

Measurements of Noise in Josephson-Effect Mixers

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Abstract—We present new heterodyne receiver results obtained at 100 GHz using resistively-shunted Nb and NbN tunnel junctions. In addition, we have carried out accurate measurements of the available noise power of these devices at the L-band (1.5 GHz) IF frequency. Both the heterodyne and the output noise measurements show that the noise of these devices can be a factor of five or more higher than that predicted by the simple current-biased RSJ model. The noise approaches the appropriate thermal or thermal and shot noise limits for bias voltages where the nonlinearity is not strong (i.e., $V > I_C R_N$), but as expected from the RSJ model, can be significantly higher at the low voltages where the mixers are typically biased. The bias voltage dependence of the noise shows structure which is associated with resonances in the RF embedding circuit. Surprisingly, we find that changes in the high-frequency (100 GHz) impedance presented to the junction can dramatically affect the magnitude and voltage dependence of the low-frequency (1.5 GHz) noise. This emphasizes the necessity of very closely matching the junction to free space over a wide frequency range.

I. INTRODUCTION

WHILE JOSEPHSON-EFFECT mixers have been shown to have low conversion loss and low local oscillator power requirements as millimeter-wave mixers, their sensitivity is not as good as SIS mixers which utilize the quasiparticle nonlinearity of superconducting tunnel junctions. Josephson mixers are known to suffer from an “excess” noise, whose origin and magnitude has been clarified by recent simulations based on the resistively-shunted junction model (RSJ) [1]. Recent progress in fabrication of high- T_C Josephson devices (mostly of SNS weak link types) has produced $I_C R_N$ products of up to 10 mV [2], [3]. These devices may be suitable for producing heterodyne receivers well into the terahertz frequency range. However, in order to draw conclusions about the expected sensitivity and technological potential of Josephson-effect mixers in this frequency regime, a firm understanding of the noise processes and their scaling will be required.

We have been engaged in studies of the noise which is present in numerical simulations using the RSJ model, and

in measurements of the heterodyne performance characterized, lithographically-controlled Josephson using Nb and NbN shunted tunnel junctions. The measurements suggest that the output noise of can be even larger than the “excess” predicted model. We have therefore undertaken accurate measurements of the output noise of these shunted junctions at intermediate frequency (IF) of 1.5 GHz, including the contributions of the IF amplifier and correct power coupling to the junction.

II. JUNCTION FABRICATION

The devices used in the experiments describe made using a process for resistively-shunted tunnel junctions described previously [4]. A submicron, high current tunnel junction [5], [6] is fabricated along with a shunt in close proximity. Junctions based both on Nb and NbN/MgO/NbN trilayers are used. The shunt reduces the junction normal-state resistance, as $I_C R_N$ product, by a factor of typically three. Shunted junctions have normal resistances (after 30–40 Ω , critical currents of 10–20 μ A, $I_C R_N$ about 0.5 mV, and are very stable with time cycling. The current-voltage characteristics are non-linear and very RSJ-like, the critical current scales with junction area and the critical current can be modulated with magnetic field. The junctions have current rises at the superconducting gap of the material (2.9 mV for Nb and approximately 1.5 mV for NbN), but this effect is small, since the current flows through the shunt resistor. Because the shunt reduces the $I_C R_N$ product and thus the critical frequency ($\omega_c = 2eI_C R_N/\hbar$), these devices should be more suitable for heterodyne detection at 100 GHz, but may not be suitable for higher frequencies.

III. HETERODYNE RECEIVER MEASUREMENTS

We have performed heterodyne detection tests using shunted Nb and NbN junctions fabricated using the process described above. The devices are fabricated on sapphire substrates and mounted in a full-height waveguide mixer mount. The mixer mount is mechanically-adjustable, non-contacting backshroud, allowing a wide variation of the impedance presented to the junction. The waveguide has a transition to a corrugated feedhorn, whose beam is then coupled outside the

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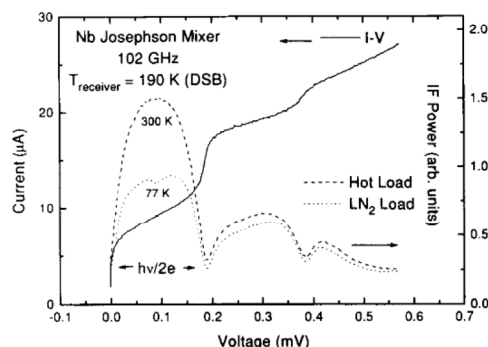


Fig. 1. Shows receiver response to hot/cold absorbers at input. Solid curve is I-V curve under 102-GHz LO radiation, dashed curve is IF output power (in arbitrary units) when receiver views a room temperature load, dotted curve is power when viewing an LN_2 soaked absorber. Horizontal axis is junction bias voltage in mV. Only the positive half of the symmetric I-V curve is shown.

through a series of cooled IR filters and a polyethylene lens. Local oscillator (LO) radiation from a Gunn diode oscillator is injected into the beam through a mylar beam splitter. The beam pattern has been measured outside the dewar, and there is negligible spillover of the receiver beam onto dewar windows and filters. All measurements were performed with the devices cooled to 4.2 K.

The junction is biased with a combination bias tee and intermediate frequency (IF) matching network, which provides an optimum match for impedances of about $90\ \Omega$ into the $50\text{-}\Omega$ IF circuit. The IF signal is amplified by a HEMT low-noise amplifier (LNA) on a 12 K stage, which has a gain of 30 dB and noise temperature of approximately 10 K. The amplifier bandpass is 500 MHz, centered at 1.5 GHz. The IF signal is then coupled to filters and room temperature amplifiers, and then finally led to a power detector. The bias electronics can be controlled using a personal computer, and current-voltage characteristics and IF power levels can be digitized and recorded for later analysis.

When illuminated with LO power, the devices develop strong Shapiro steps at the quantized voltages $V_n = nh\nu/2e$, and the IF power shows smooth peaks between the current steps (see Fig. 1). Receiver response is measured using the standard hot/cold load technique, typically with room temperature and liquid nitrogen cooled absorbers which fill the receiver beam outside the dewar. Best response is always obtained between the zeroth and first Shapiro steps, and for a local oscillator power which suppresses the critical current by approximately 50%. All of this behavior is in agreement with the predictions of the RSJ model.

A representative pumped I-V curve and hot/cold load response for a Nb shunted junction at 102 GHz is pictured in Fig. 1. When biased at the optimum voltage, this receiver has a Y-factor of 1.8, and a double-sideband receiver noise temperature of 200 K. The best sensitivity seen to date with NbN devices is 270 K (DSB), and the general receiver behavior is very similar for devices with either superconductor. The conversion efficiency is approximately -6.5 dB, and therefore the mixer noise temperature, including any front-end losses, was about 150 K. Since this device was expected to

be nearly optimal based on its observed dc characteristics, the mixer noise temperature expected from RSJ model is closer to 30 K (DSB), with about -3 dB conversion loss. Even when accounting for the slight saturation at single-sideband operation of the receiver as described, and including estimates of the front-end optical mixer output noise is probably still a factor of higher than expected.

The mixer sensitivity is strongly dependent on the position of the adjustable RF tuners, with best response at the positions which yield the maximum output power. The optimum LO power match into the mixer is also close to optimum LO power match into the receiver. As we measure the instantaneous bandwidth of the mixer by changing the LO frequency while keeping the tuner positions fixed, the noise temperature degrades by about 50% when the frequency has been displaced by the 3 GHz separating the sidebands, and then continues to increase roughly linearly with the frequency displacement. Note that this variation in receiver temperature is not due to compensation of junction capacitance, as these devices have $\omega L \gg 1$ at 100 GHz. This variation must instead be attributed to the intrinsic dependence of the mixer temperature on the driving impedance. The observed dependence may indicate that the receiver is being tuned to a largely single-sideband operation with a corresponding overestimate of the DSB noise temperature from hot/cold load measurements.

We have also made a crude measurement of the mixer sensitivity by plotting receiver output power as a function of input load temperature for liquid nitrogen, dry ice, room temperature, and heated (≈ 350 K) RF load. The results indicate that the mixer is approximately 20% sensitive to a room temperature input, and this effect probably represents a roughly 1 dB overestimate of the conversion loss. The size of this effect is reasonable given the expected low-conversion-loss SIS mixers at these frequencies. Saturation probably arises in the output because the signal swings are limited to the size of a photon step. We expect that this effect should be significantly (up to a factor of 4) stronger in Josephson-effect mixers, since the Shapiro steps are half as wide. The larger conversion loss for SIS mixers, that we observe probably tends to saturation.

The shape of the pumped I-V curves can be varied significantly as the mechanical tuners are adjusted. Several curves for a single device under illumination with LO radiation and varying tuner positions are shown in Fig. 2. The strong variation in output impedance over a wide range of driving impedances can be presented in Fig. 2. Negative differential resistance such as that in Fig. 2 is expected when the junction is driven by a largely inductive impedance [9], and the low output power probably corresponds to a capacitive drive. Both sets of curves were taken for tuner positions which were far from LO power match and therefore required more LO power to yield equivalent suppression of current. Best receiver performance is always observed for more intermediate output impedance similar to that required for a real drive impedance, which is again consistent

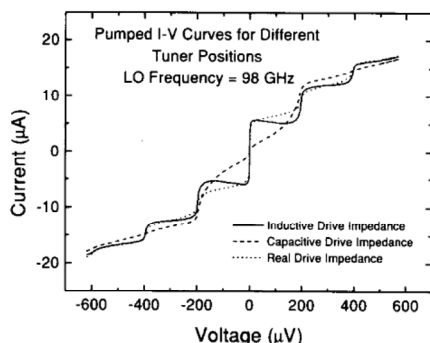


Fig. 2. Displays several I-V curves of the same junction obtained under illumination with 98-GHz local oscillator power. The different curves and the dramatically different dynamic resistances between photon steps are a result of the different positions used for the mechanical waveguide tuners. Different amounts of LO power have been used to render approximately the same degree of critical current suppression. The full line probably corresponds to an inductive driving impedance, the dashed line to a capacitive drive, and the dotted line to a real drive impedance.

model predictions that optimum mixer performance should be possible with mostly real RF impedances.

IV. NOISE MEASUREMENT TECHNIQUE

In order to verify that higher output noise is responsible for the degraded receiver sensitivity and to examine whether this noise can be reduced or eliminated, we undertook accurate measurements of available noise power produced by the junction under a variety of conditions, both with and without LO power applied. We report here only measurements in the absence of LO power, and with the optics removed so that the junction sees only 4.2 K thermal radiation at all frequencies. A block diagram of the microwave apparatus is displayed in Fig. 3. A coaxial switch [10] was inserted between the junction and the amplifier so that a variable temperature termination, similar to that described by McGrath *et al.* [11], could be substituted for the junction. Two isolators [12], each with a directivity of about 20 dB, ensure that no reflected noise waves from the amplifier contaminate the measurements. Finally, a bi-directional coupler [13] allows a test signal to be introduced in order to measure the power reflection coefficient from the junction using a procedure described below. A similar technique has been used recently by Dubash *et al.* [14] to measure the output noise of SIS mixers to high accuracy.

By heating the termination and observing the output power as a function of temperature, the noise of the IF chain and the gain of the system could be determined. A typical calibration is displayed in Fig. 4. The termination was measured to have a return loss at cryogenic temperatures of about -14 dB. The chief uncertainty in calibration is in the accuracy of the diode temperature sensor [15] used to read the load temperature. The diode was calibrated by suspending it in a liquid helium storage dewar, and we estimate the error on the IF system noise determination to be ± 0.5 K. The IF system temperatures were typically about 10 K, varying slightly depending upon the bias conditions of the low noise amplifier and the bandpass selected by using room temperature filters.

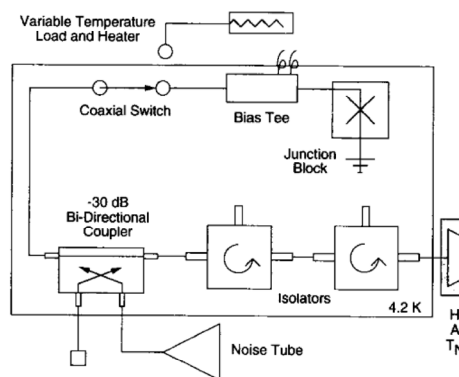


Fig. 3. A block diagram schematic of the apparatus used for noise measurements. Junction is connected to a coaxial switch, through coupler and two isolators. Coupler allows calibration of junction coefficient, and switch enables a variable-temperature termination connected to the IF input for calibration of system gain and

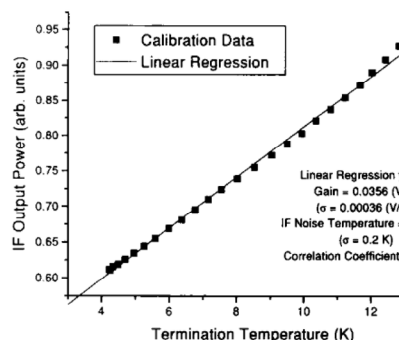


Fig. 4. A typical IF calibration using variable-temperature termination. The x-axis shows measured load temperature, and output power in corresponding to the voltage on total power detector, is displayed on the y-axis. Data points are shown along with best-fit linear regression parameters corresponding to fit. Statistical errors for fit shown by equally weighting all points and assuming that the deviation from the fit represent the uncertainties. Fits are dominated by system noise.

To determine the available noise power from the junction and thus the junction output noise temperature, it is necessary to correct for any losses and mismatch between the junction and LNA. The bi-directional coupler allowed the introduction of a signal from a noise tube to be launched into the junction. This signal was limited to a 500-MHz bandwidth at the 1.5-GHz IF frequency, and typically increased the noise by about 20%. No difference in the shape of the curve was observed between noise tube on and noise tube off, verifying that the noise did not grossly affect the junction properties. Because of the weak (-30 dB) coupler, noise is added when the noise tube is off, and this results in an increase in the measured IF system temperature of about 0.5 K. The directivity of the coupler was measured to be greater than 20 dB.

The difference in IF power with and without the noise tube applied gives a measure of the reflection coefficient of the junction. In the zero-voltage state, where resistance is zero, it can serve as a reference

The power reflection coefficient of the junction, ρ , is therefore given by

$$\rho(V) = \frac{P_{\text{On}}(V) - P_{\text{Off}}(V)}{P_{S-\text{On}} - P_{S-\text{Off}}}$$

where $P_{\text{On}}(V)$ is the power (as a function of the junction bias voltage, V) measured when the noise tube is on, and $P_{\text{Off}}(V)$ is the measured power when it is off. The denominator, $P_{S-\text{On}} - P_{S-\text{Off}}$, is the difference between those powers when the junction is in the zero-voltage state; this quantity is proportional to the strength of the coupled test signal from the noise tube. By reversing the port of the coupler through which the test signal is introduced, we can measure any loss, L , between the coupler and junction

$$L = 1 - \sqrt{\frac{P_{S-\text{On}} - P_{S-\text{Off}}}{P_{S-\text{Rev}} - P_{S-\text{Off}}}}$$

where $P_{S-\text{On}}$ and $P_{S-\text{Off}}$ are as defined above, and $P_{S-\text{Rev}}$ is the power with the noise tube signal coupled in the *reverse* direction, towards the LNA. This loss was determined to be about 0.6 dB, which is probably due to the small reflections in the coaxial switch and loss in the cabling to the bias tee. No correction for this loss is made to the estimate of the IF system temperature, which is measured including the switch. Any difference in the loss between the junction and the amplifier (for example, unequal cable lengths) relative to the loss between the variable load and the amplifier causes a small systematic error (<0.4 K) in the estimate of the amplifier contribution to the noise.

Having measured the IF reflection coefficient to the junction as a function of bias voltage, and having determined the IF system temperature through calibration with the variable temperature load, the available noise power or output noise temperature of the junction, in Kelvins, can be expressed as

$$T_{\text{Junction}} = \frac{1}{(1 - \rho(V))} \left(\frac{P_{\text{Off}}(V)}{G} - T_{\text{IF}} - \rho(V) T_{\text{Physical}} \right)$$

where $P_{\text{Off}}(V)$ is the measured IF system output with only the junction's noise at the input, G and T_{IF} are the measured IF system gain and noise temperature, and T_{Physical} is the physical temperature of the isolators, whose terminations radiate thermal noise towards the junction which is partially reflected back into the LNA. The errors in the junction noise temperature are dominated by systematic errors in the determination of the IF system temperature, and in systematic errors in the measurement of the reflection coefficient due to the finite directivity of the directional coupler, which are more severe for large reflection coefficients.

V. JUNCTION NOISE MEASUREMENTS

The apparatus and techniques described above have been used to measure the output noise temperature of both Nb and NbN shunted junctions. A plot of T_{Junction} as a function of bias voltage for a NbN device with a magnetic field applied is shown in Fig. 5. This curve displays several representative features seen in all of the measurements. First, the noise temperature above voltages comparable to the $I_C R_N$ product

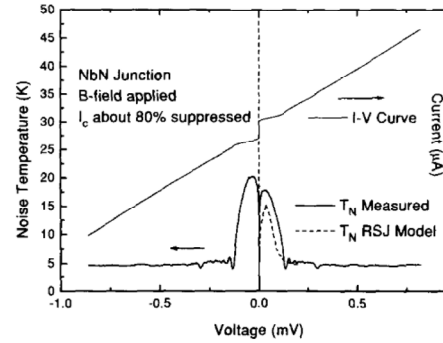


Fig. 5. Measured junction noise temperature and value calculate model are displayed as a function of bias voltage. The parameters simulation have been derived from fitting the dc I-V curve, and as thermal noise at 4.2 K is input into model. An external magnetic field applied to suppress the critical current to about one-fifth its usual dc supercurrent occurs at zero voltage, in the center of the horizontal data shows behavior similar to the RSJ model predictions, and a value consistent with thermal noise at voltages above about 0.5 mV

(in this case, about $100 \mu\text{V}$), where the junction I is linear but below the superconducting gap of the tunnel junction, is nearly constant with a value of K. One would expect that in this region the noise is mostly Johnson noise with a noise temperature equal to physical temperature of 4.2 K. Other devices show increased noise temperatures in this region, which could be due to systematic errors in the measurements, a slightly higher temperature for the device itself, or perhaps some subgap leakage of the tunnel junction. Above the voltage of the junction (not shown), the noise temperature increases linearly with bias voltage (or current), and the slope of this line is approximately 1.5–2 K per mV of bias voltage. This is as expected for our devices from shot noise. The junction has been shunted with a normal resistor that its resistance is reduced, the circuit at high voltage becomes a normal resistor with Johnson noise (not biased) in parallel with a shot-noise-producing tunnel junction. The noise should rise linearly with voltage, but with a slope reduced from the full shot-noise value¹ of 5.8 K/mV. The same factor of three to five as the resistance has been reduced. Both the observed noise floor and the behavior above the gap confirm that the calibration and measurement procedure are accurate to within the expected systematic uncertainty.

There is also a large noise spike, either positive or negative, located exactly at zero bias voltage. In all cases, the zero bias noise is consistent with the contribution of the junction alone. However, the coupling of the junction also (by definition) at this point, where the dynamic resistance is zero, so that the available power at this point is infinite. This divergence can be ignored and is not of consequence in any of the discussions below. Finally, one notices a

¹ The "effective shot noise temperature" is actually given by the current spectral density for pure shot noise, $S_I = 2eI$, and the current spectral density for thermal noise, $S_I(\text{Johnson}) = 4k_b T$, giving a noise temperature, $T_{\text{shot}} = 2eI R / 4k_b$. For a tunnel junction with no significant excess current in the linear region above the gap, R is just the bias voltage, so that T_{shot} becomes $eV / 2k_b$.

asymmetry of approximately 10% in the maximum noise value attained by the junction at equivalent positive and negative bias voltages. This asymmetry is orders of magnitude larger than the statistical errors in the measurement, and is reproducible and not dependent on the direction in which the voltage is swept. However, the sign of the asymmetry (i.e., whether the higher peak is at positive or negative voltage) can easily be reversed by changing the direction of the externally applied magnetic field. This effect must therefore be a self-field effect due to the addition of the external field with the field caused by the current through the junction or shunt resistor. The current-voltage characteristics between the two states also show small related asymmetries.

The most important feature seen in the plots are the smooth maxima in output noise temperature seen at both positive and negative voltages. These peaks occur at voltages where the device is strongly nonlinear (i.e., V less than about $I_C R_N$), and are due to noise which is converted downwards in frequency due to the Josephson effect, and also to power from the tails of the ac Josephson oscillations which can appear at the IF frequency. A theoretical curve which is obtained from the RSJ model with thermal noise, using the parameters determined from the best fit to the I-V curve, is shown for comparison. It compares relatively well with the observed behavior, showing roughly the correct magnitude for the noise and reproducing the dependence on bias voltage. Some of the sharp ripples in the experimental data are not expected, and these are related to small ripples in the I-V curve which are not present in the RSJ model.

Another similar set of curves, in which the magnetic field and the critical current suppression are minimal, are displayed in Fig. 6. Here the junction noise temperature attains much larger values before settling to the same thermal noise floor. In addition, the noise shows departures from the smooth, single maximum on either side of zero voltage which is always predicted by the RSJ model. The features in the noise again seem to be correlated with voltages where there are resonances and variations in the dynamic resistance of the junction, as seen in the current-voltage characteristic. Similar features are seen in the IF reflection coefficient of the junction, but the noise temperatures have been corrected for this variation. There must therefore be a variation in the output noise. In addition, the RSJ model predicts a maximum output noise of only about 10 times the physical temperature, or about 50 K, for realistic parameter values corresponding to this junction. The observed noise is therefore seen to be a factor of five to ten times higher than expected, which is roughly consistent with the conclusions drawn from the heterodyne measurements of these devices. While the details of the shape of the curve depend on the junction parameters, this type of behavior, i.e., large noise and strong, non-RSJ variations with bias voltage, have been observed in several devices and both superconducting materials systems investigated.

The four superposed curves in Fig. 6 are taken with the same NbN junction on subsequent cooldowns. In between cooldowns, the choke structure for the waveguide system which is deposited along with the junction onto the quartz substrate was trimmed away. This choke structure consists

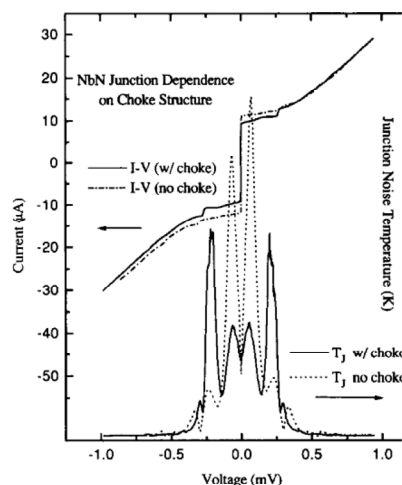


Fig. 6. Shows the effect of removing the RF choke from a NbN Junction. Left axis is current, and the full and dash-dotted curves are on subsequent cooldowns; full line is with the choke, dash-dotted line is without choke. A slight variation in the amount of external magnetic field responsible for the discrepancy in critical current. The removal of the choke has weakened the resonance visible at about 0.3 mV, and displays the junction effective noise temperature (at zero voltage) have been removed for clarity. For choke present, dotted line is after choke removal. Notice the maximum value attained by the noise, and the qualitative change (i.e., largest and second-largest peak change location).

of an alternating series of microstrip section approximately a quarter-wavelength at 100 GHz, couple the device to the waveguide. Most of the microstrip remained in order to provide a location to contact the device. Comparison of the I-V curves (although there are different amounts of trapped magnetic flux in the junction) show that the strong resonance at about 0.4 mV is weakened and moved to slightly higher voltage. The shape of the junction noise temperature has also been altered, and the distinctive double-humped shape is reproduced for any applied magnetic field. Again, the shape of the I-V curve, the presence of resonances, the low-frequency output noise of the device can be influenced by the RF impedance presented to the junction at fairly high frequencies. This dependence must be a result of the nonlinear interaction of the junction and its embedding in the waveguide. Of course the I-V curve will be dramatically different with LO illumination, and the changes in dynamic resistance of the junction will alter the appearance of the Shapiro steps, which will alter the noise on voltage, tending to smear out the resonances. The noise of the junctions when we have measured an RF source has been measured, and will be measured elsewhere.

VI. DISCUSSION AND CONCLUSION

We have performed heterodyne measurements of tunnel junctions at 100 GHz, which show fair performance, but suggest that several non-ideal effects are present. There is also a strong dependence

performance and dynamic resistance on the RF embedding impedance. Most importantly, however, these heterodyne measurements indicate that the receiver performance is probably degraded because of elevated output noise from the devices. While the RSJ model predicts that the junction noise should be a factor of five to ten above the thermal noise limit (i.e., T_N for the junction is several times T_{Physical}), we observe noise levels under some conditions which are higher than the RSJ predictions by another factor of about five.

Accurate measurements of the junction output noise at the intermediate frequency of 1.5 GHz have been performed to verify this hypothesis. The output noise of the junctions, even without local oscillator power applied, are observed to attain values higher than predicted from the RSJ model, and also show a complicated behavior with bias voltage which cannot be reproduced without inclusion of the external circuit into the nonlinear modeling of the RSJ circuit. We have shown that the low-frequency (1 GHz) output noise, and its voltage dependence, can be radically altered simply by changing the high frequency (100 GHz) impedance presented to the junction. Inspection of the I-V curves shows that the peaks in junction noise temperature are correlated with regions of high dynamic resistance, where the Josephson oscillation linewidth, and hence the "excess" noise, according to our picture for its generation [1], might be expected to be at a maximum.

It remains somewhat unclear what the implications are for the development of low-noise Josephson-effect mixers. Elevated output noise, if only a factor of five to ten times the physical temperature, would not preclude interestingly low mixer temperatures, particularly at the higher frequencies where SIS mixers are not yet available. However, our measurements show that the noise can be sensitive to the RF design of the mixer and to unanticipated resonances at high frequencies. Antenna-coupled mixer designs which are able to present a well-behaved, real impedance over a wide frequency range (e.g., self-similar structures such as log-periodic spirals [16]) should probably be used in the future.

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At present, he is a group leader at California Institute of Technology's Jet Propulsion Laboratory. His group is developing SIS tunnel junctions for heterodyne receivers.

Jeffrey A. Stern, photograph and biography not available at cation.