A SUPERCONDUCTIVE PARALLEL JUNCTION ARRAY MIXER FOR VERY WIDE BAND HETERODYNE SUBMILLIMETER-WAVE SPECTROMETRY

F. Boussaha, Y. Delorme, M. Salez, M.H. Chung[2], F. Dauplay, B. Lecomte, J.-G. Caputo[3], V. Thevenet[1]

DEMIRM, Observatoire de Paris, 77 avenue Denfert-Rochereau, 75014 PARIS-France
[1]DASGAL, Observatoire de Paris, 77 avenue Denfert-Rochereau, 75014 PARIS-France
[2]Taeduk Radio Astronomy Observatory San 36-1, Whaam-dong, Yusong-gu Taejon 305-348, South Korea
[3]INSA-LMI-Rouen, Place Emile blondel B.P 08, 76131 Mont Saint Aignan Cedex, France

Abstract

The study of submillimeter-wave radiation in astronomy and atmospheric sciences requires increasingly performant receivers, in particular allowing extended spectral line surveys. To this end, we are developing a quantum-noise limited heterodyne receiver based on SIS junction parallel arrays with broad (larger than 30%) fixed tuned bandwidth. Simulations show that networks of junctions (N>2) of micronic size, embedded in a superconducting microstrip line, can provide a bandwidth in excess of the ultimate limit for a single or even twin-junction device. These circuits can be viewed as passband filters which have been optimized by varying the spacings between junctions. The results of simulations are confirmed by the first heterodyne measurements in the 480-650GHz bandwidth, and by preliminary FTS measurements beyond. The influence of the Josephson effect in these devices is also investigated.

I - Introduction

In the mid 90s, Shi et al [1,2] of Nobeyama radio-observatory presented a new mixer design based on the association of several parallel SIS junctions in order to increase the bandwidth. They succeeded with five then ten junction arrays, in which junctions are equidistant in superconductive microstrip line. In 1998, we simulated this type of circuits and identical results were obtained. Like Shi et al, we have noted widening bandwith but accompanied by ripples especially at high frequency. Extending the principle, we simulated a new structure with the same number of junctions but with a nonuniform distribution (fig. 1.). Nonuniform arrays make it possible to further improve both frequency response and sensitivity [3]. Since, Takeda et al [4] are also developping inhomogeneous distributed junction array.

On the basis of these simulations, we compared heterodyne performance of conventional single-junction and multijunction array coming from the same wafer which has about 4.5 kA/cm² current density. The single-junction is matched by one short inductive section of microstrip followed by Tchebytchev transformer. In the multijunction approch, the mixer, composed by N junctions connected in parallel within a superconductive microstrip, is optimized like passeband filter. In this case, the SIS junctions are represented by their intrinsic parameters (e.g., capacitance, normal resistance) and the different length microstrip sections by the induced inductances [3].

The devices use the same RF filter and the same antenna. Excellent I-V characteristics of 2 and 5 parallel junction (1 or 2 μm²) arrays were obtained, with current densities : 4, 6 and 13 kA/cm². The receiver performance for some of these devices has been measered over the frequency range 480 GHz to 640 GHz, because of the availability of measurement equipments.

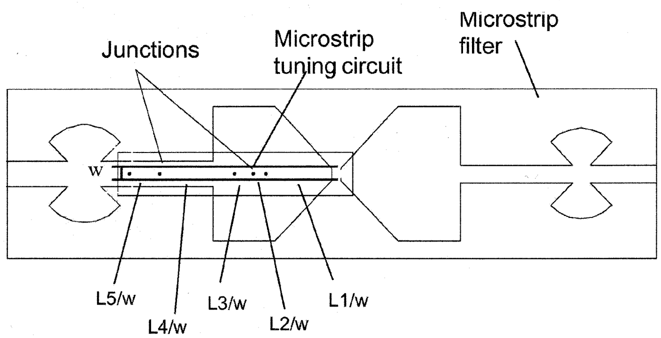

Fig. 1. Mask of non uniform distributed five junction array : L5/w=3.6, L4/w=8, L3/w=2, L2/w=1, L1/w=9.9 (w=5μm)

II-Parallel junction array fabrication process

Our process fabrication is based on "Selective Niobium Etching Process" (SNEP) [5,6]. A trilayer of Nb/Al-Al_2O_3/Nb film was first sputtered, using a DC magneton, on a 200 micrometer thick quartz quartz substrate. The first 200 nm thick Nb layer was deposited with a power of 600 W, at a rate of 2.2 nm/s ; In order to get a homogeneous layer of Al, it is necessary to let cool the substrate (1 hour in our case) before its deposit. The 10 nm thick Al layer was deposited with power of 100 W, at a rate of 0.5 nm/s. The tunnel barrier was built by thermal oxidation of the Al layer, using pure O_2 at pressure of 10^{-2} mbar during 30 mn. To prevent any damage of Al layer, The deposition of the 100 nm top Nb layer was performed at a reduced power : 300 W, 1nm/s. A positive S1828 photoresist was used to define the RF filters and DC lines. The Nb/Al-Al_2O_3/Nb film in excess was etched away with a reactive ion etching process : the SF_6 flow was 60 sccm with 60 W of RF power. The next step consists in the definition of junctions area. The photolithography process was accurately calibrated to get simultaneously several small junctions with same area, in confined space. The upper layer of Nb is etched with 20 sccm of SF_6 and 6 sccm of O_2 at a pressure of 3.10^{-2} mbar and a power of 60 W ; the etching rate was around 3 nm/s. To prevent short-circuits between the base electrode and the Nb contacts, the resist is etched by high pressure O_2 plasma at a flow of 80 sccm and 80 W of RF power. A 250 nm of SiO is evaporated to isolate the junctions area and the excess is removed by lift-off. After cleaning with an Ar RF plasma, the junctions are connected by a 400 nm film sputtered in four time at a rate of 1 nm/s and 300 W and patterned by lift-off.. Finally, a 200 nm gold film was evaporated follow-up the lift-off in order to obtain the electrical contact. The yield was about 80 %.

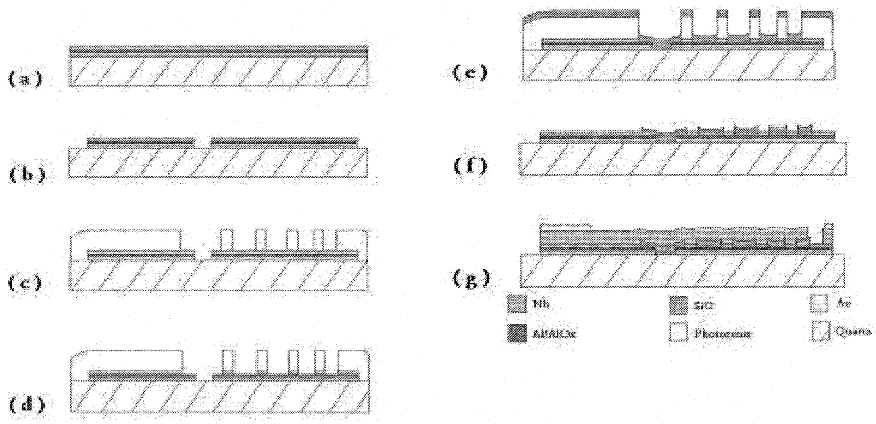

Fig.-2. Parallel junction array process fabrication (a) Sputtering Nb/ Al-Al_2O_3/Nb deposition (b) Trilayer etching : definition of RF filter (c) Definition of multijunctions (d) Upper electrode etching (e) Self-aligned deposition of SiO insulating layer (f) Appearance of multijunctions (g) Nb interconnection layer and gold contact pads

III-Results

All the devices were measured in the same mixer waveguide block at 4.2 K. DC and IF connections to the devices are made at one end through a SMA connector and at the other end via a ground return to the mixer block with gold wire. No IF matching circuit was used. The IF signal is amplified by a 4-8GHz cryogenic HEMT preamplifier. The double sideband (DSB) receiver noise temperature is obtained by measurement of the Y factor method.

The five parallel 1μm^2 junction array and 2μm^2 single-junction normal resistance were respectivily around 12 Ω and 30 Ω. We assumed that junction specific capacitance is 80 fF/μm^2. The IV characteristic pumped by 650 GHz LO radiation of multijunction array is shown in figure 3. A receiver noise temperature of 176 K DSB was meseared at this frequency. Over the frequency range 480 GHz to 640 GHz, the noise temperature of both single-junction and 5 junction array is shown in figure 4. With the multijonctions, we measured around 400 K noise temperature almost in all bandwidth, unlike single-junction response frequency which quickly degrades from 560 GHz, to reach average 1300K over the rest of the bandwith. Elsewhere, the noise temperature remains high because of the poorly matched IF output on one hand, and because of the large contributions of Rf quasi-optics noises (bad mixer block) on the other hand. The equivalent noise temperature of IF-chain was about 25 K. Using the "intersecting lines" method [8], we estimated the equivalent noise temperature of Rf contributions at all frequencies. For unkown reasons, we found very high values : average 250 K. The worst noise temperature was at 605 GHz LO. This same frequency corresponds to a dip in the FTS (fig. 5.) for jc=13 kA/cm^2 (heterodyne measurements not yet done). Possibly, this resonance is due to the mixer block and device independent.

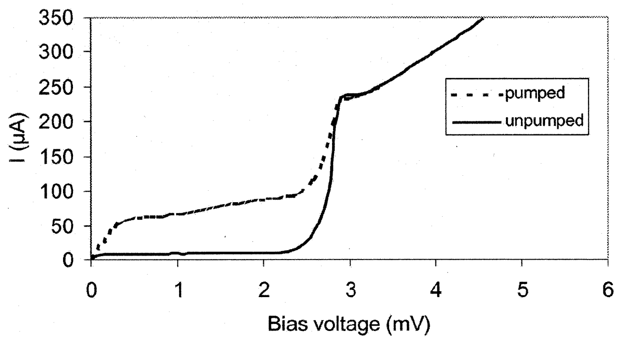

Fig. 3. Unpumped and pumped IV curves of 5 parallel junction arrays (4,5 kA/cm²) by applied microwave radiation at 650 GHz

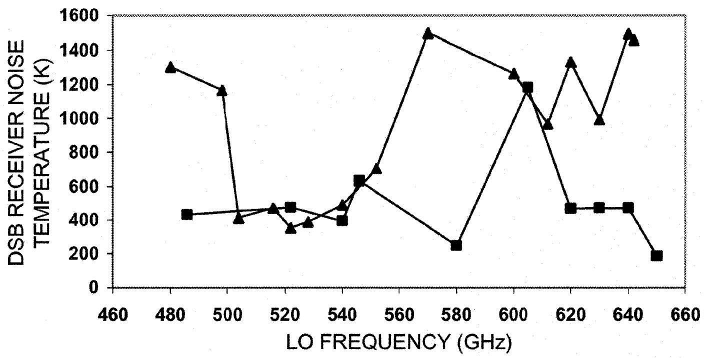

Fig. 4. Receiver noise temperature versus LO freqency for single junction (triangles) and for 5 parallel junction array (squares)

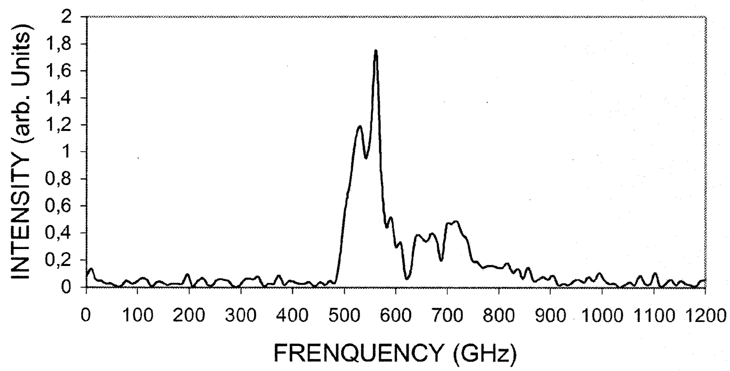

Fig. 5. FTS response of a 5 parallel junction array with jc=13 kA/cm².

Josephson effect

The figure 5 shows the evolution of critical current I_{max} at zero bias-voltage vesus applied magnetic field. The Josephson current cannot be supressed entirely and there remains a residual current about 2 to 5μA except for one value of the current in the coils (6.45mA).

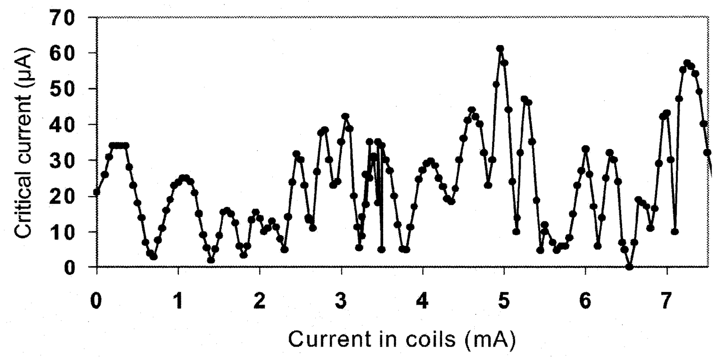

Fig. 5. Evolution of critical Josephson current versus magnetic field in multijunction array

In the 5 junction array, using a constant voltage bias, several steps and negative resistances have been observed in both the unpumped and pumped IV curves, as shown by figures 6-a and 6-b (for 542 GHz LO), enhanced or reduced by the magnetic field.

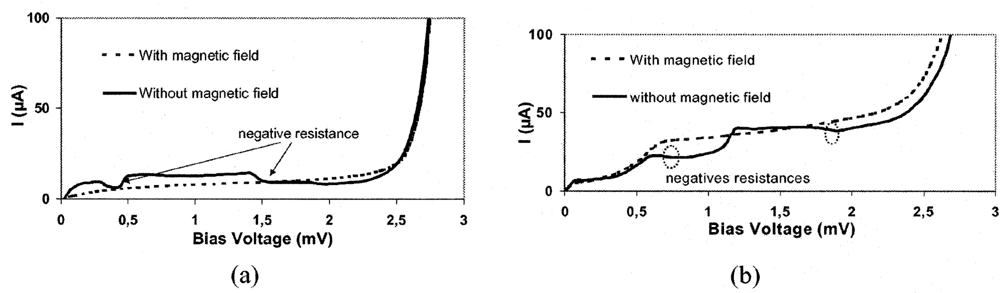

Fig. 6. Multijunction array : negatives resistances in both (a) unpumped and (b) pumped IV by applied microwave radiation at 542 GHz LO

Although similar steps induced by Josephson pair tunneling, with or without LO, are a common feature of SIS mixers, those steps in 5-junction arrays have a qualitatively different look and behaviour. Their oddity is particularly striking when no LO nor any magnetic field is applied, as they strongly remind of the "zero field steps" (ZFS) seen in long Josephson junctions in which solitons propagate. Indeed, we observed three steps at 0.5, 1 and 1.35mV bias (fig. 8.).

If the multijunction structure, which is electrically equivalent to a long junction, can increase the mixer bandwidth, it also supports static and dynamic Josephson current modes different and more complex than the single junction. This was a theoretical expectation of ours, and more will be presented on this in another aticle. It potentially has consequences on mixer sensitivity. In the presence of LO, the steps are more difficult to suppress than in single-junction circuits.

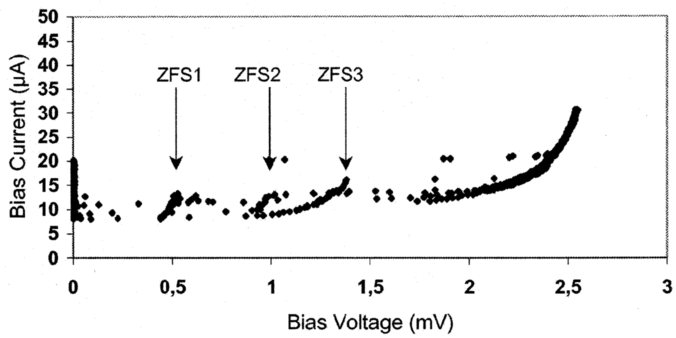

Fig. 8. ZFD apparition in multijunction array

The figure 9 shows the noise temperature measured with 5 junction array versus consumed OL power at 650 GHz. We note that there is an optimal power around 25-40 nW, but also that is another local minimum at higher power can exist. Thus, the LO power is not necessarily proportional to number of junctions. This result is important and was predicted by simulations based on Tucker theory [3,7]. In figure 10, each curve represents one junction. We note that a limited number of junctions provide the mixing while the others play a passive role.

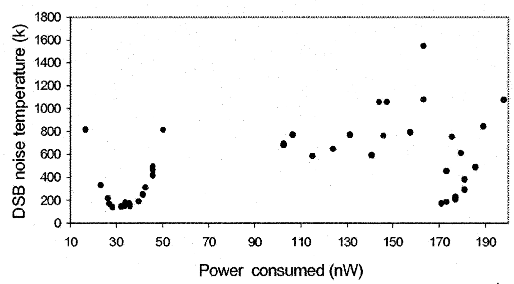

Fig. 9. 650 GHz LO power consumed by the 5 junction array

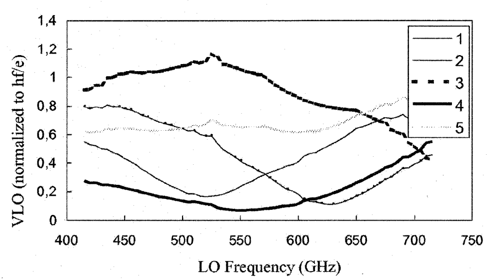

Fig. 10. Simulation of LO power consumed for each junction

IV-Conclusion

We succeeded to obtain high quality 5 junction array at medium and high current density (4.5,6 and 13 kA/cm²) in spite of the difficulty of fabricating arrays of rigorously identical junctions. The comparative heterodyne measurements of single junctions and distributed junction arrays confirm the simulations about widened bandwidth and average power necessary to drive the mixer. The Josephson current manifestation behavior is certainly more significant but does not seem to influence the SIS mixing operation.

Acknowledgment

The authors would like to thanks J.M. Krieg, G. Beaudin and Y. Viala for their continued support. We also thank B. Jackson from SRON for FTS measurement. The multijunction array development is funded by the french space agency (CNES, contract # 714/cnes/99/7759/00) and the Institut National des Sciences de l'Univers (INSU).

References

[1] S.-C. Shi, T. Noguchi and J. Inatani, 1997, "Analysis of the bandwidth performance of SIS mixers with distributed junction arrays", *Proc. 8th International Symposium on Space Terahertz Tech.* 81.

[2] S.-C. Shi, T. Noguchi, J. Inatani, Y. Irimajiri, and T. Saito, 1998, "Experimental results of SIS mixers with distributed junction arrays", *Proc. 9th International Symposium on Space Terahertz Tech.* 223

[3] M. Salez, Y. Delorme, M. H. Chung, F. Dauplay, "Simulated performance of multi-junction parallel array SIS mixers for ultra broadband submillimeter-wave applications", *Proc. 11th International Symposium on Space Terahertz Tech.* 343.

[4] M.Takeda, T.Noguchi and S.-C Shi, "Predicted Performance of superconductor-Insulator-Superconductor Mixers with Inhomogemous Distributed Junction Arrays", , Jpn. J. Appl. Phy., 39, PP.5095-5098 (2000).

[5] Yuda M, Kuroda K and Nakamo J 1987 Japan. J. Appl.Phys.26

[6] Gurvitch M, Washington M A, Huggins H A, Rowell TM 1983 IEEE trans. Mag 19 791

[7] J. R. Tucker and M. J. Feldman, 1985, "Quantum detection at millimeter wavelengths", *Rev. Mod. Phys.*, **57,** 1055

[8] Qing Ke and J. Feldman " A Technique for noise measurement of SIS Receivers", 1994 IEEE trans. Mag 42, 752