mechanism and to determine the performance when the multijunction operates as a source in order to design new circuits at desired frequencies. Preliminary simulations on similar arrays using this model indicate that depending on geometry, current density, SIS junctions and superconductive stripline electrodes intrinsic parameters, solitons (fluxons), can be generated in the multijunction circuit in Flux Flow Oscillator (FFO) regime [10].

CONCLUSIONS

We investigate a non-uniform arrays of small Nb/AlO_x/Nb junctions with ~ 10 kA/cm² of current density operating as submm signals generator. Using the heterodyne technique and a second SIS junction circuit used as a mixer, we made preliminary measurements indicating with no ambiguity that resonances can generate submm-wave signals. However, to confirm these results, more measurements are needed. Based on a sine-Gordon equation, an accurate model for the non-uniform junction arrays has been developed, giving excellent fits to experiments in the static regime, and on the verge of explaining the fluxon-based resonances observed in the dynamic regime.

ACKNOWLEDGMENT

The authors would like to thanks G. Beaudin and J-M. Lamarre for their continued support. The circuits and the mixer blocks were optimized by Y. Delorme and F. Dauplay. The parallel junction arrays is sponsored by the Centre National d'Etudes Spatiales (CNES) and the Institut National des Sciences de l'Univers (INSU).

REFERENCES

[1] V. Koshelets and J. Mygind, "Flux Flow Oscillators for Superconducting Integrated Submm Wave Receivers," *Studies of High Temperature Superconductors 39 (2001)*, 213–244,. Ed. A.V. Narlikar, NOVA Science Publishers, New York.

[2] V.P. Koshelets, S.V. Shitov, A.B. Ermakov, O.V. Koryukin, L.V. Filippenko, A. V. Khudchenko, M. Yu. Torgashin,P. Yagoubov, R. Hoogeveen, O.M. Pylypenko, "Superconducting Integrated Receiver for TELIS", *Report 2ET06 at the Applied Superconductivity Conference ASC'2004*, USA, October 2004.

[3] M. Salez, Y. delorme, M.-H. Chung, F. Dauplay, "Simulated Performance of multi-junction parallel array SIS mixers for ultra broadland submillimeter-wave applications ", *Proc. 11th International Symposium on Space Terahertz Technology*, Ann Arbor, MI, May 1-3, 2000.

[4] M. Salez, F. Boussaha, Y. Delorme, F. Dauplay, B. Lecomte "Observation of terahertz fluxons in superconducting junction non-uniform arrays" (to be published).

[5] F. Boussaha, M. Salez, Y. Delorme, B. Lecomte, F. Dauplay, A. Feret, J. M. Kreig, J. Spatazza, C. Chaumont, M. Chaubet. "Broadband submillimeter receivers using same mechanical block" *Proc. 16th International Symposium on Space Terahertz Technology*, Goteborg, 2005.

[6] Boussaha F.; Salez M.; Delorme Y.; Féret A.; Lecomte B.; Westerberg K.; Chaubet M. "Submillimeter mixers based on superconductive parallel junction arrays" SPIE; *1st Int.Symp. Microtechnologies for the New Millennium 2003*; Maspalomas; Canary Islands; Spain ; 19-20 mai 2003.

[7] M. Salez, Y. Delorme, I. Peron, B. Lecomte, F. Dauplay, F. Boussaha, J. Spatazza, A. Feret, J. M. Krieg and K. -F. Schuster, "A 30% bandwidth tunerless SIS mixer of quantum-limited sensitivity for Herschel/HIFI band 1" *Proc. of the SPIE conference on Telescopes and Astronomical Instrumentation, Hawaii,* Vol. 4855, pp. 402-404, 2002.

[8] A. Ustinov, M. Cirillo, B. H. Larsen, V. A. Oboznov, P. Carelli, and G. Rotoli, Phys. Rev. B 51, 3081 1995.

[9] J. H. Miller, G. H. Gunaratne, J. Huang, and T. D. Golding Appl. Phys. Rev. Lett. 59, 3330 1991.

[10] L. Loukitch, Ph. D. thesis, Institut National des sciences applisquées, Rouen, France.

[11] J. G. Caputo and L. Loukitch, SIAM J. Appl. Math 67 810 2007

[12] M. Salez, F. Boussaha, L. Loukitch, J-G. Caputo "Interference filter properties of non-uniform Josephson junction arrays" *J. Appl. Phys*, Octobre 2007.

[13] KOSMA : Physics Institute of the University Cologne – Germany