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Abstract

We have made accurate measurements of the noise and gain of heterodyne mixers employing small area ($1\mu m^2$) $Ta/Ta_2O_5/Pb_{0.9}Bi_{0.1}$ superconductor-insulator-superconductor (SIS) tunnel junctions. These junctions have very low sub-gap 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 percent 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.

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Heterodyne receivers which use quasiparticle SIS mixers have been shown to be the coherent receivers with the lowest noise over much of the millimeter and sub-millimeter 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 recent modeling in that we deduce accurate imbedding admittances under experimental conditions, and use these admittances to predict both mixer noise and mixer gain.

The performance of any phase-preserving linear amplifier is limited by the Heisenberg uncertainty principle. The general theoretical treatment by Caves[7] shows that any narrow-bandwidth phase-preserving linear amplifier must add noise with spectral density

$$S_N \geq | 1 - G_P^{-1} | \hbar\omega/2, \qquad (1)$$

referred to the input. Here G_P is the photon number gain, and ω is the angular frequency of the signal to be amplified.

An SIS mixer is a phase-preserving linear photon number amplifier as long as it is operated in the weak signal limit. Therefore, the quantum limit (1) applies. Since an SIS mixer almost always operates in the regime of large photon number gain, equation (1) reduces to

$$S_N \geq \hbar\omega/2. \qquad (2)$$

The Tucker theory predicts the noise performance of an SIS mixer that arises from fluctuations in the quasiparticle tunneling currents. This noise has a minimum value of $\hbar\omega/2$ for a single-sideband (SSB) mixer, and zero for a symmetric double-sideband (DSB) mixer.[8] This theory is incomplete in that it treats the radiation

as a classical field. Wengler and Woody[9] extended the Tucker theory to the case of quantized radiation fields. They showed that the additional noise that arises from the quantization of the radiation field is $\hbar\omega/2$ for an SSB mixer, and $\hbar\omega$ for a DSB mixer. When we add these uncorrelated contributions to the noise, the minimum noise of an SIS mixer is $\hbar\omega$ for an arbitrary image termination. In this letter we choose to consider the vacuum fluctuations incident on the mixer as part of the signal. Thus, the quantum limit is taken to be the noise added by the mixer. Expressed in units of quanta, the quantum limit is 0.5 for a SSB mixer, and zero for a DSB mixer.

Accurate measurements of mixer noise and gain were required for this work. The methods and the apparatus that were used are described elsewhere.[10,11] The mixer block was a quarter-height W-band (75-110 GHz) waveguide with an adjustable non-contacting backshort. Coherent radiation at the local oscillator (LO) frequency of ~95.0 GHz was fed to the mixer through a cooled crossed-guide coupler. The 23-dB loss of the coupler served to attenuate room-temperature thermal radiation. The straight-through arm of the coupler was terminated by a specially designed variable temperature RF waveguide load[10] which provided a calibrated single mode black-body signal with spectral density S_l.

The mixer was tuned by injecting a monochromatic signal through the LO waveguide at either the upper or lower sideband. In each experiment, appropriate parameters were optimized to maximize the output power P_{IF} of the 1.35 GHz IF system, and hence the SSB coupled gain.

The IF power from the mixer was coupled to a liquid Helium temperature GaAs high electron mobility transistor (HEMT) amplifier through a quarter-wave microstrip matching transformer.[11] A 30-dB directional coupler was used to measure the power reflection coefficient $|\rho_m|^2$ between the mixer output and the input of the IF amplifier. A cooled coaxial switch and a specially designed variable-temperature coaxial IF load[10] were used to characterize the noise spectral density S_{IF} and the gain-bandwidth product GB_{IF} of the IF system.

In each experiment, four values of the temperature of the RF load were chosen in the range from 1.3K to 20K, and four corresponding values of the input spectral density S_1 were calculated from the Planck black-body expression plus $\hbar\omega/2$ for vacuum fluctuations. The output power at the IF frequency P_{IF} was measured for each load temperature. A substantial part of P_{IF} is due to noise sources in the measurement apparatus, which can be measured and subtracted. The various contributions to P_{IF} can be written

$$P_{IF} = GB_{IF} \left\{ S_{IF} + \rho_m^2 S_B + G_m (1 - \rho_m^2) \left[S_m + S_{LO} + \alpha S_B + (1-\alpha) S_1 \right] \right\}, \quad (3)$$

where G_m is the available gain of the mixer, S_m, S_{LO}, and S_B are, the spectral densities of the noise added by the mixer, the room temperature noise leaking down the LO waveguide, and the Helium bath, respectively, also α is the attenuation between the RF load and the mixer. Losses due to impedance mismatch at the signal frequency are included in the mixer gain. We are interested in the added mixer

noise S_m and mixer gain G_m which can be obtained from the slope and intercept of the best linear fit to plots of P_{IF} as a function of S_1.

The experiments reported here were carried out on a single junction which had a normal resistance of 72 Ω at 1.3 K. Both the normal resistance and the shape of the I-V curve remained constant over a period of six months, even though the junction was stored at room temperature in a desiccator during much of that time. This durability is in contrast to the behavior of earlier Tantalum junctions[5] and is attributed to the 150 Å overlayer of indium deposited on top of the counter-electrode.[12]

The I-V curves of the Tantalum junctions used in this experiment showed extremely sharp current rises at the sum-gap voltage as well as extremely low sub-gap leakage current. 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 0.8 V_{gap} is less than 0.05 I_c. The dc I-V curve of the junction is shown in Fig. 1a. Junctions of this quality are ideal for testing quantum mixer theory.

For the purposes of this paper, mixer performance is characterized by the spectral density of added mixer noise in units of quanta of the incoming radiation field, and the available conversion gain of the mixer. The available gain is defined as the ratio of the available power at the IF port to the available power at the signal port. Operationally this is determined by measuring the coupled gain (transducer gain), and correcting it for the measured reflection at the IF port[5]. The available gain is independent of the IF load impedance, and thus can be directly calculated from Tucker's theory.

The noise for the mixer studied 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 to give maximum coupled gain. Mixer noise was found to be a minimum of 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 for which the quantum limit is 0.5 quanta. To our knowledge, this experimental value is the lowest mixer noise, in terms of mixer quanta above the appropriate quantum limit, that has been accurately measured to date. The peak in mixer noise around 90 GHz is a region where our mixer mount could not provide optimum imbedding admittances.

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).

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 pumped current at the dc bias point. It is difficult, however, to determine directly the imbedding admittances at the upper and lower sideband frequencies.

Several approaches can be used to determine the imbedding admittances. First, numerical modeling of the imbedding structures could be carried out. While this may be feasible in simpler situations, the complexity of our mixer block makes this process tedious and of questionable reliability. The second method is to measure the admittance of a large scaled model of our mixer block at lower frequencies (3 - 10 GHz), where accurate network analyzers are available. While this method is much simpler, it suffers from the difficulty of determining the exact position of the backshort in the 90 GHz mixer block under our experimental conditions.

The Tucker theory provides a way of deducing the high frequency properties of a mixer from its dc I-V curve[13] provided that the dc I-V curve of the junction is influenced only by elastic tunneling processes.[14,15] The I-V curves of our devices closely resemble those calculated using the BCS density of states and elastic tunneling theory. Therefore, the imbedding admittance can be determined by studying the shape of the pumped I-V curve. We used the voltage match method described elsewhere[16,17] to determine a range of imbedding admittance consistent with the shape of the pumped I-V curve. 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 range of imbedding admittances consistent with a specific experimental configuration. The agreement obtained between experimental and calculated pumped I-V curves is of higher quality than in previous work.

The procedure we used is as follows: we first measured the unpumped dc I-V curve and then pumped the mixer at the upper side-band frequency and then at the lower side-band frequency. We measured several pumped I-V curves, and deduced the imbedding admittances at the upper and lower side bands from these curves. These admittances were used in the Tucker theory to predict mixer noise and available gain.

To test this procedure, we carried out a relatively 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 curve fitting procedure does not yield exact imbedding admittances, it is only possible to extract a range of values of predicted performance. This is done 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 consistent with the conclusions reached by McGrath et al.[5] We have also observed similar behavior in other experiments involving this mixer.

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 experimental and calculated I-V curves pumped at the upper and lower sideband frequencies are shown in Fig. 1b and 1c. The admittances used for these calcuations are the same as those used to calculate the solid lines in Fig 3.

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 nonequilibruim effects, so 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.[18] 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 non-equilibrium 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,[11] or theoretical expectations.[15]

We have accurately measured the performance of an SIS mixer operating in the quantum limit where the noise is limited by the uncertainty principle. Our mixer noise is a maximum of 0.42 quanta above the quantum limit. This is, to our knowledge, closest approach to the quantum limit measured in any mixer. We have calculated pumped I-V curves in nearly perfect agreement with those measured in the experiment. Using admittances deduced from the fitting parameters and the Tucker theory of quantum mixing, we have predicted mixer performance in good agreement with the experimentally measured performance.

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1. a) dc I-V curve of the junction studied at Temperature 1.3 K. 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 the upper and lower side band admittances used in the calculation of the solid lines shown in Fig. 3. All I-V curves were measured with no applied magnetic field.

2. Added mixer noise as a function of frequency. The horizontal line at $S = 1/2$ is the 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.

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.

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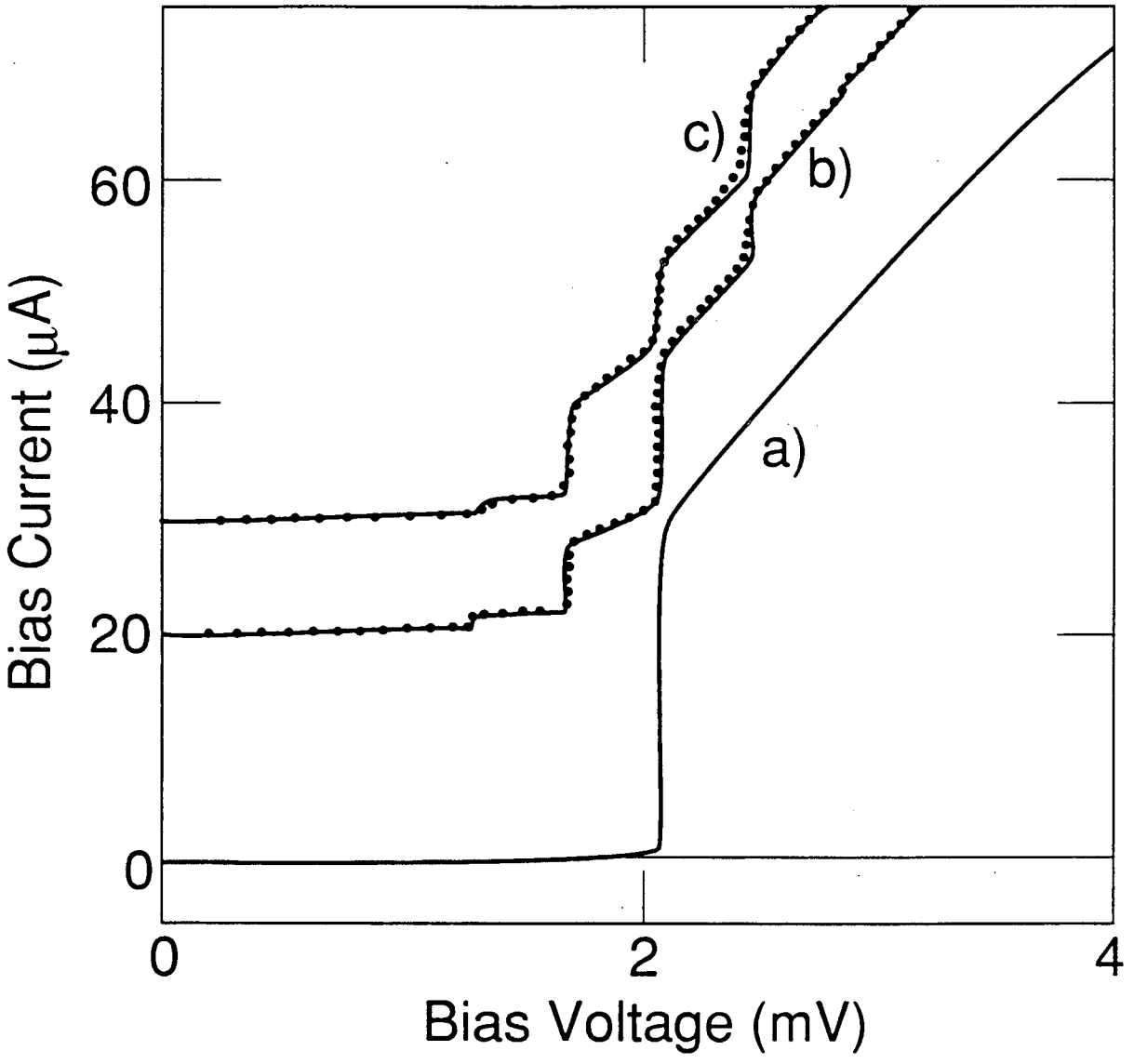

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Figure 1

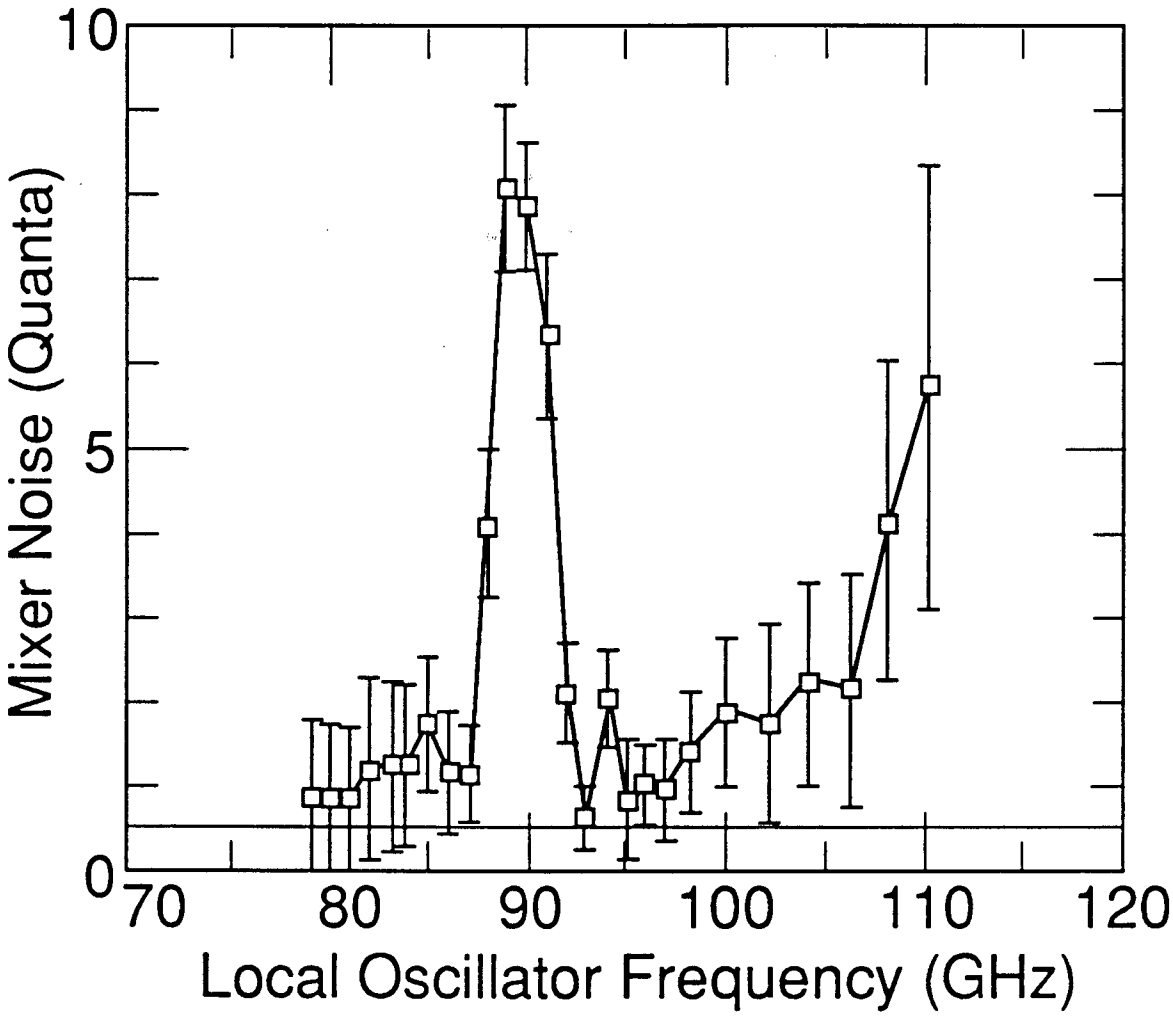

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Figure 2

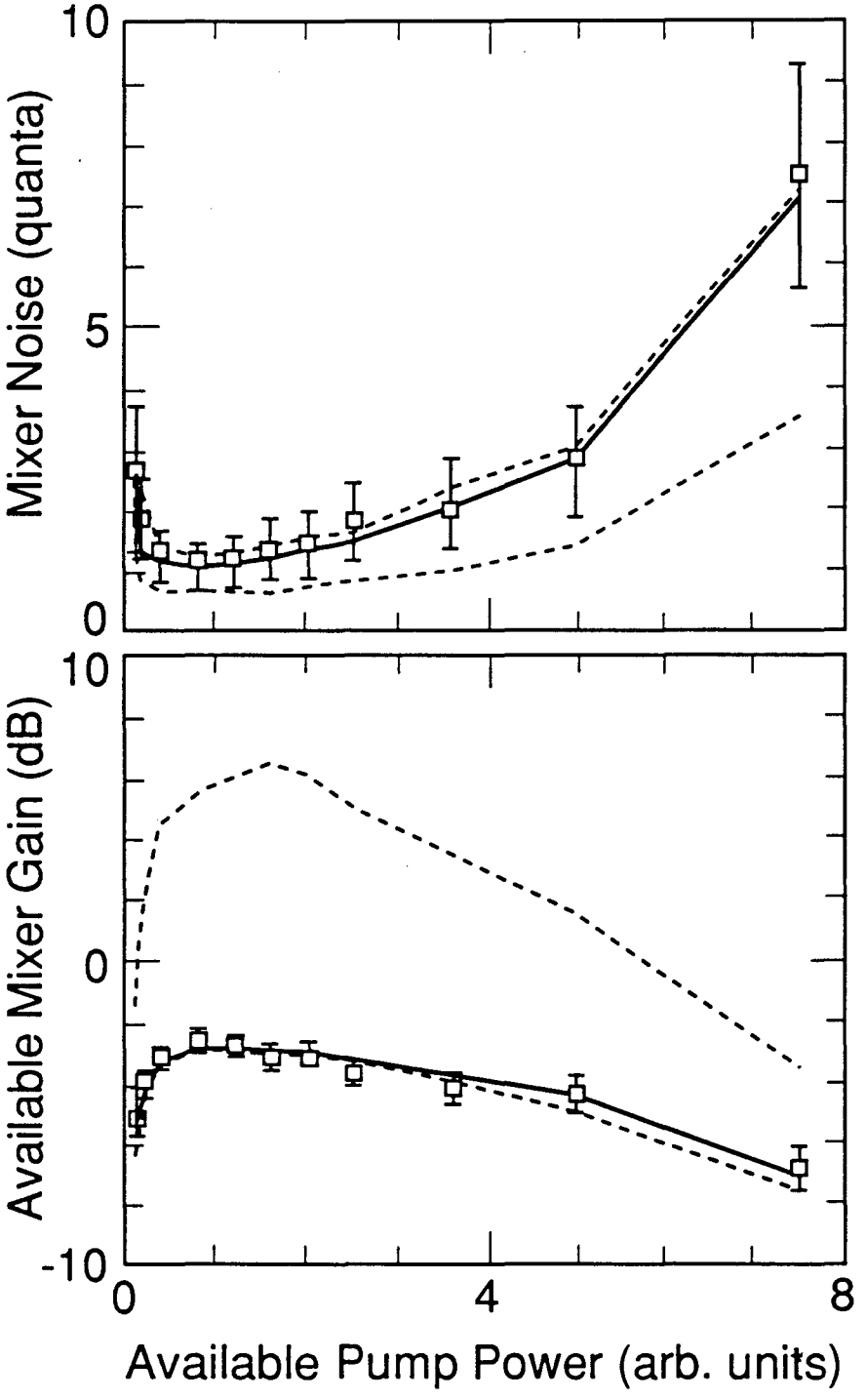

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Figure 3

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