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New elements for analysis of series arrays of superconducting junctions for submillimeter heterodyne detection

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Abstract: Some specific features of series arrays of superconducting junctions used as mixing elements in radioastronomical spectroscopy are analysed. The influence of the area and insulating barrier inhomogeneities between the different junctions is examined with a simple and accurate technique. It uses the variation of the maximum Josephson currents of the individual junctions as a function of an applied external magnetic field. It is also shown with this technique that the possibility for some junctions of the array to trap some random flux can prevent stable and sensitive operation of the mixer. Some experimental performances of mixers working near 380 and 550 GHz with series arrays are given. The difficulty of fully suppressing the Josephson currents of each junction at a time appears to be partly responsible for lower sensitivity and instabilities. Another cause of degraded performance comes from the different embedding impedances of each individual junction at the working frequency. It is due to a spreading of the geometrical parameters either of the junctions or of the individual tuning circuits used to compensate the junction capacitance for the 550 GHz mixer. The best performance of the array is then the result of a compromise where all junctions do not operate with optimum efficiency.

1. Introduction

Heterodyne receivers using SIS (Superconductor-Insulator-Superconductor) junctions are the most sensitive receivers for radioastronomical spectroscopy in the millimeter and submillimeter frequency range. They have proven to work well up to 650 GHz and some of the most recent results are presented in [1-8]. Due to the high intrinsic shunt capacitance of such junctions caused by the very thin insulating barrier between the superconductors, two different technological choices can be made for high-frequency operation of SIS mixers: reduction of the junction area or use of arrays of larger area junctions in series. Both allow reasonable value of the normal resistance R_N in the range 60 - 120 ohms combined with a low intrinsic capacitance for good matching conditions of the signal.

The use of integrated tuning circuits to resonate this capacitance [9] is another means of bypassing this drawback for small or large area junctions though it is valid only for a limited frequency bandwidth. In the case of large area junctions, arrays are still desirable to achieve a normal resistance high enough for a good coupling of the signal with the RF environment, especially for waveguide mixers. Moreover, large area junctions have the advantage of a higher saturation signal power and they need a lower magnetic field to cancel the Josephson current, source of instabilities and noise especially at high frequencies (above 300 GHz) [10].

Electron-beam lithography is used in order to fabricate SIS junctions with very small areas down to 0.1 square-micron [11]. Very good performance has been obtained with such devices [5-7]. However, conventional photolithography (for example see [12]) provides junctions with areas as small as one square-micron whose performances have been demonstrated up to 500 - 550 GHz, either used as single or twin junctions [1-4] or in series arrays [6, 8].

A critical point of series arrays of junctions is the inhomogeneities of area and insulating barrier between the different junctions. First, a method using the variation of the individual critical Josephson currents of the different junctions of the array as a function of an applied external magnetic field is

presented to analyse the behavior of series array and to draw some quantitative conclusions [13]. Then some experimental features specific to series arrays of Nb/Al-AlOx/Nb junctions encountered during the course of experiments are presented: the influence of the number of junctions in series on an SIS receiver performance near 380 GHz [14] is described and its causes are examined. Besides, the influence of individual integrated tuning circuits on the performance of an SIS receiver for 550 GHz [6] is analyzed.

Some conclusions about the use of series arrays of junctions are drawn.

2. Analysis of Josephson critical currents for SIS junctions series arrays

One of the major features of the Josephson critical current is its dependance upon the magnetic flux lying through the junction. For a single circular junction the critical Josephson current is given by [13, 15]:

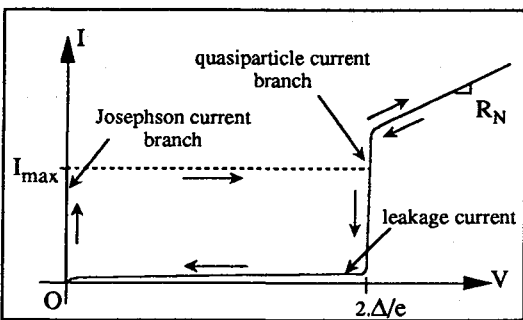
$$I = I_{\max} \cdot \sin(\varphi_0) \quad \text{with} \quad I_{\max} = I_0 \cdot \left| \frac{J_1 \left[\frac{\pi \cdot \sqrt{\phi_x^2 + \phi_y^2}}{\phi_0} \right]}{\frac{\pi \cdot \sqrt{\phi_x^2 + \phi_y^2}}{2 \phi_0}} \right| \quad (1)$$

where I_0 is the maximum Josephson current in absence of magnetic field, φ_0 the difference of phase between the two superconductors, $\phi_0 = h/(2e)$ is the flux quantum, ϕ_x and ϕ_y are the fluxes associated to the projection of the total magnetic field H along the two perpendicular axis x and y respectively (the z -axis is perpendicular to the plane of the junction), J_1 is the Bessel function of the first kind.

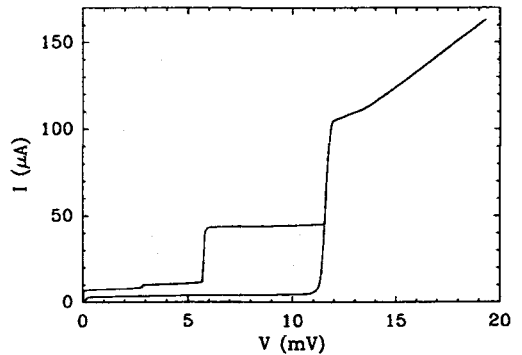
In each direction the total magnetic field is the sum of two components. The first one is due to some trapped flux caused by some random perturbations of the magnetic environment. The second one comes from an external tunable magnetic field produced by a superconducting coil located close to the mixer block along the x -direction. Such a magnetic field is necessary to suppress Josephson noise and instabilities during the operation of SIS mixers above 300 GHz [10]. Then, one has the relations:

$$\phi_x = \phi_x^{\text{external}} + \phi_x^{\text{trapped}} \quad \text{and} \quad \phi_y = \phi_y^{\text{trapped}} \quad (2)$$

A superconductor is characterized by two different kinds of charge carriers: Cooper pairs and quasiparticles. As a consequence, two different current regimes can take place: the zero-voltage Josephson current associated to the Cooper pairs and the quasiparticle current present for $V \geq 2\Delta/e$ where Δ is the energy gap of the superconductor. Then the current biased I - V curve of an SIS junction exhibits a hysteresis (see figure 1(a)) that can be interpreted as the preference of the junction to stay in its initial regime for a small variation of the bias current.



(a)



(b)

Figure 1(a): Typical DC I - V characteristics for a current biased single SIS junction showing the hysteresis between the Josephson and quasiparticle current regimes. **1(b):** Digitized experimental DC I - V characteristics for a four-junction series array showing peaks at some multiples of the gap voltage $2\Delta/e$. One can observe three different maximum Josephson currents corresponding to different fluxes trapped in three junctions. In this case two junctions have nearly the same maximum Josephson current.

The Josephson branch is described by the variation of the phase φ_0 defined above which meets the condition $I_{\text{bias}} = I_{\text{max}} \cdot \sin(\varphi_0)$. The switch from the Josephson current regime to the quasiparticle regime occurs when $\sin(\varphi_0)$ reaches its maximum.

For series arrays of junctions, a given impressed bias current corresponds to a pair regime for some junctions and to a quasiparticle regime for the other ones, depending whether the maximum Josephson current $I_{\text{max}}(n)$ of the n -th individual junction is higher or lower than the bias current.

As a consequence, the DC I-V curve exhibits some peaks at $n \cdot (2\Delta/e)$ as shown in the digitized I-V curve of a series array of four Nb/Al-AlOx/Nb junctions in figure 1(b).

Three peaks are visible in this figure at zero-voltage and about 2.8 and 5.6 mV, that is at once and twice the gap voltage of an SIS junction. One can notice in figure 1(b) the absence of a peak at three times the gap voltage, it means that two junctions have almost the same maximum Josephson current and switch at the same time.

A maximum Josephson current $I_{\text{max}}(n)$ does not always correspond to the same physical junction because the $I_{\text{max}}(n)$ are sorted in increasing order due to the current-controlled bias system. The maximum Josephson current of a physical junction is accounted by its magnetic field dependence as explicated in (1) and (2). Therefore the order of the $I_{\text{max}}(n)$ can change for different values of the applied magnetic field.

Some discrepancies between the individual maximum Josephson currents due to dispersion in area of the different junctions can be observed in absence of trapped magnetic field. But larger discrepancies can be seen because each junction can trap individually some random flux though the applied tunable external field is the same for all junctions. It is then possible to determine the values of the trapped fluxes in each junction [13] by fitting the experimental curves with the calculated curves using (1) and (2). A typical experimental dependance of the maximum Josephson currents as a function of the external magnetic field for a four-junction array is given in figure 2.

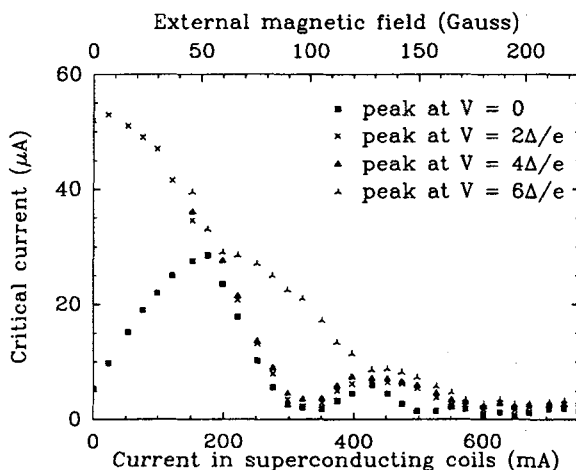


Figure 2: Maximum Josephson current vs tunable external magnetic field for each junction of a four-junction array [13].

One can see in this figure that three junctions trapped no or little magnetic field and show nearly the same dependence whereas the fourth junction trapped nearly one quantum flux. As a result, it is not possible to suppress the Josephson currents of the four junctions at a time unless applying a very strong external magnetic field.

Then the analysis of the different maximum Josephson currents as a function of an applied magnetic field is a simple and convenient way to diagnose in situ the behavior of a series array of junctions installed in a mixer block. The cancellation of the Josephson currents, cause of instabilities and additional noise, is of primary importance above 300 GHz in order to operate SIS mixers. As a consequence, it becomes more difficult to operate an array when the number of junctions in series increases. One could argue that a strong enough magnetic field would overcome this problem. This is not the case for junctions of the order of one square-micron for which this magnetic field - inversely proportional to the diameter of the junctions - would become close to the critical magnetic field for which superconductivity is broken. When the magnetic field approaches this critical value, the quality of the I-V curve is degraded and the performance of the SIS mixer is reduced [7]. Then a trade-off between the total SIS array capacitance and the quality of the Josephson current suppression has to be found.

3. Influence of the number of junctions in series on the SIS receiver performance

Some series arrays of two, three and four circular SIS junctions in series have been manufactured [12] for an SIS mixer designed to operate at 374 GHz on a balloon-borne receiver of the french space agency (CNES) [16]. The diameters of the junctions have been chosen to provide about the same total normal resistances R_N in the range 110-150 ohms for each kind of array. As a consequence the total capacitances of the different arrays are also in the same range corresponding to an $\omega R_N C$ product of about 10 at 374 GHz. Six different arrays have been measured in a mixer block, some of their performance obtained using the Y-factor method are presented in [14]. All of them are summed up in Table 1 with the most relevant characteristics of the arrays. One can clearly see that the receiver temperature noise increases with the number of junctions in series.

Table 1: Characteristics of series arrays of SIS junctions and performance of the 374 GHz SIS receiver with these arrays.

Number of junctions in series	2			3	4	
Junction diameter (μm)	1.1			1.5	1.9	
Normal resistance (Ω)	118	143	150	137	113	115
External applied magnetic field (Gauss)	270	185	175	255 (2 quanta)	192 (2 quanta)	195 (2 quanta)
DSB receiver noise temperature (Kelvin)	300	310	360	470	525	> 850 (LO starve)

Figure 3 shows the DC I-V curves of three different arrays with two, three and four junctions in series, they are normalized to their gap voltage and normal resistance. The I-V curves have about the same quality and, since the normal resistances and all other parameters of the mixer are nearly the same, similar performances are expected. This is not the case since series arrays of four junctions exhibit a noise which is at least 50 % higher than the noise measured for the two-junction arrays. Two reasons can explain these discrepancies.

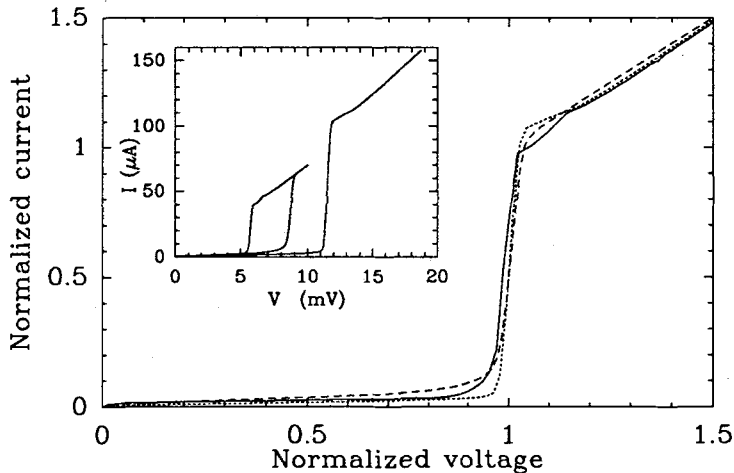


Figure 3: Digitized normalized DC I-V curves of three different arrays of two, three and four junctions in series. The inset shows the I-V curves in real units with their different gap voltages.

First, as mentioned in section 2, the small differences in area between the junctions of the array and the possibility for some of them to trap some flux can prevent the full cancellation of the Josephson currents which are associated to some additional noise. A second reason is due to the slightly different areas of the junctions and to some inhomogeneities between their respective barriers: then the local oscillator (LO) power applied to the array is not equally shared between the different junctions. As a consequence the optimum bias points for each junction of the array are different and the best performance of the array results from a trade-off since all junctions are not operated for optimum performance. This aspect will be reviewed in more details in the next section.

4. Influence of integrated tuning circuits on the behavior of series arrays of junctions

At high frequencies, individual integrated tuning circuits are used to compensate the parasitic capacitance of each junction [6-8] at the working frequency of the receiver. The high selectivity of such resonant structures makes the requirements in junctions areas and mask alignment during the fabrication process very stringent, especially above 500 GHz where a difference of tuning circuit length of 1 μm can lead to a shift of resonance frequency of more than 20 GHz.

An SIS receiver designed for 547 GHz was developed and tested at the Jet Propulsion Laboratory (JPL) in California using series arrays of two one square-micron junctions with integrated tuning circuits fabricated at the Ecole Normale Supérieure of Paris [6] and also single sub-square-micron junctions made at JPL [11]. For the series arrays a slight difference in the resonance frequencies of the junctions with their dedicated tuning structures may lead to rather different embedding impedances for the individual junctions at both the local oscillator and signal frequencies. An example of digitized pumped and unpumped I-V curves is shown in figure 4 to highlight this point.

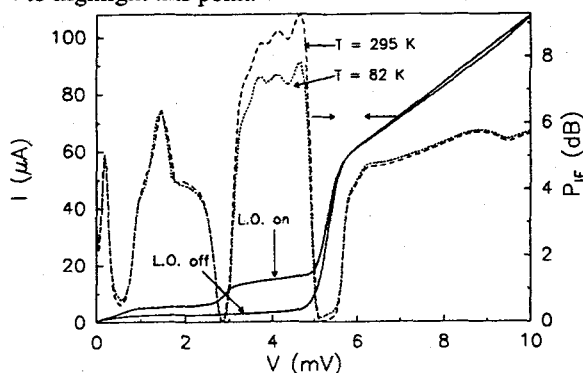


Figure 4: Current vs voltage (solid lines) and output power P_{out} vs voltage (dashed lines) for an array of two one-square-micron junctions.

In this case the LO power is not equally shared between the junctions then one can observe two photon-assisted tunneling steps of different heights on the I-V curve. The output power for hot and cold broadband loads simulating the signal power are also plotted in the same figure as a function of the bias voltage. Two main features of these curves can be outlined. First, one can notice a peak near 1.4 mV and some ripples around 4 mV on the output power curves. They are due to some remaining Josephson currents not fully cancelled because of discrepancies in the areas of the different junctions as discussed in section 3. The other remarkable feature is the different output levels associated with the two steps of the DC I-V curve. The same imposed DC bias current flowing through the series array is associated with different individual DC bias voltages for each junction caused by different levels of LO pumping. As a result the two junctions respond independently to the signal. Then the series array performance is optimized when only one junction is active whereas the second junction is a passive source of noise since its bias voltage is close to its gap voltage. Then a series array of two junctions having different tuning circuits (due to some misalignments during fabrication for example) can be seen as two junctions of different areas in series since their residual capacitances at the frequency of operation are different. This comparison is only true from the point of view of the mixing behavior. Nevertheless, though not fully optimized, series arrays still perform well and a DSB receiver noise temperature of 340 K has been reached at 547 GHz with a series array of two one square-micron junctions which is about 60-140 K higher than the performance obtained with single 0.25 square-micron junctions fabricated at JPL [6].

5. Conclusion

The difficulty of fabricating arrays of rigorously identical junctions leads to the persistence of residual Josephson currents and to a reduction of the efficiency in the individual junctions. For this reason, even if series arrays of junctions can reach the same performance as single junctions in theory [17], some differences can appear in experiments especially at high frequencies where integrated tuning circuits are used along with junctions of higher current densities and smaller areas. Nevertheless operation with series arrays of two junctions still gives good performance up to 550 GHz [6, 8] though they are more difficult to operate. The above mentioned measurements tend to favour operation of single junctions even fabricated with conventional photolithography and the drawbacks of low normal resistance and high

capacitance can be overcome with appropriate tuning circuits. In this case the Josephson currents are easier to cancel. Such a solution is desirable especially for frequencies above 500 GHz where interactions between quasiparticle and Josephson currents become overwhelming and for future space applications where long term reliability is essential and interventions are possible only through remote-controlled systems.

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