Submillimeter-wave Emitted by small parallel Josephson junction arrays

F. Boussaha, A. Féret, M. Salez, C. Chaumont, B. Lecomte, J-M. Krieg and L. Lapierre

Abstract— **We report the first heterodyne measurements of microwave radiation emitted by a parallel Josephson junction array at submm-wave frequencies. The array consists of 5 small Nb-based Josephson junctions non-evenly distributed in a superconductive microstrip and designed for RF coupling in the 480-640 GHz range. The microwave radiation was detected using a SIS-mixer spectrometer optimized in the same range. We observed submillimeter-wave emission when the array was biased on certain Josephson steps, at the fundamental frequency of 493 GHz and 2nd harmonic frequency of 242 GHz. This strongly suggests that such non-uniform junction arrays optimized for RF-coupling, in spite of their strongly discretized nature, can host fluxon-induced resonances, which one can use in several areas of submillimeter-wave technology and superconductive digital electronics.**

Index Terms—**Josephson junction array, Submillimeter waves, fundamental radiation, harmonic radiation.**

I. INTRODUCTION

SIS (Superconductor-Insulator-Superconductor) junction is widely used in the submillimeter waves detection ranging particularly from 0.3 to 1.5 THz [1-2]. It became a standard and inescapable component thanks to its high sensitivity, able to approach the limited quantum. [3-4] have successfully demonstrated the ability of the parallel quasiparticule tunnel SIS junction arrays to produce low noise frequency mixer in wide bandwidth. In this case, the mixer is optimized by considering the Josephson current completely suppressed when a sufficient external magnetic field is applied perpendicularly to the plan of the array. Conversely, when the complex Josephson current is considered, this same parallel Josephson junction array is potentially able to generate radiations at millimeter and submillimeter waves range. In deed, as in long Josephson junction (LJJ), resonances appear in the *I-V* curve at non-zero voltage values when an external magnetic field is applied [5]. The corresponding frequency is obtained by $f=2eV_{array}/h$. A fundamental issue is to know the ability of the parallel junction array to produce a real and usable submillimeter signals. In this paper, we report the first measurement results of parallel junction radiation in the submm-wave range using the heterodyne technique.

Manuscript received 20 April 2009. This work is supported by the French Space Agency CNES. Paper titles should be written in uppercase and lowercase letters, not all uppercase. Avoid writing long formulas with subscripts in the title; short formulas that identify the elements are fine (e.g., "Nd–Fe–B"). Do not write "(Invited)" in the title. Full names of authors are preferred in the author field, but are not required. Put a space between authors' initials.

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II. CIRCUIT

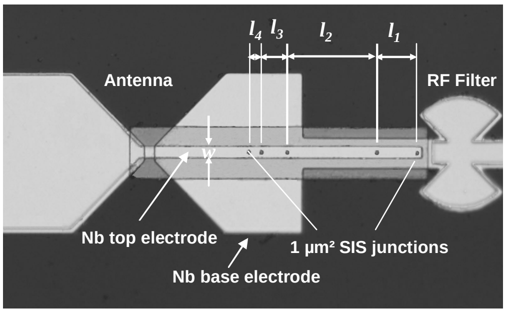

Fig. 1. Photograph of parallel Josephson junction array integrated with bowtie antenna and RF choke filter. The circuit is constituted of 5 Nb/Al-AlO_x/Nb identical junctions of l_jxw_j=1x1 µm² embedded in superconductive Nb/SiO/Nb stripline of width w=5 µm. The lengths separating the junctions are l_1 = 20 µm, l_2 = 42, l_3 = 12 µm and l_4=6 µm. Nb/Al-AlO_x/Nb is made up of 200 nm Nb-base-electrode, 10 nm Al and 400 nm Nb-top- electrode. The thickness of the SiO layer is 250 nm.

We investigated non-uniform parallel junction arrays whose number and spacing between the junctions have been optimized only in order to achieve broadband submillimeter-wave heterodyne quasiparticle SIS mixers [3-4]. As is shown in figure 1, the circuits defined on 50µm-thick fused quartz substrate are made up of 5 Nb/Al-AlO_x/Nb 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 spacing between junctions, allowing to tune out the tunnel barrier capacitance at desired frequencies, were optimized for best RF coupling in 480-640 GHz allowing well detection, but also well emission, of submillimeter-wave signals in that range. The circuit is placed in a waveguide mount providing purely real, near-constant 50 Ω source impedance over the whole band of 480-640 GHz, with no mechanical tuner [5]. The fabrication process is detailed in [6].

III. MEASUREMENTS AND RESULTS

The measurements were performed using the setup bench shown in figure 3. Two identical mixer blocks optimized at 480-640 GHz frequency range were employed, each in its own liquid helium cryostat, respectively hosting the junction array used as a submm-wave source, and a twin-junction as the SIS mixer [6]. 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.

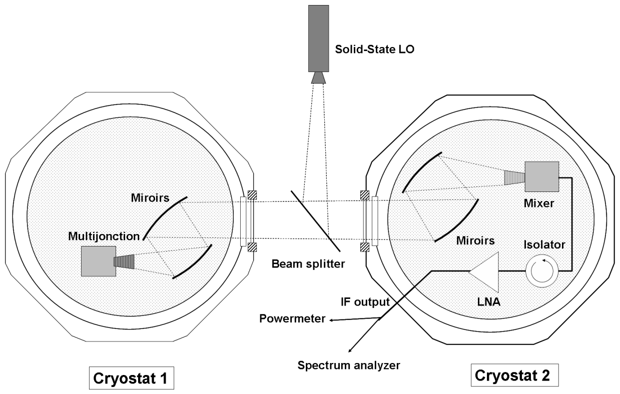

Fig. 2. Setup bench to characterize resonances observed in 5 Nb/Al-AlO_x/Nb junction array IV curve. Cryostat 1 and cryostat 2 contain respectively the junction array operating as submillimeter wave generator and the twin-junction as mixer.

The Josephson currents are entirely suppressed in the twin-junction and must be finely controlled in the junction array by a magnetic field generated by NbTi superconductive wire coiled around a cryoperm core. On its quasioptical path, the RF signals from the junction array 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 twin-junction mixer.

Figure 3 displays resonances appearing in the *I-V* curve of the array whose current density is 10 kA/cm² for different values of applied external magnetic field, measured at 4.2 K. Three Josephson resonances emerged at V_{array} ~ 0.5 mV, 0.84 mV and 1.02 mV when the magnetic field ranges from 60 to 83 Gauss. The corresponding fundamental frequencies ($f= 2eV_{array}/h$) are ~ 242, 406.5 and 493.6 GHz.

To determine which Josephson resonances, i.e. which frequencies could be measured with our setup, we characterized the RF coupling bandwidths of both the emitter (junction array) and the detector (twin-junction), by Fourier Transform Spectrometry technique (FTS). The instantaneous frequency response of the twin junction mixer and the junction array are respectively 410-640 GHz and 430-630 GHz frequency range [4]. The table 1 that summarizes the available frequencies shows that in this case only the fundamental of the third resonance and the 2nd harmonic of the first resonance can be measured.

Heterodyne measurements

First, the circuit was voltage-biased on the third resonance at V_{array} = 1.01 ± 0.005 mV then 1 ± 0.005 mV mV (voltages correspond to the maximum current where we expect maximum output power, before escaping to another state that is either the next resonance or the gap voltage). The respective frequencies are f_{array} ≈ 488.2 ± 2.42 GHz GHz and 483.4 ± 2.42 GHz, whereas the solid-state LO was tuned at f_{LO} = 493.8 GHz. The external magnetic field of 87 Gauss was applied. The twin-junction mixer is biased at 1.9 mV where it is most sensitive. The IF power spectrum measured across the 4-8 GHz frequency range is shown in figure 4.

TABLE 1 VOLTAGES AND CORRESPONDING FREQUENCIES GENERATED BY THE 5 PARALLEL JOSEPHSON JUNCTION ARRAY

N	V (mV)	FUNDAMENTAL (GHz)	HARMONIC 2 (GHz)
1	0.5	242	**484**
2	0.84	406.5	813
3	1.02	**493.6**	987.2

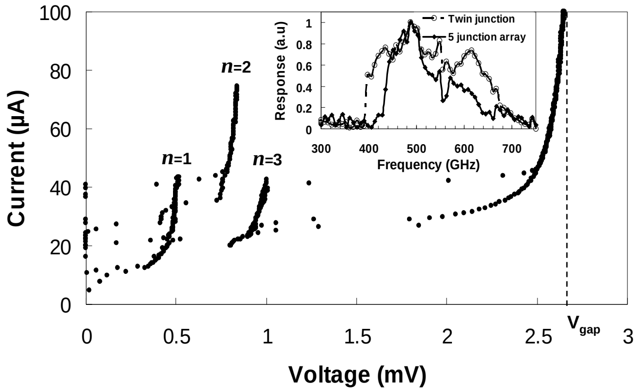

Fig. 3. *I-V* characteristic of the parallel Josephson junction array measured at T = 4.2 K. Three resonances appear when weak external magnetic field is applied. The insert shows the rf bandwidths of both the array and the SIS receiver (twin junction) measured by FTS technique (Fourier Transform Spectrometry).

Results

Reproducible spectral structure is obtained only in the presence of the resonance (ON). The change of the bias voltage value from 1.01 ± 0.005 mV (488.2 ± 2.42 GHz) to 1 ± 0.005 mV (483.4 ± 2.42 GHz) led the shift of the spectral structure position from f_{IF} ~ 4.3 GHz to f_{IF} ~ 7 GHz confirming the spectral structure to be a beat product at $f_{IF} = |f_{LO}-f_{array}|$.

Using the first resonance, similar measurements were performed. The junction array was current-biased at 0.5 ± 0.005 mV corresponding to 483.5 ± 2.5 GHz with 60 Gauss of applied magnetic field. Similar spectral structures were obtained as shown in figure 5. The solid-state LO was first tuned at 490.1 then at 491.5 and 493.1 GHz. The position of the structure shifted accordingly. When the array was biased on the second resonance, all frequencies of which (fundamental and harmonics) are completely outside of rf bandwidths, no beat signal was detected. In all detection, the IF signal was broad with a Full Width at Half Maximum

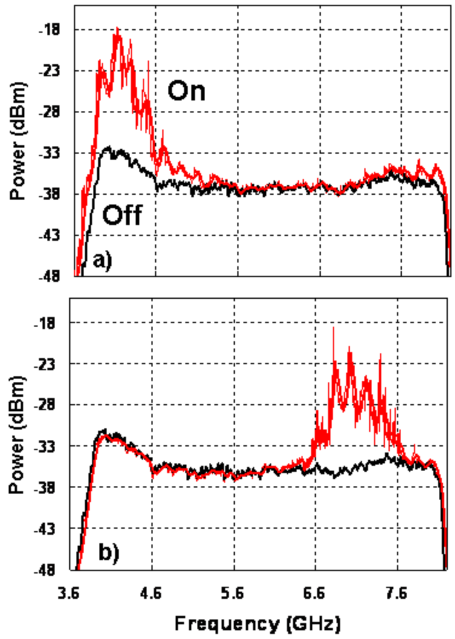

Fig. 4. IF power spectrum measured across the IF band of 4-8 GHz. The junction array is biased on the third resonance at a) 1.01 ± 0.005 mV then b) 1 ± 0.005 mV. The solid-state LO is tuned at 494 GHz.

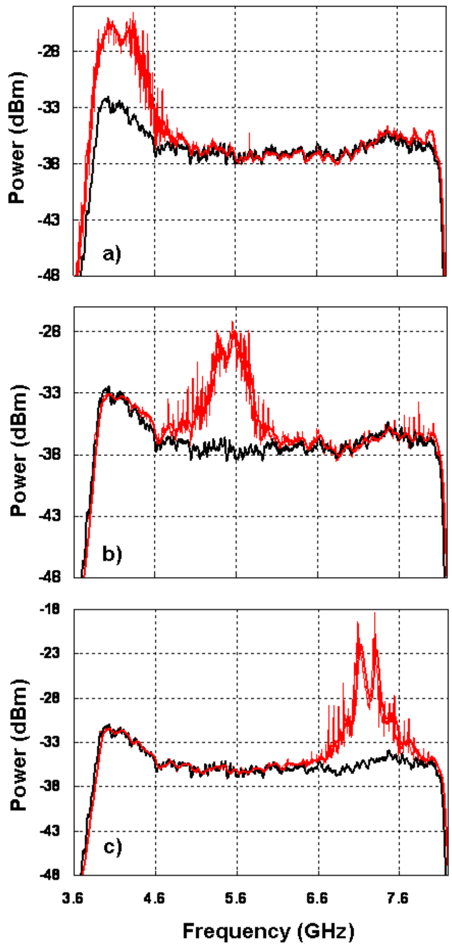

Fig. 5. IF power spectrum measured across the IF band of 4-8 GHz. The array is biased at 0.5 ± 0.005 mV corresponding to 483.5 ± 2.5 GHz. The solid-state LO is first tuned at a) 490.1 then at b) 491.5 and c) 493.1 GHz.

(FWHM) ~ 200 – 300 GHz. This is probably due to the instability of our voltage-bias: narrower IF signal by ~ 20 % using the more stable current-bias mode, was obtained. In addition, the LO source was not phase locked, nor was the array magnetically shielded. With the use of a phase lock loop, a very stable current-bias and the array magnetically shielded, the linewidth can be greatly reduced. We also noted the presence of 200 MHz noise signal probably caused by one of the measurement instruments.

The radiation reported here is probably generated by dynamic fluxons and the observed resonances as Fiske steps. Under the influence of the magnetic field, fluxons propagate unidirectionally and synchronized to cavity mode standing waves. *Further details are given in* [7].

IV. Conclusion

We investigate a non-uniform array of small $Nb/AlO_x/Nb$ Josephson junctions with ~ 10 kA/cm² of current density operating as submm signals generator. Using the heterodyne technique, the measurements indicate with no ambiguity that SIS junction array can generate submm-wave signals at its fundamental and harmonic frequencies. They open the way to on-chip integration of heterodyne receivers with the digital processing unit. They could be used as local oscillator instead of a LJJ (Long Josephson Junction), suitable to deliver higher output power with larger bandwidth. Indeed, LJJ has an impedance often < 1Ω while the small junction array can present several tens of ohms. Moreover, non-uniform arrays can be designed to provide very wide coupling bandwidths.

Acknowledgment

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