The Josephson Self-Oscillator Mixer as a Submillimeter and Far-Infrared Detector

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Abstract—**The Josephson self-oscillator mixer has potential detector applications at submillimeter frequencies. A quantitative investigation of noise effects and of its physical origin is performed with measurements of monochromatic radiation in the frequency range 0.1–2 THz.**

I. Introduction

RECENT publications [1], [2] show that the Josephson mixer with external local oscillator (LO) has performances which compare favorably in the millimeter range with Schottky diodes. In this frequency domain, where tunable radiation sources are easily available, the LO is not a problem and it does not appear that the Josephson oscillator mixer presents a very interesting alternative. The situation is different in the submillimeter and far-infrared regions, where the availability of an internal oscillator easily tunable in a wide frequency range constitutes a considerable advantage.

The Josephson oscillation has already been used for frequency conversion of monochromatic radiation [3], [4], and it has been demonstrated that this method could be applied up to the far infrared [5]. The main source of difficulty of this mode of operation in a practical device is the important linewidth of the frequency-converted signals (of the order of 1 GHz), which is related to the Josephson-oscillation linewidth. It is the reason why up to now the self-oscillation has been only used in a millimeter-wave down-converter to detect wide-band signals [6].

Several ways may be considered to overcome this difficulty: a) the Josephson-oscillation linewidth Δf_0 may be strongly reduced by coupling the junction to a cavity tuned at the IF [3] or with low-impedance junctions ($\ll 1\ \Omega$), since Δf_0 is related to the dynamic resistance at the operating point; b) Δf_0 may also be reduced with the use of an external adequate shunt to suppress the effect of low-frequency noise in the junction; c) the selection of a wide IF bandwidth B allows to make full use of the frequency-converted signals ($B \gtrsim \Delta f_0$).

The first method does not appear to allow the realization of an easily tunable receiver, well coupled to the external radiation source, which impedance is often a few $10^2\ \Omega$. This point is particularly crucial for a low-noise receiver operating in the millimeter or submillimeter-wave region. The second method implies the use of a high intermediate frequency (IF $\gtrsim$ 5 GHz) larger than the cutoff frequency of the shunt. We believe that this method should be used in a practical device.

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We have actually selected the last method to develop the use of the self-oscillation as LO in heterodyne detection of submillimeter and far-infrared monochromatic radiation. We have used this receiver to investigate the internal-noise properties of point contacts in the far infrared.

II. The Josephson Oscillator Mixer in the Far Infrared

In a Josephson self-oscillator mixer [3], [4] an external signal of frequency f_e and power level P_e is mixed with the Josephson oscillation of frequency f_0 and linewidth Δf_0 which corresponds to a junction, e.g., a superconducting point contact, which is biased at a finite voltage $V_0 = (hf_e/2e)$. The intermediate-frequency chain at $f_i = |f_0 - f_e|$ has a bandwidth B. The two basic problems in this mode of operation are related to the linewidth Δf_0 of the Josephson oscillation and to phase-locking effects.

The linewidth Δf_0 is due to the low-frequency noise in the junction, which frequency modulates the Josephson current, and in the far infrared Δf_0 is of the order of a few gigahertz for typical junctions with a normal resistance equal to a few ohms. If monochromatic signals are to be detected, this may result in a loss of information. Moreover, if Δf_0 is larger than B, this leads to additional conversion losses and a severe decrease of sensitivity may result.

On the other side, we have previously reported [7] that with small values of f_i, a synchronization of the Josephson oscillation occurs easily with increasing power level P_e of the external signal. This limits practically the dynamic range where the oscillator mixer may be used in the small-signal domain such that the external radiation level is well under the threshold where steps appear in the VI characteristic. If the previous condition is fulfilled, the Josephson oscillation is not perturbed by phase locking, even if $\Delta f_0 > f_i$ as observed experimentally.

In the present experiments we have taken advantage of this result and used available IF equipment with relatively wide bandwidth to limit the conversion losses at the IF ($f_i = 350$ MHz, $B = 500$ MHz, $f_i = 500$ MHz, $B = 200$ MHz, and $f_i = 550$ MHz, $B = 900$ MHz). The mixing signal is coupled directly to the IF chain in the present case and a much better coupling of the junction to the IF amplifier is obtained than in the previous experiments with 9 GHz IF [4], where the mixing product was reradiated by the junction. The maximum gain of the IF chain is 75 dB and its input noise temperature 530 K. A further increase in sensitivity is obtained by phase detection as the HF external radiation is chopped at a few 10^2 Hz.

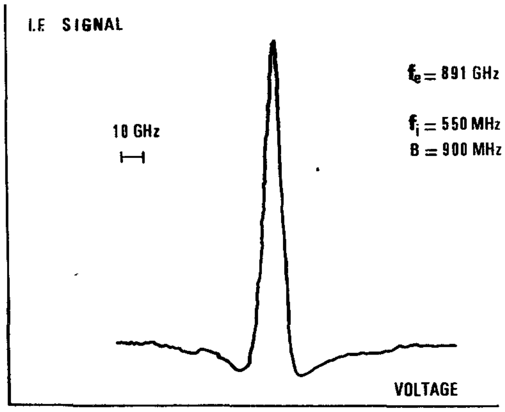

Fig. 1. Heterodyne detection of a monochromatic radiation at 145 GHz using the Josephson oscillation as the local oscillator. The Josephson linewidth Δf_0 is small enough ($\Delta f_0 \simeq 0.1$ GHz) comparative to the intermediate frequency so that the two image frequencies $f_0 = f_e \pm f_i$ are clearly seen. The normal junction resistance is $R_N = 0.25\ \Omega$.

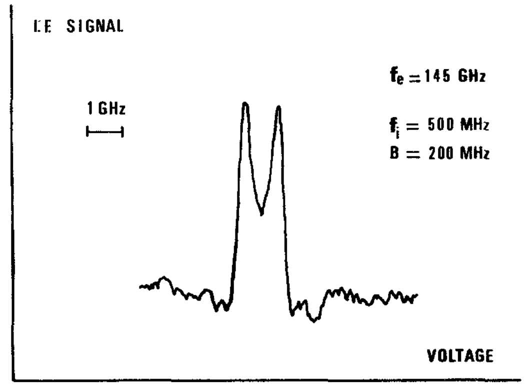

Fig. 2. Heterodyne detection of the radiation emitted by an HCN laser. The Josephson linewidth is much larger than the IF and the two image frequencies are confounded. The normal junction resistance is $R_N = 9\ \Omega$.

The experimental setup is very similar to one previously described [4]. The *Nb-Nb* point contact is situated transversely in an *X*-band waveguide which behaves as an oversized waveguide for all HF frequencies used. A small spherical mirror behind the contact focuses the HF radiation on the junction. A black polyethylene low-pass filter at 4 K is situated in front of the junction. Low-pass filters ($\sim$0.1 s) are situated on the four junction leads and a part of the circuit bias resistance is near the junction at 4 K.

With this equipment we have realized down-conversion of high-frequency monochromatic signals of 145 and 891 GHz. At 145 GHz, we have been able to detect frequency-converted signals corresponding to HF radiation about 20 dB under the level of appearance of an induced step in the VIC. Fig. 1 shows the response obtained with a junction of rather low impedance ($R_N = 0.25\ \Omega$). In that case, the Josephson linewidth Δf_0 is small enough ($\simeq$0.1 GHz) so that the two lines corresponding to the two image frequencies $f_0 = f_e \pm f_i$ are clearly seen. This type of result, which is similar to previous results with $f_i = 9$ GHz [4], demonstrates that the mechanism of frequency conversion is well involved in these experiments. With junctions of higher impedance, the two lines corresponding to $f_0 = f_e \pm f_i$ progressively overlap. Fig. 2 shows a typical result when the external signal is the radiation of an HCN laser at 891 GHz with a linewidth equal to a few tens of kilohertz. Here again the HF radiation level is well under the level of appearance of an induced step in the VIC. The Josephson linewidth and, therefore, the signal linewidth at the IF ($\Delta f_0 \simeq 6.7$ GHz) are here much larger than the IF (350 MHz) so that the two image frequencies are practically confounded. Therefore, such a result allows a measurement of the Josephson linewidth Δf_0. As could be expected, the IF detected signal increases linearly while its linewidth remains constant with the incident radiation power level up to the formation of steps in the VIC.

These different results show that the Josephson self-oscillation can be used as a LO to realize heterodyne detection of millimeter to far-infrared monochromatic (or narrow-band) signals.

On the other hand, this device allows one to observe directly the Josephson oscillation in the far infrared, a domain of frequency where there is actually a lack of experimental results. Again we point out that contrary to our previous experiments, the external signal level is so weak that the Josephson oscillation remains unperturbed. We have used this method to directly measure the Josephson linewidth and thus the internal noise of the junction for Josephson frequencies in the millimeter to the far-infrared range.

III. Noise in a Point-Contact Josephson Junction

An exact experimental knowledge of the internal noise of the junction is an important question for the two following reasons.

From a practical point of view, the internal noise is responsible for the ultimate sensitivity of the device. In the Josephson mixer with external LO [1], [2], it is related to the noise temperature T_M referred to the input. In the Josephson oscillator mixer, the internal noise is also responsible for the linewidth Δf_0, and then of excess conversion losses if $\Delta f_0 > B$.

On the other hand, the main physical origin of the internal noise in a superconducting point contact is still an open question. Some of the already existing results [9], [10] are well explained by the theory developed for oxide tunnel junctions where the noise is mostly due to the fluctuations of the dc pair and quasi-particle current components in the junction. Other results [11] have been interpreted assuming that the only source of noise is the thermal noise of the junction normal resistance, the observed excess noise being attributed to complex nonlinear mixing processes.

Noise measurements at very high frequencies such that $\Omega = (\omega_e/\omega_c) \gtrsim 1$ ($\omega_c = 2eR_N I_c/h$) seem to be very useful as in these conditions the previous nonlinear processes are negligible, and linewidth measurements allow one to directly reach with good precision the internal noise level of the junction [17]. Moreover, a direct comparison of the two limit models previously described is easier in the far-infrared region where the quantum energy eV is larger than the thermal energy kT (at 4.2 K $kT/e = 360\ \mu$V, a voltage corresponding to a Josephson frequency $\simeq 175$ GHz). In this frequency region, the theory valid for tunnel junctions predicts a linear dependance of noise with the total current I_0 of the junction, while the thermal noise of the normal resistance of the junction is independent of I_0. However, some complications may appear at frequencies corresponding to energies larger than the gap energy where the simplified model of the resistively shunted junction is no longer valid.

Fig. 2 gives a good example of linewidth measurements at 891 GHz. The dc parameters of the point contact measured on the VI characteristic are: $I_0 = 225\ \mu$A, $R_N = 9\ \Omega$, $R_d = 10\ \Omega$, and the measured linewidth $\Delta f_0 =$ 6.7 GHz (± 10 percent). The calculated linewidth [12], [13][1] assuming shot noise is with the previous junction parameters

$$\Delta f_0 = 2\pi \left(\frac{2e}{h}\right)^2 eI_0R_d^2 \simeq 5.8 \text{ GHz } (\pm 10 \text{ percent}).$$

The calculated linewidth assuming thermal noise from the normal resistance [14] is

$$\Delta f_0 = 2\pi \left(\frac{2e}{h}\right)^2 \frac{2kT}{R_N} R_d^2 \simeq 1.9 \text{ GHz } (\pm 10 \text{ percent}).$$

These results show that a much better agreement is obtained with the shot-noise limit. The quantitative agreement with the theory valid for tunnel junctions is not as satisfactory with junctions of lower R_N, and an excess noise of about a factor 2 is generally found relatively to the shot-noise limit.

We have also tested the dependence of the Josephson linewidth with the dc current amplitude flowing in the junction. Fig. 3 shows the variation of the noise for the same junction which is proportional to $\Delta f_0/R_d^2$, at Josephson frequencies between 145 and (2 × 891) GHz. The solid line represents the theoretical curve calculated from the theory, assuming shot noise.[1] The dashed line corresponds to the thermal-noise limit. The junction normal resistance is only 2 Ω and, as previously noted, the experimental points are systematically above the theoretical curve corresponding to the shot-noise limit, but we observe a steady increase with the current when $eV \gg kT$, which represents, owing to the precision of the experiments, a good approximation of the expected linear dependence. This clearly shows at least that the Josephson linewidth is dependent of the junction current. These results confirm previous observations at lower frequencies [9], [10] and strongly suggest that noise in point contacts is better explained assuming shot noise associated with the dc currents flowing in the junction [18].

[1] The complete theoretical expression for the Josephson linewidth assuming shot noise associated to the pair current I_p [13] and quasi-particle current I_{qp} [12] is

$$\Delta f_0 = 2\pi \left(\frac{2e}{h}\right)^2 \left(eI_{qp} \coth \frac{eV}{2kT} + 2eI_p \coth \frac{eV}{kT}\right).$$

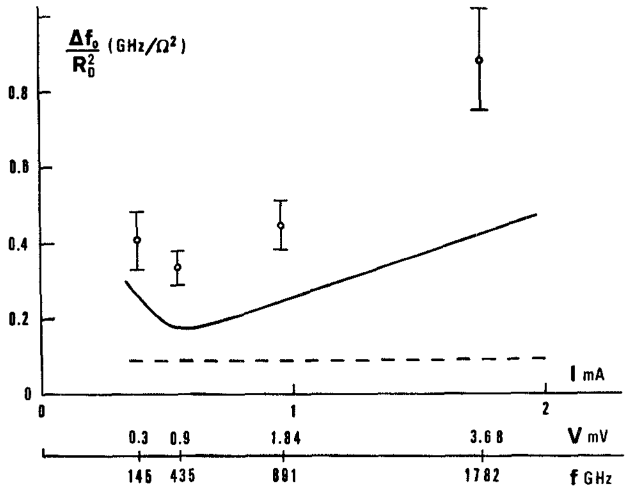

Fig. 3. Dependence of the internal noise in a Josephson point contact on the total dc current. The solid line represents the theoretical curve calculated from the theory assuming shot noise.[1] The dashed line corresponds to the thermal-noise limit [14]. These results are obtained using external radiation at 145 and 891 GHz and their harmonics (lower horizontal scale).

IV. Conclusion

These preliminary results demonstrate that the Josephson oscillator mixer has potential applications in the far infrared. Calculations show that the ultimate performances of the Josephson mixer and oscillator mixer are similar [15], [8]. The main point to solve with any Josephson device is the coupling to the high-frequency signal and this problem may be solved at frequencies >300 GHz with optical methods. The absence of an external LO at these frequencies and the wide-range tunability is a great advantage of the Josephson oscillator mixer; for example, in spectroscopic studies.

However, the relatively large value of the natural Josephson linewidth may limit its application if selectivity is required. We have found that this linewidth is better explained assuming shot noise associated with the total current in the junction than by thermal noise associated with the normal resistance. However, the effect of internal noise can be strongly reduced using a shunt resistance to short out the low-frequency noise in the junction. For example, linewidths of the order of a few megahertz at a frequency of 1 THz should theoretically be obtained with a 10^{-2}-Ω shunt.

References

[1] Y. Taur, J. H. Claassen, and P. L. Richards, "Josephson junctions as heterodyne detectors," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 1005–1009, Dec. 1974.

[2] P. L. Richards, J. H. Claassen, and Y. Taur, "Josephson effect mm receivers," in *Proc. Int. Conf. Low Temperature Physics*, vol. 14 (Otaniemi, Finland, Aug. 1975).

[3] A. Longacre, "Direct demonstration of Josephson frequency conversion," in *Proc. 1972 Applied Superconductivity Conf.* (Annapolis, MD, May 1972).

[4] G. Vernet and R. Adde, "Josephson frequency conversion with point contacts used as oscillator-mixer," *J. Appl. Phys.*, vol. 45, pp. 2678–2688, June 1974.

[5] G. Vernet, J.-C. Hénaux, and R. Adde, "L'oscillateur-mélangeur Josephson dans l'infra-rouge lointain," in *J. Nationales Micro-ondes* (Limoges, France, Mar. 1976).

[6] R. S. Avakjan *et al.*, "Millimeter wave band signal conversion in *S-C-S* Josephson junctions with self-pumping," *IEEE Trans. Magnetics*, vol. Mag-11, pp. 838–840, Mar. 1975.

[7] G. Vernet and R. Adde, "Influence of an external radiation on a Josephson oscillator and phase locking effects," *IEEE Trans. Magnetics*, vol. Mag-11, pp. 825–828, Mar. 1975.
[8] R. Adde and G. Vernet, "High frequency properties and applications of Josephson junctions from microwaves to the far infrared," in *Proc. NATO Summer School on Small Scale Superconductivity* (Gardone Riviera, Italy, Sept. 1976).
[9] H. Kanter and F. L. Vernon, "Current noise in Josephson point contacts," *Phys. Rev. Lett.*, vol. 25, pp. 588–590, 1970.
[10] G. Vernet and R. Adde, "Linewidth of the radiation emitted by a Josephson point contact," *Appl. Phys. Lett.*, vol. 19, pp. 195–197, 1971.
[11] J. H. Claassen, J. H. Taur, and P. L. Richards, "Noise in Josephson point contacts with and without rf bias," *Appl. Phys. Lett.*, vol. 25, pp. 759–761, 1973.
[12] D. J. Scalapino, "Current fluctuations in superconducting tunnel junctions," in *Proc. Symp. Physics of Superconducting Devices* (Univ. of Virginia, Charlottesville, Apr. 1967).
[13] M. J. Stephen, "Noise in the ac Josephson effect," *Phys. Rev.*, vol. 182, pp. 531–538, 1969.
[14] K. K. Likharev and V. K. Semenov, "Fluctuation spectrum in superconducting point contact junctions," *JETP Lett.*, vol. 16, pp. 442–445, May 1972.
[15] A. N. Vystavkin *et al.*, "*S-c-s* junctions as non linear elements of microwave receiving devices," *Rev. Phys. Appl.*, vol. 9, pp. 79–110, Jan. 1974.
[16] Since at high frequencies $\Omega \gtrsim 1$, the voltage source model is again a good approximation for a point contact obeying the familiar RSJ model, the results of the calculations originally developed for voltage-biased tunnel junctions may be used to investigate the influence of a driving noise current. Therefore, in this situation ($\Omega \gtrsim 1$) the only problem to be solved concerns the physical origin of the internal noise in the junction.
[17] *Note added in proof:* In a recent paper under publication, Tinkham *et al.* have investigated the heating effects in metallic Josephson devices which lead to a noise temperature increasing linearly with the applied voltage (or frequency) at very high frequencies. Therefore, the thermal noise model also gives in these conditions a linear increase of the Josephson linewidth with voltage. However, for a frequency of 1 THz, an estimation of these heating effects for our contacts seems to indicate that they should still be quite negligible.

Results, Potentials, and Limitations of Josephson-Mixer Receivers at Millimeter and Long Submillimeter Wavelengths

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Abstract—**Millimeter-wave mixers using Josephson point contacts are described, which exhibit a conversion loss $L_c = 9.5$ dB and a noise temperature $T \sim 223$ K for $\lambda \geq 0.95$ mm. Their potentials and limitations in noise, bandwidth, drive power, and stability for receiver applications are discussed.**

I. Introduction

Millimeter-wave mixers using Josephson point contacts have been found to exhibit very low noise. Using these devices noise temperatures of less than 100 K have been measured for frequencies up to about 100 GHz [1]–[3]. No quantitative data are available for the middle and upper millimeter-wave as well as the submillimeter-wave range, where these devices are particularly attractive because of their low intrinsic noise, their wide bandwidth, and their low local-oscillator (LO) power requirements. We report here on a Josephson-mixer receiver which is tunable over the entire 220–325-GHz waveguide band ($0.92 < \lambda < 1.36$ mm), a frequency region where component fabrication difficulties become extremely severe due to small size (e.g., internal waveguide dimensions of 0.43×0.86 mm). Based on these results, potentials and limitations for receiver applications up to 600 GHz are discussed.

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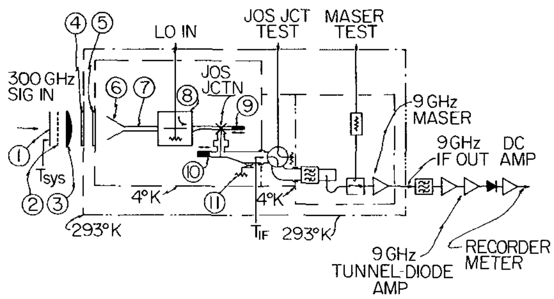

Fig. 1. Block diagram of 300-GHz Josephson-mixer receiver. Component numbers refer to Table I.

II. Description of an Experimental Josephson-Mixer Receiver for $\lambda \sim 1$ mm

A block diagram of a system designed for use as a spectral-line receiver on a millimeter-wave antenna is shown in Fig. 1. The beam of the 300-GHz signal, which is high-pass filtered by means of a screen filter, enters the stainless-steel liquid-helium Dewar through two windows and is focused by a dielectric lens into a scalar horn. The LO signal is injected via a special integrated cross-guide coupler. Following that is the Josephson mixer with a