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Experimental evidence of Josephson noise in superconductor-insulator-superconductor quasiparticle mixers

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Josephson currents have been observed to drain instabilities and decrease the sensitivity of a heterodyne superconductor-insulator-superconductor (SIS) receiver operated at submillimeter wavelengths. A static magnetic field is usually applied on the SIS junction to reduce the magnitude of its critical Josephson currents and enable quasiparticle mixing. We measured the SIS mixer output power at the intermediate frequency (IF) versus the dc bias voltage of an array of two $1 \mu\text{m}^2$ Nb/Al-Al₂O₃/Nb junctions. We show evidence of additional, magnetic-field-sensitive noise, peaked at the Shapiro steps voltages, which is due to high-frequency Josephson currents converted to the IF by quasiparticle mixing. © 1997 American Institute of Physics.
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I. INTRODUCTION

The Quantum Theory of Mixing developed by Tucker,¹ which describes the behavior and performance of a superconducting quasiparticle mixer does not account for the Josephson² tunneling of Cooper pairs through the insulating barrier. Commonly, the Josephson currents induced by the optimum bias voltage are considered shunted by the junction intrinsic capacitance for signal frequencies lower than 200 GHz. Indeed, for such frequencies of operation, the optimum mixer bias voltage is close to the gap voltage and corresponds to a Josephson frequency of the order of twice the gap energy, i.e., much higher than the frequency of operation.

When the signal frequency increases, the Josephson frequency (related to the optimum bias voltage) decreases and gets closer to the signal frequency. As a consequence, the Josephson currents are not shunted as much as at lower frequencies.³ In the case of strong Josephson currents, the junction suffers from dramatic instabilities and stable bias is not even possible (drop-back effect).⁴ A static magnetic field is then used to suppress the Josephson current's amplitude as it allows stable bias in most cases. However, we show in this article that even in the case of satisfactory cancellation of the dc Josephson current in the $I-V$ curve, there is still some additional noise that can be attributed to Josephson high-frequency currents.

II. EXPERIMENTAL SETUP

The measurements presented below were performed using a superconductor-insulator-superconductor (SIS) mixer developed at Jet Propulsion Laboratory (JPL)⁵ for observing

the ground state transition of H₂¹⁸O at 547 GHz. They were achieved with a series array of two $1 \mu\text{m}^2$ Nb-AlO_x-Nb junctions.

The junctions were fabricated at the Ecole Normale Supérieure⁶ using dc sputter trilayer deposition for Nb and Al, and photolithography for junction definition. The critical current densities were in the range 8–13 kA/cm², the normal resistance was in the range 15–20 Ω per junction and the intrinsic capacitance was about 95 fF/μm² (Ref. 6). The local oscillator source used for the mixing process was a Gunn diode followed by a doubler and a tripler. The mixer output power was amplified with a low-noise 1.4 GHz high electron mobility transistor amplifier cooled at liquid helium temperature. The signal coming out of the cryostat was further amplified at room temperature, filtered over 300 MHz bandwidth and detected with a bolometer. A superconducting magnet was used to modulate the Josephson amplitude and thus improve receiver performance. It was designed to provide a magnetic field of about 800 G at the junction location for a current through the coil of 1 A. This was sufficient since 1 flux quantum in the junction corresponds to about 340 G.

III. MEASUREMENTS

The measurements were performed at liquid helium temperature. We varied the external magnetic field, the local oscillator power and frequency, and studied the receiver output power for hot and cold loads as a function of the bias voltage.

In the hot and cold loads receiver output power measurements, we observed some sharp structures located at the first two Shapiro step voltages [see Fig. 1(a) at 491 GHz and Fig. 1(c) at 530 GHz] as deduced from the Josephson voltage-frequency relation $f=483 \text{ GHz/mV}$. In the pumped and unpumped $I-V$ curves 1(b) and 1(d) [associated, respectively, to Figs. 1(a) and 1(c)], no Josephson structures were present

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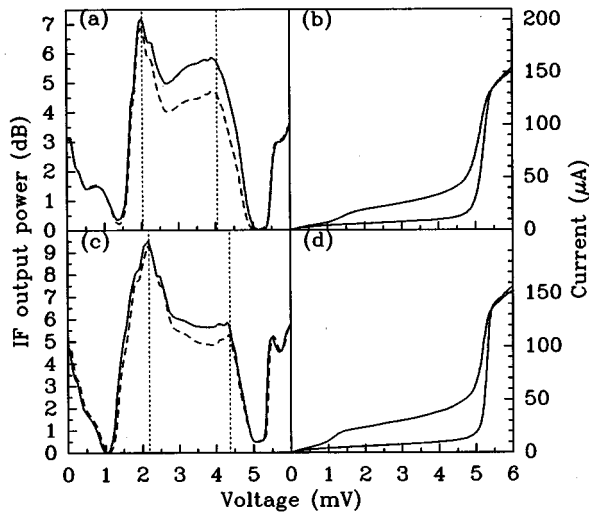


FIG. 1. (a) Output power measurements as a function of bias voltage at 491 GHz for hot and cold loads, $B=607$ G. (b) Pumped and unpumped $I-V$ curves corresponding to (a); (c) Output power measurements as a function of bias voltage at 530 GHz for hot and cold loads, $B=318$ G. (d) Pumped and unpumped $I-V$ curves corresponding to (c). The vertical dashed lines correspond to the first and second Shapiro step voltages. Some peaks are visible in the output power curves at the Shapiro steps though no structure is present in the $I-V$ curves.

due to satisfactory cancellation (less than 1%) of the Josephson currents from a magnetic field set optimally to 607 G at 491 GHz and to 318 G at 530 GHz. The locations of the Shapiro steps are indicated as calculated from the voltage-frequency Josephson relation and correspond very well to the location of the peaks. One can also notice that the influence of Josephson currents was stronger at the first Shapiro step.

Using the hot and cold loads' output power values, we were able to calculate the receiver noise temperature, and we denoted some additional noise peaked around the Shapiro step voltages [see Fig. 2(a) at 491 GHz and 2(b) at 530

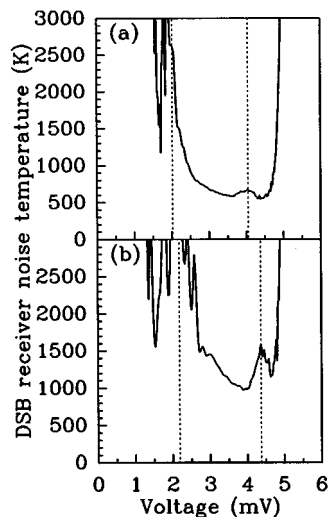


FIG. 2. Double side band (DSB) receiver noise temperature vs bias voltage for (a) $f_{lo}=491$ GHz, $B=607$ G; (b) $f_{lo}=530$ GHz, $B=318$ G. The vertical dashed lines correspond to the first and second Shapiro step voltages.

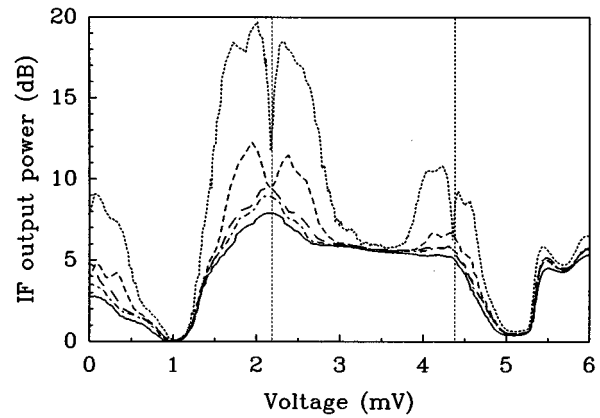


FIG. 3. IF output power for different values of the external magnetic field. Note $f_{lo}=530$ GHz. From down to up, $B=465, 410, 398, 371,$ and 304 G. The drop in the output power for high Josephson currents is due to the IF mismatch caused by the Josephson zero impedance current at the Shapiro steps. The vertical dashed lines correspond to the first and second Shapiro step voltages.

GHz]. At the second Shapiro step location, the extra noise was, respectively, about 25% and 50% of the quasiparticle noise as estimated from the noise baseline close to the peaks.

We then measured the receiver output hot load power at 530 GHz for different values of the magnetic field (Fig. 3): the heights of the peaks were very sensitive to the magnetic field amplitude. These peaks could then be attributed to Josephson noise. The physical mechanism is that for voltage biases corresponding to Josephson frequencies close to the receiver input ports (signal, image, and harmonics), the high-frequency currents generated inside the junction were converted down to the intermediate frequency (IF), hence producing additional noise.⁷ The origin of this noise is the coupling between the pair current and the thermal photon field of the junction.^{7,8} The widths of the peaks ranged from about 0.5 to 1.5 mV which is considerable compared to the quasiparticle step width (3 to 4 mV here). The occurrence of two Josephson noise peaks over the first quasiparticle step would decrease significantly the voltage bias range available for operation. In Fig. 3, one clearly sees that the output power was quite independent of magnetic perturbation only for the 3.25–3.75 mV voltage range. When increasing the amount of Josephson current flowing through the junction, one can notice a modification of the shape of the peaks that were superimposed with a V-shaped drop in the output power. This drop was due to a strong mismatch occurring at the Shapiro voltages because of the zero impedance current. This effect was particularly noticeable in Fig. 4, where we increased the local oscillator power by 2 dB (dashed line) and by 4 dB (dotted line) at a fixed frequency (540 GHz). In the regions where Josephson peaks were present, the receiver was very unstable, especially for high levels of local oscillator power.

It is important to point out that the extra output power brought by Josephson noise was seen at the Shapiro step voltages, even though the dc currents seemed properly cancelled (at least below 1% of the total Josephson current).

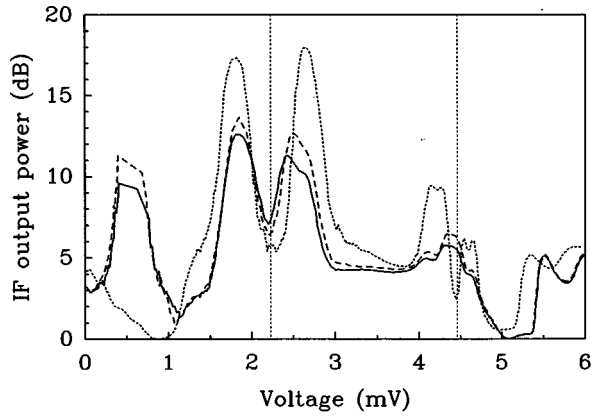


FIG. 4. IF output power for increasing values of the local oscillator power. Solid line: 0 dB, dashed line: 2 dB, dotted line: 4 dB. Note $f_{lo} = 540$ GHz; $B = 291$ G. The vertical dashed lines correspond to the first and second Shapiro step voltages.

Indeed, we never observed in this experiment the complete suppression of the Josephson noise peak in the receiver output power. Two main reasons can account for some residual Josephson currents flowing through the SIS junctions:

- (1) First, we used series arrays of two junctions. The individual junctions may not require the same magnetic field for full cancellation of their respective Josephson currents, due to slight differences of insulator thickness or junction size or shape resulting from the fabrication process.⁹ The effect of the series structure on the Josephson current cancellation was not visible in the $I-V$ curve in the present case. This means that when the critical current of one junction was reduced to less than $1 \mu\text{A}$, the other one was also less than $1 \mu\text{A}$. This implies that the discrepancy in the junctions' sizes was too small to be measured in the $I-V$ curve.⁹ But it could block the Josephson noise peak suppression in the receiver output power. The same feature can appear if a small amount of magnetic flux is trapped in one of the two junctions only.
- (2) Second, it could be that the $1 \mu\text{m}$ -sized, high-current-density SIS junctions were not small compared to the estimated Josephson length λ_J of about $3 \mu\text{m}$ in our case. As a consequence, the Josephson currents could not be totally suppressed. However, the residual Josephson currents may be too low to be observed in the dc $I-V$ curve.

This can be qualitatively explained by simple considerations about the amount of power involved in the physical processes. Because of the extreme sensitivity of SIS receivers, the amount of signal power than can be detected is very small. For instance, Fig. 1(a) shows that the output power increases by about 1 dB at 4 mV between liquid nitrogen temperature (77 K) and room temperature (295 K) blackbodies used as broadband calibration loads. This means that an additional input power of $k_B \Delta T B$ where k_B is the Boltzman constant, $\Delta T = 295 - 80$ K and B is the receiver total bandwidth of 300 MHz, causes an IF output power increase of 1 dB. In this case, $k_B \Delta T B$ corresponds to about 900 fW. By

comparison, the 2 dB extra IF output power brought by Josephson currents at the first Shapiro step at about 2 mV [Fig. 1(a)] can be considered as an extra signal of about 3 pW. This rf power would correspond to a rf current amplitude of about $0.3 \mu\text{A}$, assuming that the mixer impedance at the rf frequency is 40Ω .

From the Josephson equations: $\partial\varphi/\partial t = [2eV(t)]/\hbar$ and $I_{Jos} = I_1 \sin(\varphi)$, we calculated the ratio of the rf Josephson current amplitude I_{rf} to the dc critical current amplitude I_1 , assuming that the junction was biased to the first Shapiro step. Then, the Josephson frequency is equal to the local oscillator frequency. We took into account the local oscillator power in the voltage bias $V(t) = V_0 + v_{lo} \cos(\omega_{lo}t)$, where v_{lo} is the local oscillator amplitude, ω_{lo} is the local oscillator angular frequency, and V_0 is the voltage bias at the first Shapiro step.

It is found that

$$\left| \frac{I_{rf}}{I_1} \right|^2 = [J_0(2\alpha) + J_2(2\alpha)]^2 - 4J_0(2\alpha)J_2(2\alpha)\cos^2 \varphi_0,$$

where α is $ev_{lo}/\hbar\omega_{lo}$, J_0 denotes the Bessel function of first kind and n th order.

Using the same type of calculation, we derived the amplitude of the first Shapiro step I_{dc} :

$$\left| \frac{I_{dc}}{I_1} \right|^2 = J_1^2(2\alpha)\sin^2 \varphi_0.$$

This leads to the maximum values $I_{rf}/I_1 = 0.71$ and $I_{dc}/I_1 = 0.57$, assuming $\alpha = 0.8$ (from the measured pumped $I-V$ curve) and taking the phase at origin $\varphi_0 = \pi/2$. The dc critical current I_1 corresponding to a rf amplitude I_{rf} of $0.3 \mu\text{A}$, calculated above from the output power curve feature at the first Shapiro step, is estimated to be about $0.42 \mu\text{A}$, which is below the minimal detectable current in the $I-V$ curve. Moreover, the onset of current at the first Shapiro step I_{dc} is estimated to be about $0.24 \mu\text{A}$ which is also too low to be detected.

This simple calculation illustrates the fact that dc Josephson currents of $1 \mu\text{A}$ (either at zero voltage or at the first Shapiro step) which are barely detectable in the $I-V$ curve are able to produce some considerable output power at the intermediate frequency of the SIS mixer. Consequently, the correct suppression of Josephson currents in the dc $I-V$ curve is not a reliable way to suppress high-frequency Josephson currents.

IV. CONCLUSION

These measurements put in evidence a major contribution of Josephson currents to the output noise of a SIS quasiparticle mixer at submillimeter wavelengths. This noise is important essentially around the Shapiro steps voltages, where the Josephson frequencies correspond to the signal (for single side-band and double side-band mixers) and image (for double side-band mixers) ports frequencies. It has been reduced by applying a suitable magnetic field. However, we found that some Josephson noise remains even when dc Josephson currents seemed suppressed below the 1% level in the $I-V$ curve. In this case, its associated voltage

range is of the order of 0.5–1 mV, which is considerable compared to the quasiparticle step width (3–4 mV) and the Josephson noise magnitude is of the order of the quasiparticle noise magnitude. Also, the voltage range where Josephson peaks are present in the IF output power curve appears as a range of strong instability with respect to local oscillator power variations and magnetic perturbations. The cancellation of Josephson currents obtained by reducing the height of the Shapiro steps in the I – V curve is rough and does not allow us to minimize the associated noise in a systematic way. The output power versus voltage curve is more sensitive to the presence of Josephson currents since it provides a quantitative measurement of the effective Josephson noise converted to the receiver IF output. Nevertheless, these measurements show that the cancellation of the Josephson currents is not systematically achievable and the contribution of these currents to the receiver output noise is not to be neglected.

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