JOSEPHSON-EFFECT MIXERS USING SHUNTED Nb AND NbN TUNNEL JUNCTIONS

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Abstract

We present test results of a 100 GHz waveguide receiver using resistively-shunted Nb and NbN tunnel junctions. These junctions were fabricated with a process similar to that used previously with Nb junctions [1], which produces non-hysteretic devices with normal-state resistances of 30-50 Ohms, and I_cR_n products of 0.5-0.75 mV. The best receiver temperature obtained to date with NbN is 270 K (DSB) with 6-7 dB of conversion loss. A receiver temperature of 390 K (DSB) was previously obtained with Nb junctions; these devices showed qualitative agreement with the predictions of the simple DC and RF current-biased RSJ model. The improvement in receiver performance is probably due to improved RF coupling of the junctions, and due to the higher I_cR_n products of NbN. However, these NbN devices display different pumped I-V curves and IF power curves than predicted by the RSJ model. We show that these effects can be caused by the strong interaction of the junction with the embedding circuit, and conclude that an accurate model of the impedance presented to the junction will have to be included in the RSJ simulations to compare with the observed performance.

Introduction

We are studying the performance of Josephson-effect mixers using resistively-shunted tunnel junctions in order to develop a better understanding of their behavior, the sources of noise and its limitation, and to determine how to optimize their performance. Also, we wish to compare the observed behavior and performance with the theoretical predictions of the so-called RSJ (resistively shunted junction) model, so that there will be a guide to the expected performance for different frequency regimes and device parameters. This work may be important as high-Tc SNS devices become available [P.A. Rosenthal and E.N. Grossman, these proceedings] with large I_cR_n products, for they provide the possibility of using Josephson mixers at frequencies in the terahertz range, above the range where SIS mixers are currently available. In contrast, due to the extremely short coherence lengths of the high-Tc materials, junctions suitable for quasiparticle (SIS) mixers may not be feasible with these materials.

Device Fabrication

We have applied the technique used for creating non-hysteretic Nb Josephson devices[1] to NbN/MgO/NbN tunnel junctions. First the junction trilayer is fabricated, then the junction areas are patterned by electron-beam lithography and subsequently etched using reactive-ion etching (RIE) in the standard method [3]. After planarization of the etched area with evaporated SiO, a AuGe resistor is fabricated on top of the SiO, and the junction and resistor are then contacted with another layer of NbN. A photomicrograph of a completed Nb junction is shown in Figure 1a. Since the bottom of the etched trilayer lies under the resistor, it acts as a ground plane, and the resistor structure can be analyzed as a lossy transmission line. The impedance of this short microstrip structure is purely real, even up to frequencies comparable to the gap frequency of the superconductor, thus providing the desired broadband shunt. However, the section of superconductor which contacts the junction and resistor creates a non-negligible parasitic capacitance when compared to the very small area tunnel junctions used, and therefore the area of this contact pad must be kept to a minimum. From a knowledge of the geometry and thickness of the insulator (SiO), we estimate this parasitic capacitance to be 7-8 fF.

Shunting of the junction is necessary to reduce the McCumber beta parameter ($\beta_c = 2eI_cR_N^2C/\hbar$) of the unshunted tunnel junctions. Junctions with β_c values greater than one have hysteretic I-V curves [4], and their dynamics can be complicated, including the possibility of chaos. Reduction of β_c is accomplished by resistive shunting, which reduces β by the square of the ratio of the initial junction resistance to the final resistance of the parallel combination of the junction and the resistive shunt. However, this shunting has the undesirable effect of reducing the I_cR_n product of the junction. For the NbN junctions used, the critical current density was about $33kA/cm^2$, and the specific capacitance is estimated to be about $150fF/\mu m^2$ [5], giving an unshunted β of about 12. Thus the optimal shunted junction for these parameters would have a shunt resistance of about one-fourth of R_n, and thus an I_cR_n reduced from the unshunted value of 3.0 mV to 0.8 mV. In order to maintain high enough resistances for the final device, very small ($0.3\mu m$ on a side) area junctions must be used, and the parasitic capacitance will be comparable to the junction capacitance. This further reduces the final I_cR_n product attainable. The I-V curve of a typical device is shown in Figure 1b. This device had a critical current of 11 microamps and a normal state resistance of 39 Ohms, giving an I_cR_n product of 430 microvolts. The I-V curve is nonhysteretic and follows the RSJ model.

Mixer Modelling

Mixer performance can be predicted using the RSJ model, in a method similar to that used by Taur[6], but extended to the case of finite junction capacitance. The

RSJ model assumes a simple linear resistance and an ideal Josephson element, whose current is given by $I_c sin\phi$. Nonzero junction capacitance can be included as well. The circuit is shown in Figure 2. Using the customary normalized units;

$$v = \frac{V}{I_c R_n} \qquad i = \frac{I}{I_c} \qquad \tau = t\,\omega_c$$

$$z = \frac{Z}{R_n} \qquad \Omega = \frac{\omega}{\omega_c}$$

$$\beta_c = \frac{2e}{\hbar} I_c R_n^2 C \qquad \omega_c = \frac{2e}{\hbar} I_c R_n$$

the equations of motion are given by:

$$v = \dot{\phi}$$

$$\beta_c\,\ddot{\phi} = i_{DC} + i_{LO}\,\sin(\Omega_{LO}\tau) - \sin(\phi) - v$$

where the differentiation is with respect to the normalized time, τ.

The bias current provided to the junction includes the DC bias, a local oscillator current, and noise currents due to the Johnson noise of the resistor. These differential equations can be integrated to determine a voltage waveform, which is then Fourier transformed. From this information, we determine the three-port mixer conversion matrix and noise correlation matrix. Mixer performance can then be optimized as a function of IF and RF impedances using standard linear circuit analysis. In this approach the embedding impedances are implicitly assumed not to affect the nonlinear dynamics of the junction; the noise and conversion matrices are determined using the infinite embedding impedance (i.e. current bias), and are assumed to be independent of the impedances connected (in very narrow frequency ranges) to the ports.

For this current-biased RSJ model, we find that the best mixer performance is expected for normalized frequencies of about a half ($\Omega_{LO} = 0.5$), with β values of about

0.8. Predicted mixer noise temperature and conversion efficiency for an optimized case are shown in Figure 3. Here, the best RF impedance (assumed to be the same at both sidebands) is about 3 to 5 times the junction normal state resistance, and real or with a small inductance. The IF impedance is about 3 times R_n. Notice that for nonhysteretic junctions, the ωRC product at the LO frequency is less than one, so compensation for the reactance of the junction capacitance (i.e. tuning circuits) should not be important for the performance. Also, since the preferred impedances are high compared to the junction impedance, the current biased approximation should be valid. Very good mixer performance is predicted under these assumptions, with double-sideband mixer temperatures of about 25 K, and a conversion gain of - 3 dB.

Nb Mixer Results

The Nb and NbN shunted junctions were both tested in a waveguide receiver similar in design to those used at the CSO [7,8]. The junctions are fabricated on thin quartz substrates, with an integrated RF choke structure on the substrate. This choke structure functions to short the superconductor to the waveguide walls at RF frequencies, while passing the IF and DC bias. This substrate is then mounted across a full-height waveguide mount with two adjustable (backshort and E-plane) tuners. The waveguide feeds a horn and polyethylene lens, with the beam coupled out through a mylar dewar window. Cooled filters of quartz/black polyethylene and fluorogold prevent IR radiation from heating the junctions. The IF signal is fed to a cooled HEMT amplifier with a noise temperature of about 10 K and gain of 30 dB. Receiver performance is estimated using the standard hot/cold load technique.

The pumped I-V curve and hot/cold IF power response as a function of bias voltage for a Nb Josephson device at 94 GHz are shown in Figure 4a. As expected the best response is found in the middle of the first photon step (i.e. between the 0-th and 1st Shapiro steps, at about 100 microvolts), with a local oscillator power applied which is sufficient to suppress the critical current (i.e. 0-th Shapiro step) to about half its initial value. The best receiver performance observed was 390 K (DSB) receiver temperature, and -6.5 dB conversion gain. This device was not optimal in several ways, however. First, this device was too strongly shunted, and had an I_cR_n product of only about 200 microvolts. Secondly, this first batch of devices was fabricated on 0.2 mm thick substrates, while the integrated choke structure was designed assuming a 0.1 mm substrate. This probably had the effect of reducing the coupling to the waveguide, and reducing the effectiveness of the adjustable tuners, thereby limiting the range of embedding impedances possible.

Figure 4b shows the I-V curve and low frequency noise power in the absence of signal (i.e. a 0 K load at the input) from a current-biased RSJ simulation using parameters corresponding to the Nb data. The similar shapes of the I-V curve and output power curve suggest that the current-biased model adequately describes this junction. The best mixer performance was found at the maximum output power of the mixer, and with the backshort adjusted for maximum LO coupling. The slope of the photon steps was basically independent of tuner position. The optimal RF embedding impedance for this device was predicted by the current-bias RSJ model to be about 1 to 2 times R_n (or 30-60 Ohms and real), due to its lower I_cR_n product. The model further predicts mixer noise temperatures of 100-200 K (DSB), which is still substantially lower than the observed 350 K. Some of this discrepancy might be due to imperfect coupling due to the unoptimized choke structure and front end losses.

NbN Mixer Results

NbN junctions produced using the resistive-shunting process were also tested in the same receiver. These devices were superior in two respects: the I_cR_n product of

400-500 microvolts was optimal for frequencies of about 100 GHz, and they were fabricated on thinner substrates, thus improving their coupling to the waveguide. The effect of the tuners on the LO coupling and pumped I-V curves was much stronger. Indeed the photon step varied from the case where the slope was about 0.5 to 1.0 times the normal state resistance of the device, to the case where there were nearly infinite impedance steps, depending on the backshort position. The best receiver response was found on relatively low slopes, despite the fact that best IF match should occur at about 3-4 times R_n. The current-biased RSJ model predicts that the best performance would coincide with relatively large output impedances of perhaps 10 times R_n (i.e. steep slope on the photon step), but we were unable to obtain mixer results for these conditions, because the bias circuit oscillated. We intend to modify the DC bias circuit to allow operation in this regime. A hot/cold response curve and pumped I-V curve are shown in Figure 5a. The best receiver temperature of 270 K (DSB) at 105 GHz was obtained in the center of the photon step, and the conversion efficiency was about -7 dB.

Obviously, this device shows a qualitatively different behavior from the more weakly coupled Nb devices or the current-biased RSJ model. Furthermore, the difference in IF power curves for the hot and cold loads raises the possibility that nonheterodyne response or saturation could be occurring. It is unlikely that this difference is due to the different material, but is most likely due to the strong coupling of the junction to the external circuit. An extremely simple model for the embedding circuit, shown in Figure 2b, suggests that this is true. We modified the RSJ equations of motion to include a simple R-L-C series circuit, connected in parallel with the junction. The LO current was injected in parallel with the external resistor, and the L and C serve to couple this external circuit to the junction only in some frequency range near the LO frequency. The pumped I-V curve and low frequency power simulated using this model with arbitrary parameter choices of R about 1/2 R_n and a Q of about 4. are shown in Figure 5b. The slope of the I-V curve has been greatly reduced from the typical value from the current-biased RSJ model of about 3 times R_n, and the power curve shows a shape suggestive of the observed double-humped behavior.

Clearly, an accurate representation of the impedances presented to the junction by the waveguide mount will be necessary to understand the behavior observed with the NbN junctions. The qualitatively different character of these devices may mean that the dynamics of the junction have changed significantly due to the influence of the external circuit. This in turn could have implications for the optimization of mixer performance different from those inferred from the current-biased modelling. Furthermore, it may be that certain quasioptical coupling schemes which present a real, slowly varying impedance over a wide frequency range (e.g. spiral antennas, [9]) may be advantageous, as they better approximate the current-biased case. Finally, it is possible to include the broadband signal from hot/cold loads coupled into the device once the embedding circuit is included in the simulations, which would allow the investigation of possible saturation effects.

Conclusions

We have tested Josephson-effect mixers using Nb and NbN shunted junctions at 100 GHz, and obtained receiver temperatures of 390 K (DSB) and 270 K (DSB), respectively. The NbN junctions were well coupled to the waveguide mount, and showed behavior qualitatively different from either the Nb junctions or the simulations using the current-biased RSJ model. We believe that this effect is due to the effect of the embedding circuit on the junction's dynamics. More study will be needed to compare in detail with the simulations, and to investigate the optimization of the mixer under these conditions.

The modelling performed so far predicts that receiver temperatures less than 100 K are possible. It will be important to understand the behavior of these mixers and their optimization so that this experience can be applied at higher frequencies with high-Tc devices.

Research supported by NASA Grant NAGW-107, NASA Code R funding to JPL, SDIO/IST, and a NASA Graduate Student Researcher Fellowship (R. Schoelkopf).

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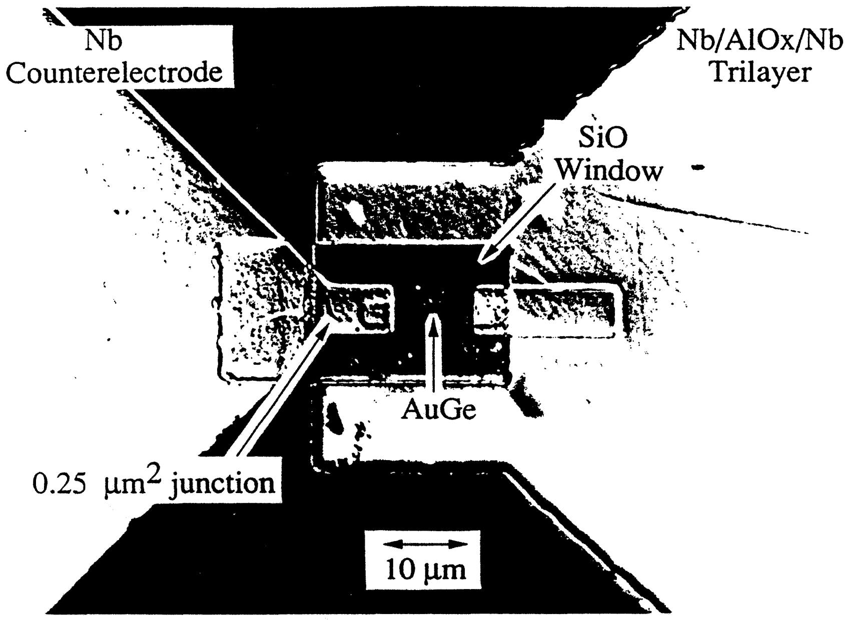


FIGURE 1a)

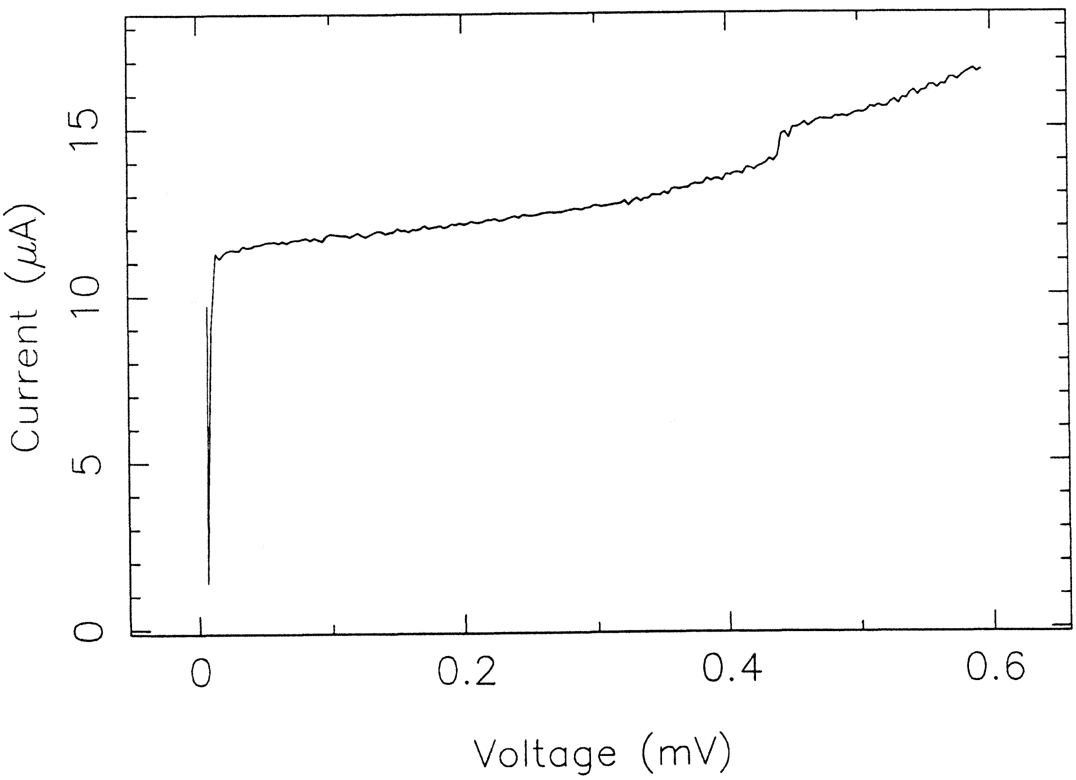
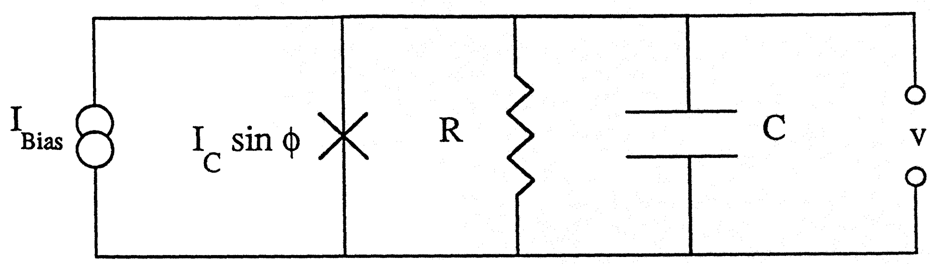


FIGURE 1 b)

a)



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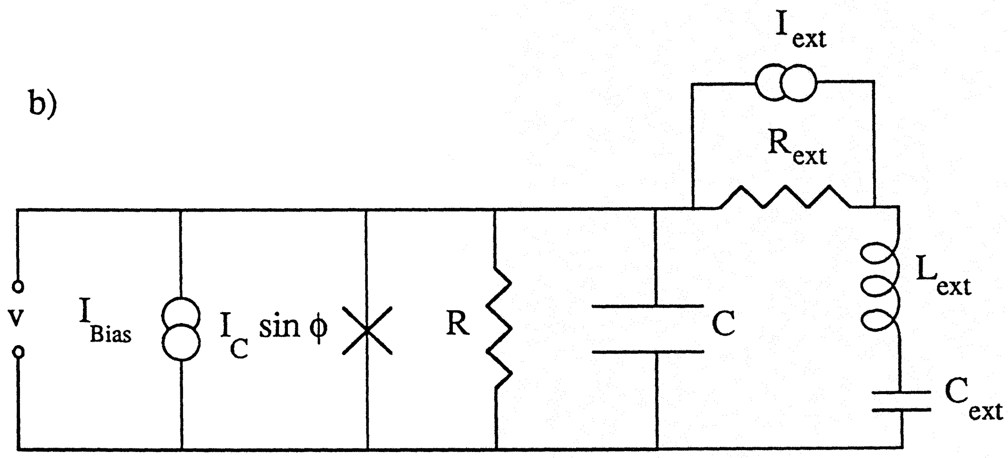

Figure 2: a) The current-biased RSJ model, consisting of a linear resistor, capacitor, and ideal Josephson element with sinusoidal current dependenence on phase.
b) A simplistic model of the RSJ junction plus external circuit. The external L and C serve to couple the external resistance and current source only over some frequency range. This circuit can at least qualitatively reproduce the behavior seen in strongly-coupled junctions.

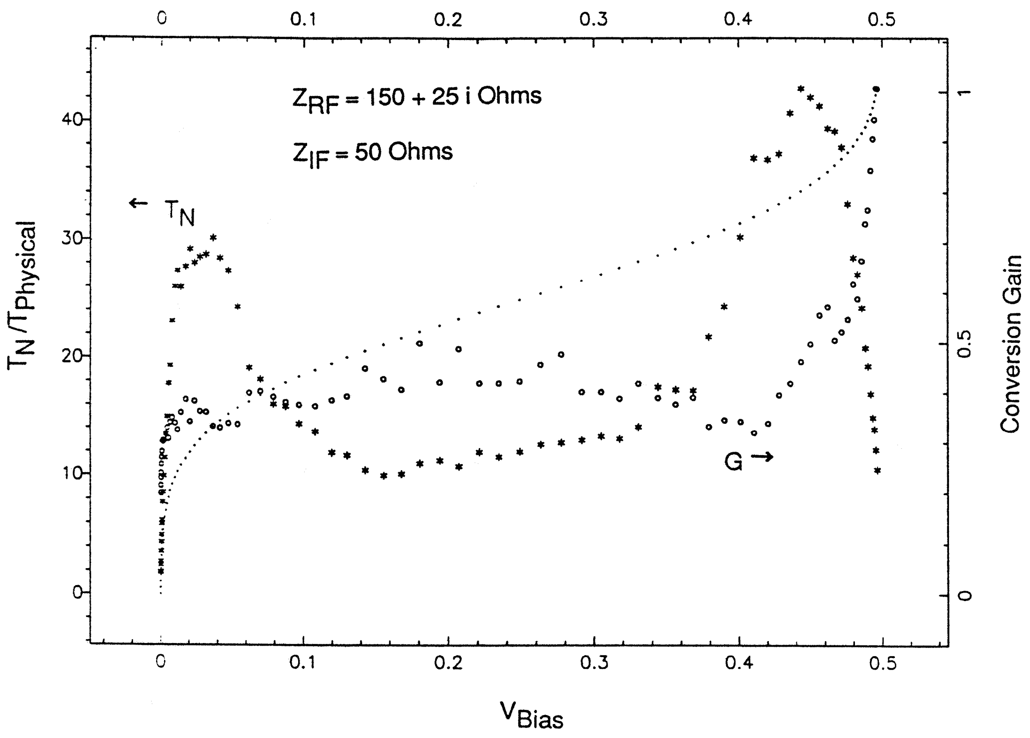

Figure 3: Mixer noise temperature and conversion efficiency as predicted by current-biased RSJ simulations for a Josephson mixer operated at 100 GHz with an IcRn product of 0.4 mV and a normal-state resistance of 50 Ohms. Filled dots are pumped I-V curve, showing first Shapiro step. Asterisks are single-sideband mixer temperature normalized to the physical temperature. Open circles are conversion efficiency, in linear units. Model predicts receiver temperatures of about 50 K (DSB), with 3 dB conversion loss.

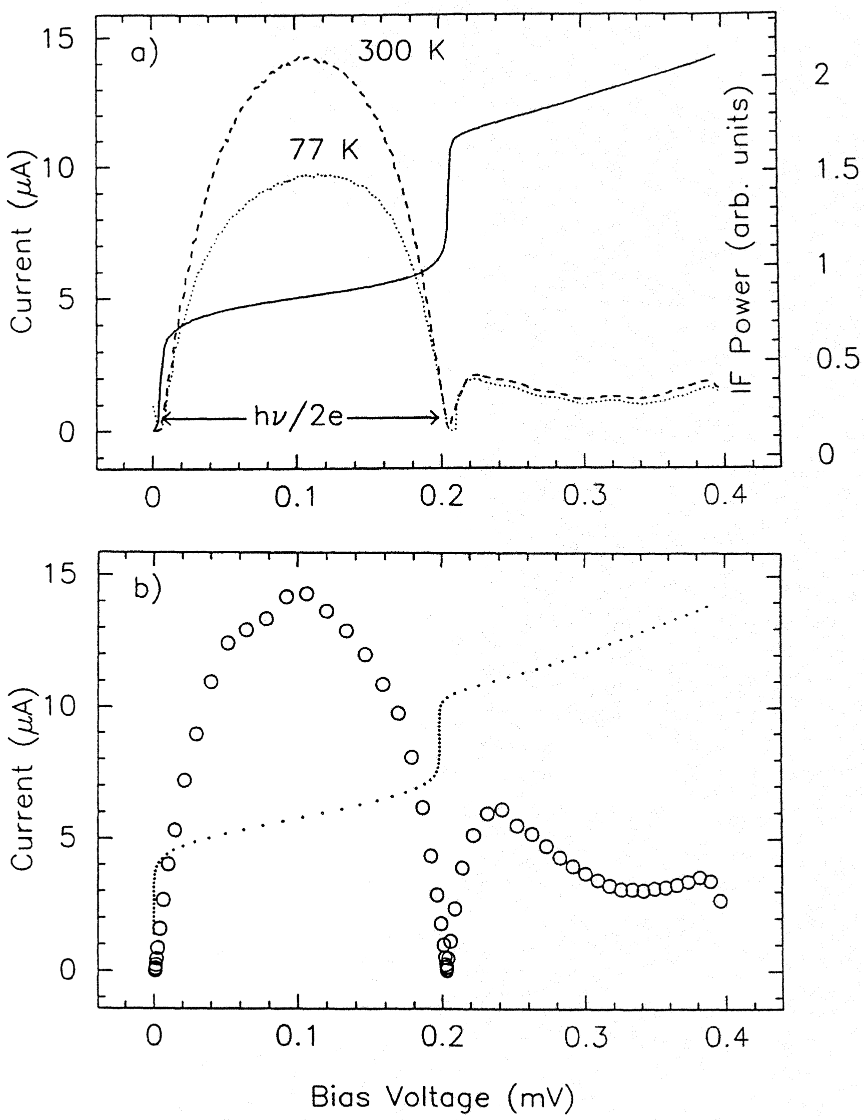

Figure 4: Heterodyne response of Nb Josephson-effect mixer.
a) Shows I-V curve with local oscillator applied (solid line). IF output power vs. bias voltage is shown for room temperature (dashed line) and 77 K loads at the receiver's input. Receiver has noise temperature of 400 K (DSB) and conversion efficiency of 0.2 (i.e. -6.5 dB).
b) Low frequency output noise expected from numerical simulations of current-biased RSJ model in the absence of signal (i.e. for a 0 K load). Mixer shows good qualitative agreement with model predictions.

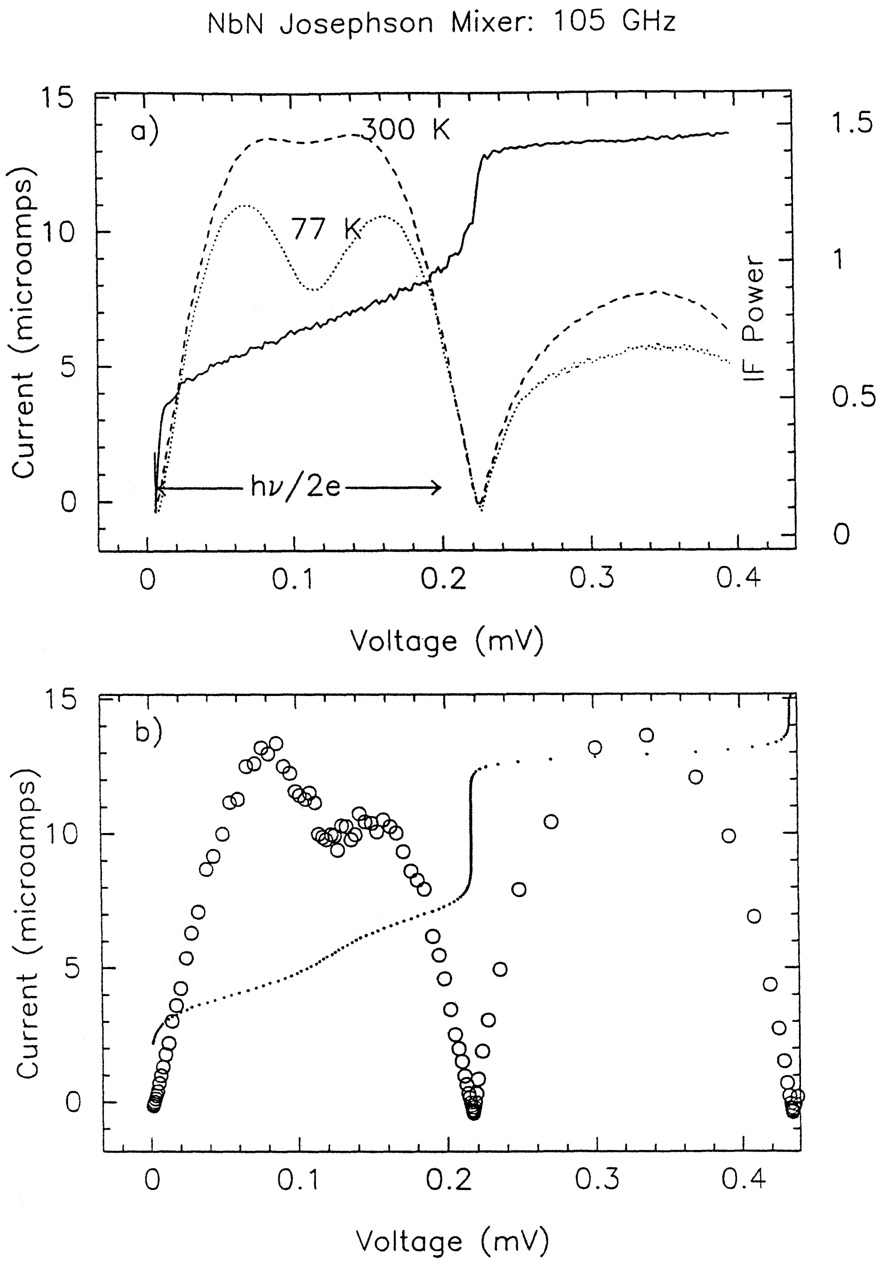

Figure 5: Heterodyne response of NbN Josephson-effect mixer.
a) Shows I-V curve with local oscillator applied (solid line). IF output power vs. bias voltage is shown for room temperature (dashed line) and 77 K loads at the receiver's input. Receiver has noise temperature of 270 K (DSB) and conversion efficiency of -7 dB.
b) Low frequency output noise expected from numerical simulations of RSJ model driven by RLC series circuit (see Fig 2 b). Model reproduces the shapes of pumped I-V curve and IF power curve.