JOSEPHSON NOISE IN SIS RECEIVERS

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Abstract: The tunneling of Cooper pairs through the barrier of a superconductor-insulator-superconductor (SIS) junction (Josephson effect) is a major drawback for the operation of an SIS mixer (generation of instabilities and noise). For frequencies lower than 200 GHz, the junction capacitance is usually sufficient to shunt the rf Josephson currents. At higher frequencies however, an external magnetic field needs be used to suppress this effect.

I present here a calculation of the noise equivalent power generated by the high frequency Josephson currents fluctuating at the signal and image ports and mixed to the output, under the assumption that the Josephson currents are sufficiently small to allow stable bias. In this calculation, possible additional losses due to Josephson effects are neglected.

I - Introduction

In the Quantum Theory of Mixing developped by J. Tucker [1], the Josephson tunneling of Cooper pairs through the junction barrier is neglected. The Josephson currents are considered either shunted by the junction intrinsic capacitance or suppressed by external magnetic field.

This assumption is justified at detection frequencies lower than 200 GHz with no magnetic field applied, and at higher frequencies each time a proper magnetic cancellation of the Josephson current is available.

If not suppressed, the Josephson currents are the source of drastic instabilities such as the drop-back effect, when non-zero voltage bias is not possible. In the better case, they are accountable for supplementary noise in the output power [2]. See figure 1 and 2 [10].

In experimental situations however, an intermediate situation is very often encountered: the Josephson currents are sufficiently small to allow stable bias but there is some residual Josephson current on the I-V curve at zero voltage. This is the case, for instance, in SIS junction arrays with small dishomogeneities between the junctions, and in space embarked devices where there is no possibility to adjust the current in the superconducting coils [3]. This is the reason why having an estimation of the Josephson noise mixed into the output of the receiver in this particular case is of great practical interest.

II - General formulation of pair and quasiparticle currents for the evaluation of mixer performances

The more general formulation of tunneling currents through an SIS junction has been derived by Werthamer [4] and includes contributions of the quasiparticle and pair currents:

$$\Im(t)=\Im m\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} d\omega d\omega'\left\{W(\omega)W^*(\omega')e^{-i(\omega-\omega')t}\, j_1(\omega'+\tfrac{1}{2}\omega_0) + W(\omega)W(\omega')e^{-i(\omega+\omega')t+i\varphi+i\alpha}\, j_2(\omega'+\tfrac{1}{2}\omega_0)\right\}$$

where

$\omega_0=2eV_0/h$

j_1 and j_2 are the quasiparticle and pair current amplitudes, $W(\omega)$ is related to the voltage impressed accross the junction and is given by

$$\int_{-\infty}^{+\infty} d\omega\, W(\omega)\, e^{-i\omega t} = \exp\left\{-i(e/h)\int_{-\infty}^{t} dt' \int_{-\infty}^{+\infty} dx E_x(x,t')\right\}$$

In the quantum theory of mixing, only the first term, i.e. the term related to single particle tunneling is used. Due to the expression of the voltage bias accross the junction, the function $W(\omega)$ is identified to

$$W(\omega') = \sum_{n=-\infty}^{+\infty} J_n(\alpha)\delta(\omega'-n\omega_{lo})$$

where

$$\alpha = eV_\omega/h\omega$$

$$V(t) = V_0 + V_\omega \cos \omega_{lo} t$$

These expression enable to calculate the I-V characteristic of the junction in the presence of the local oscillator drive from the I-V characteristic without radiation applied. Including experimental parameters such as the source and load admittances, the small signal admittance matrix, the gain and the quasiparticle shot noise can be derived.

The expression of the quasiparticle shot noise in terms of the mixer noise temperature is given by

$$kT_M = \frac{1}{4G_S|\lambda_{01}|^2} \sum_{m,m'} \lambda_{0m}\lambda^*_{0m'}H_{mm'}$$

where $H_{mm'}$ is the quasiparticle current correlation matrix and the λ_{0m} are related to the small signal impedance matrix coefficients

$$\lambda_{0m} = Z_{0m}/Z_{00}$$

The quasiparticle current correlation matrix can be expressed in terms of the power spectral density of the quasiparticle current fluctuations which is related to the quasiparticle response function via a fluctuation-dissipation relation. This leads to the following expression [1-5]

$$H_{mm'} = e \sum_{n,n'=-\infty}^{+\infty} J_n(\alpha)\, J_{n'}(\alpha)\, \delta_{m-m',n'-n} \times$$

$$\left\{\coth\left[\frac{\beta}{2}(eV_0+n'h\omega_{lo}+h\omega_{m'})\right] I_{qp}\left(V_0+\frac{n'h\omega_{lo}}{e}+\frac{h\omega_{m'}}{e}\right) + \coth\left[\frac{\beta}{2}(eV_0+nh\omega_{lo}-h\omega_{m'})\right] I_{qp}\left(V_0+\frac{nh\omega_{lo}}{e}-\frac{h\omega_{m'}}{e}\right)\right\}$$

Using these equations it is possible to compute the mixer noise temperature for a given experimental situation. The thermal noise due to the physical temperature of the signal and image ports can be added without difficulty, but it is not the purpose here, since we want to compare an estimation of the Josephson noise to the quasiparticle shot noise.

III - Calculation of the Josephson noise

Following a similar approach, it is possible to express the pair current correlation matrix in terms of the pair (and quasiparticle-pair) current response function I_{pair} and $I_{qp\text{-}pair}$. See figure 3.

A complete expression for the quasiparticle and pair mixing process is given by Shen [5]. However his equations can not be solved analytically because of the hysteretic behavior of the junction.

The pair current fluctuations arise from the interaction of the pair current with the blackbody radiation field of the junction. The power spectrum of these fluctuations has been derived by Rogovin and Scalapino in the case of linear first-order process [6].

$$P_{I_{pair}}(\omega) = \frac{e}{\pi}\left\{ I_{pair}(V_0 + h\omega/2e)\coth\left(\beta(eV_0 + h\omega)/2\right) + I_{pair}(V_0 - h\omega/2e)\coth\left(\beta(eV_0 - h\omega)/2\right)\right\}$$

$$P_{I_{qp\text{-}pair}}(\omega) = \frac{e}{\pi}\left\{ I_{qp\text{-}pair}(V_0 + h\omega/2e)\coth\left(\beta(eV_0 + h\omega)/2\right) + I_{qp\text{-}pair}(V_0 - h\omega/2e)\coth\left(\beta(eV_0 - h\omega)/2\right)\right\}$$

These expressions are used to calculate $H_{mm'}$ with the following approximations.

The voltage sweep impressed accross the junction should be changed by the presence of Josephson currents and a rigorous derivation should include self consistent derivation of this voltage [7], hence the $W(\omega)$ functions should be changed from the simple quasiparticle mixer. The above-made assumption that the Josephson currents remain small allows to keep the same expression for the $W(\omega)$ functions since we state that the voltage bias remains stable. The formula giving the mixer noise temperature for quasiparticle, where the normalised impedances λ_{0m} are assumed to remain unchanged from the zero-Josephson effect case, is then used.

The physical interpretation for doing such, is that there is a possibility, frequently encountered in practice, to operate a receiver even in the case of non totally suppressed Josephson effect, without any strong modification of the mixer's behavior but with additional noise. Of course this calculation is expected to give an order of magnitude of the Josephson noise only in the case of small currents.

IV - Computer simulation results

The Josephson noise is calculated for a junction with normal resistance $R_n = 60\ \Omega$ and gap voltage $V_g = 2.8$ mV, for a local oscillator frequency of 540 GHz. In the results presented below, the shunting effect of the junction capacitance is not considered because we assume that the matching conditions are optimized at the signal and image frequencies.

	$V_0 = 1.12$ mV (1st Shapiro step)	$V_0 = 2.23$ mV (2nd Shapiro step)
T_M (quasiparticle)	110 K (SSB)	33 K (SSB)
T_M (1% Jos. eff.)	**32 K (SSB)**	**40 K (SSB)**
T_M (5% Jos. eff.)	**160 K (SSB)**	**200 K (SSB)**

V - Interpretation of excess noise in arrays

The experimental mixer noise temperature in arrays is always found higher than in theoretical predictions. Small surface discrepancies could slightly change the magnetic conditions from one junction to the other and some residual Josephson current in one junction could be accountable for the excess noise.

VI- Interpretation of excess shot noise in non-irradiated SIS junctions

Dubash et al. [8] measured shot noise in SIS junctions with no radiation applied. See figure 4.

For simple quasiparticle shot noise, the noise power as a function of bias voltage should be directly proportional to the I-V curve. However, they found an important excess noise at the gap voltage, sensitive to magnetic field.

Taking into account the pair shot noise, shown to be proportional to the pair response function plotted on figure 3, the excess noise is perfectly understandable. However, the junction capacitance has to be considered here, as it lowers the sub-gap Josephson currents [7] and decreases significantly the Josephson noise for voltages smaller than the gap voltage.

VII - Conclusion

This way of calculating the contribution of Josephson currents to the receiver noise temperature is really a first step, as many approximations have been made. The quantitative results, however, prove very interesting as they tend to demonstrate that the occurrence of even small Josephson currents rises significantly the total mixer noise temperature.

This enables to attribute the excess noise in arrays to Josephson noise, and probably also some excess noise in single-junction detectors.

The role of the capacitance of the junction has not been detailed here, since we assumed that it was shunted by some integrated tuning structures, but the twofold role of the matching structures has to be investigated in details.

Further investigations would also include the evaluation of additional losses due to Josephson currents, or maybe the possibility of additional gain as observed in ref [2].

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Figure caption:

Figure 1: I-V characteristic of a two-junction array, with 380 GHz radiation applied, with Josephson current not suppressed (solid line) and suppressed by external magnetic field (dashed line). *(After Febvre et al., 3rd Int. Symp. on Space Terahertz Technol., March 1992)*

Figure 2: Receiver output power (hot load) for 540 GHz radiation with: a) I_{coils} = 389 mA (Josephson current well suppressed), b) I_{coils} = 361 mA, c) I_{coils} = 513 mA, d) I_{coils} = 458 mA. *After Febvre et al. [10].* Junction tests reported in [9].

Figure 3: Normalized pair (solid line), quasiparticle-pair (dotted line) ans sum (dashed line) response functions as derived in ref. [6]

Figure 4: Shot noise measured in SIS junction. *After Dubash et al. [8].*

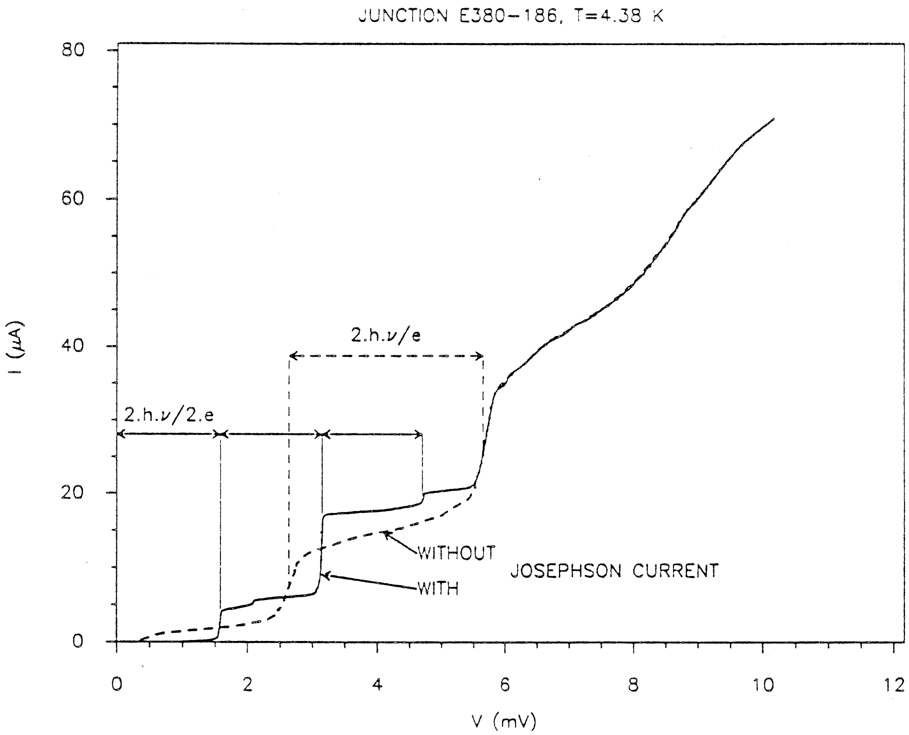

Figure 1

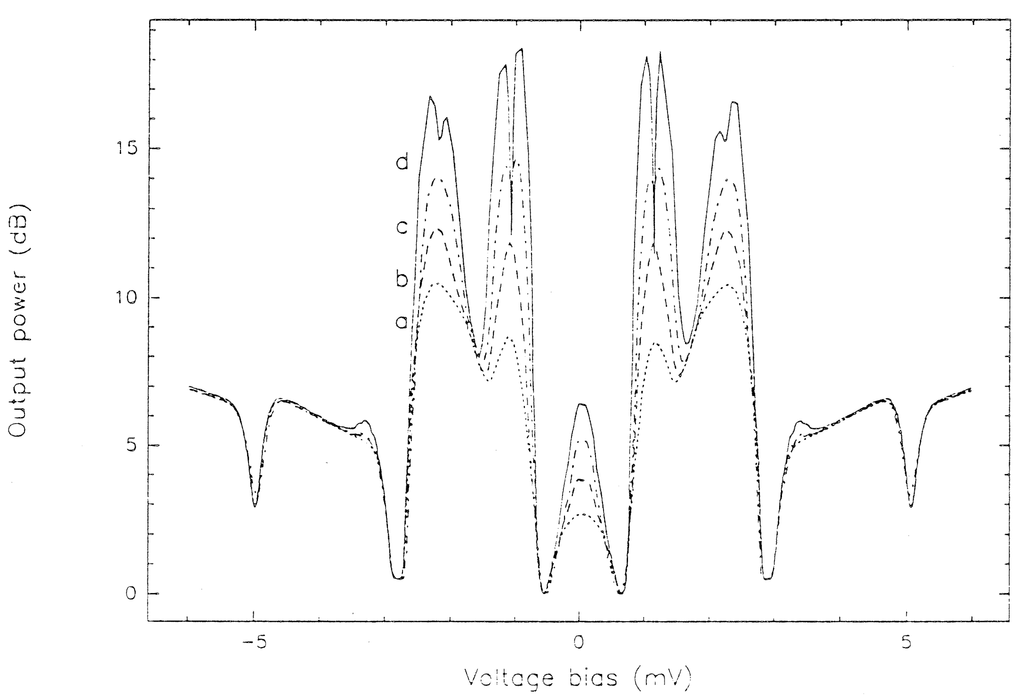

Figure 2

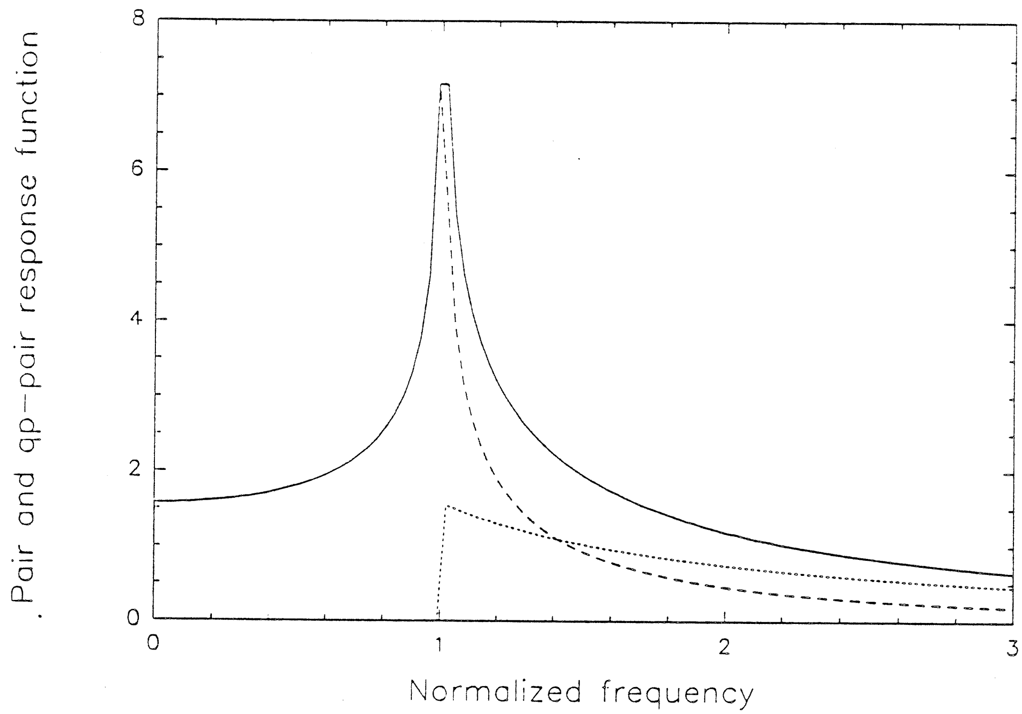

Figure 3

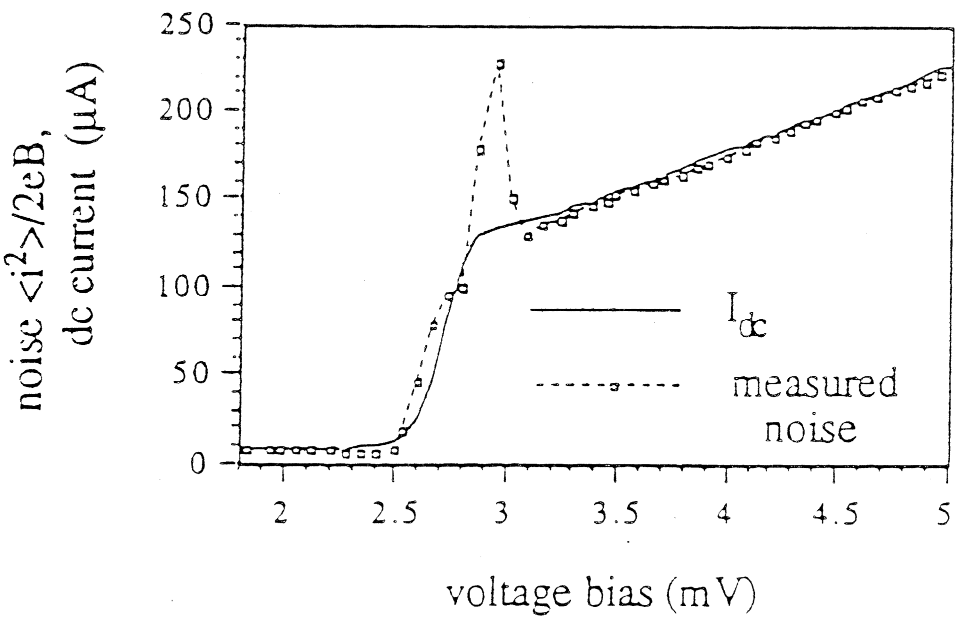

Figure 4