Quantum-limited heterodyne detection of millimeter waves using superconducting tantalum tunnel junctions

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We have made accurate measurements of the noise and gain of heterodyne mixers employing small-area (1 μm^2) $Ta/Ta_2O_5/Pb_{0.9}Bi_{0.1}$ superconductor-insulator-superconductor tunnel junctions. These junctions have very low subgap leakage current and an extremely sharp current rise at the sum gap. We have measured an added mixer noise of 0.61 ± 0.31 quanta at 95.0 GHz, which is within 25% of the quantum limit of 0.5 quanta for a single-sideband mixer. Values of the imbedding admittances are deduced from the shapes of *I-V* curves pumped at the upper and lower sideband frequencies. Using these admittances, the mixer performance calculated from the quantum theory is in good agreement with the experiment.

Heterodyne receivers which use quasiparticle superconductor-insulator-superconductor (SIS) mixers have been shown to be the coherent receivers with the lowest noise over much of the millimeter and submillimeter range of the electromagnetic spectrum. [1] However, even the best of these receivers have fallen short of the performance which is predicted by the Tucker theory of quantum mixing.[2,3] Because of the lack of detailed comparisons between experimental and theoretical performance, it has been unclear whether the discrepancy between actual performance and predicted performance is due to difficulties in coupling the signal to the mixer, or problems with the theory.

Several authors have made quantitative comparisons of SIS mixer performance to theory. Feldman *et al.*[4] obtained good agreement with theoretical predictions of mixer gain at 115 GHz using imbedding admittances measured from a scaled model. However, they did not determine mixer noise accurately enough for a comparison with theory. McGrath *et al.*[5] made an extensive comparison between theory and experiment at 36 GHz. They concluded that the theory overestimates the gain, and underestimates the noise by a significant amount. These authors did not measure the imbedding admittances involved in the actual experiment, and therefore could only compare experimental performance with that predicted with the imbedding admittance optimized for best performance. The allowable range of admittance was determined from a scaled model.

In this work we carry out a detailed analysis of the performance of high quality, small-area (1 μm^2) $Ta/Ta_2O_5/PbBi$ tunnel junctions[6] used as quasiparticle mixers near 90 GHz. This work differs from that quoted above in that we deduce accurate imbedding admittances under experimental conditions, and use these admittances to predict both mixer noise and mixer gain.

The noise performance of any phase-preserving linear amplifier (such as a mixer operated in the small signal limit) is limited by the Heisenberg uncertainty principle. Analysis[2,3,7-9] shows that the spectral density of the added noise added refered to the input of a single-sideband (SSB) mixer referred to the input is $\hbar\omega/2$. Here ω is the angular frequency of the incoming radiation. Thus the quantum limit for a SSB mixer can be expressed as 0.5 quanta of added noise.

Accurate measurements of mixer noise and gain were required for this work. The methods and the apparatus that were used, using variable temperature blackbody sources, are described in detail elsewhere.[10,11] The output of the 1.4 GHz intermediate frequency (IF) system was measured as the temperature of the radio frequency (rf) load (blackbody) at the mixer input was varied from 1.3 to 20 K. A coaxial switch and a variable temperature IF load[10] were used to characterize the noise spectral density and gain-bandwidth product of the IF system. The mixer block[11] was a quarter-height W-band (75–110 GHz) waveguide with an adjustable noncontacting backshort, which was the only tuning element used.

The experiments reported here were carried out on a single junction which had a normal resistance of 72 Ω at 1.3 K. The current-voltage (*I-V*) curve of the junction is shown in Fig. 1(a). The voltage width ΔV over which the sum-gap current step rises from 0.1 to 0.9 of its full value is less than 0.01 mV. The leakage current at $0.8V_{gap}$ is less than $0.05I_c$. The junction properties remained unchanged for more than six months despite room-temperature storage and many thermal cycles. Junctions of this quality are ideal for testing quantum mixer theory.

For the purposes of this letter, mixer performance is characterized by the spectral density of added mixer noise in units of quanta of the incoming radiation field, and the

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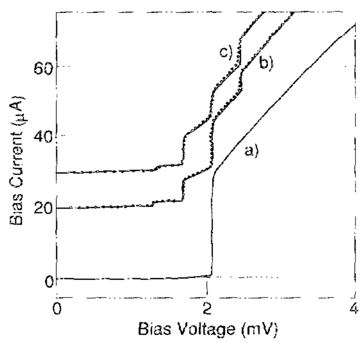

FIG. 1. (a) Measured dc I-V curve of the Ta junction studied. (b) Experimental and calculated pumped I-V curves. The solid line is the calculated curve. Experimental data points are represented by dots. The pump frequency was 96.35 GHz. The imbedding admittance used in the calculation was $Y = 0.14 + 0.08i\ \Omega^{-1}$. (c) same as (b), except that the pump frequency was 93.65 GHz and imbedding admittance was $Y = 0.04 + 0.18i\ \Omega^{-1}$ These are upper and lower side band admittances used in the calculation of the solid lines shown in Fig. 3. All I-V curves were measured at $T = 1.3$ K with no applied magnetic field.

available conversion gain of the mixer, defined as the ratio of the available power at the IF port to the available power at the signal port.

The measured mixer noise is plotted as a function of local oscillator frequency in Fig. 2. At each frequency, the backshort position, the available local oscillator power, and the dc bias voltage were optimized using a coherent signal source to give the maximum coupled gain. The peak in mixer noise around 90 GHz is a region where our mixer mount could not provide favorable imbedding admittances. The minimum measured value of added mixer noise was 0.61 ± 0.36 quanta at 93.0 GHz. The sideband ratio at this operating point was 9.8 dB, essentially making this a SSB mixer. To our knowledge, this experimental value is the closest approach quantum limit that has been accurately measured to date.

To compare our experimental results with the Tucker theory, we carried out computer simulations of mixer performance. All calculations were done using a three-port model, that is, with currents generated at the second and higher harmonics assumed to be shunted by the relatively large geometrical capacitance of our junctions ($C = 160$ fF, which yields $\omega R_n C \approx 14$ at 190 GHz).

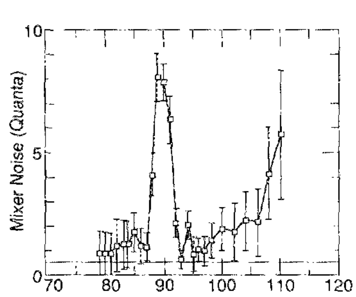

FIG. 2. Added mixer noise as a function of frequency. The horizontal line at $S = 1/2$ is quantum limit imposed by the uncertainty principle. Here the $S = 1/2$ vacuum fluctuations already present on the signal are not included in the mixer noise.

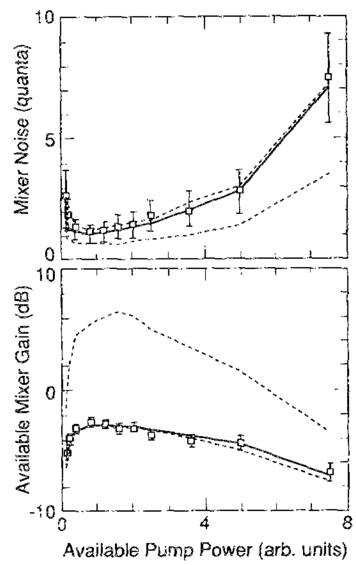

FIG. 3. Added mixer noise and available gain as a function of LO pump power with $f_{LO} = 95.0$ GHz, $V_{dc} = 1.956$ mV. The dashed lines are the limits of the performance that are consistent with I-V curve shape. The solid line is the best fit to measured performance, with $Y_{USB} = 0.14 + 0.08i\ \Omega^{-1}$ and $Y_{LSB}\ 0.04 + 0.18i\ \Omega^{-1}$. All measurements were performed with no applied magnetic field.

In this model, the added noise and the available mixer gain depend on the dc I-V characteristic, the dc bias point, the amplitude of the local oscillator drive voltage, and the imbedding admittance at the upper and lower sideband frequencies. The dc I-V curve and the dc bias point are easily measured. The amplitude of the LO drive voltage can be deduced from the dc current in the pumped, biased junction. It is difficult, however, to determine directly the imbedding admittances at the upper and lower sideband frequencies.

To simplify comparisons with theory, we carried out a simple experiment which involves only one pair of imbedding admittances. We measured mixer noise and available gain as a function of pump power for a specific, fixed dc bias voltage, pump frequency, IF frequency, and backshort position with no external magnetic field applied. The available gain and mixer noise as functions of available pump power are shown in Fig. 3.

Since the I-V curves of our devices closely resemble those calculated using the BCS density of states and elastic tunneling theory, the imbedding admittance can be determined by studying the shape of the pumped I-V curve.[12,13] We used the voltage match method described elsewhere[14,15] to determine a range of imbedding admittance consistent with the shape of I-V curves obtained when the mixer was pumped at the upper and then at the lower sideband frequency. Comparisons between admittances determined by scaled model measurement and those deduced from I-V curve shapes show good agreement. This work represents the first systematic application of this method to obtain a detailed model of the performance of a real mixer. The agreement obtained between experimental and calculated pumped I-V curves shown in Fig. 1 is of higher quality than in any previous work. The admittances obtained in this way were used in the Tucker theory to predict mixer noise and available gain.

A range of values of predicted performance is obtained by exhaustively sampling on a grid of admittance combinations consistent with the shapes of the I-V curves pumped at the upper and lower sideband frequencies. The range of mixer noise and coupled gain into which 95% of the predicted values fall is indicated by the dashed lines in Fig. 3. The experimental values are consistent with the predicted range of performance, but are at the poor performance (high noise, low gain) end of the range. This is the same trend reported by McGrath *et al.*[5]

By choosing one specific set of imbedding admittances within the allowed range, we are able to calculate mixer gain and noise that agrees with experiment within experimental error. This comparison is represented by the solid lines in Fig. 3. The admittances used for these calcuations are the same as those used to calculate the pumped I-V curves in Figs. 1(b) and 1(c).

It is useful to consider effects that could cause discrepancies between calculated and experimental mixer performance. It is possible that the Tucker theory overestimates the performance when the dc I-V curve is used to predict high-frequency behavior. This could occur if the unpumped dc I-V curve is influenced by nonequilibrium effects, so it does not accurately represent the density of states. A very small negative dynamic resistance observed on the sum-gap current rise indicates that the high current density of our junctions[6] heats the quasiparticles and sharpens the current rise at the sum-gap voltage.[16] The time scale of this effect is much longer than one cycle of the local oscillator, and the high-frequency behavior is not accurately determined by the dc I-V curve. A second possibility is that the leakage current does not arise from tunneling, so is not correctly modeled by the Tucker theory. If this effect is important it could explain our relative success because the effect would be minimized in our low-leakage junctions. It is possible that the determination of imbedding admittance using pumped I-V curves gives incorrect results, either due to nonequilibrium phenomena, leakage currents, or other effects. We consider this unlikely because of the good agreement between the admittance deduced by the fitting procedure and those measured using a scaled model,[17] or theoretical expectations.[13]

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