Heterodyne Mixing and Direct Detection in High Temperature Josephson Junctions*

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Abstract

We have examined various properties of high characteristic frequency YBCO superconductor-normal-superconductor (SNS) Josephson junctions that are important to their performance as low-noise THz frequency mixers. Without far-infrared laser illumination, the microwave frequency noise temperature of our lowest noise device shows good agreement with the predictions of the resistively shunted Josephson model in applicable regions of bias. It has a maximum noise temperature of 36±4 K at a physical temperature of 4 K. When illuminated with a 404 GHz far-IR laser local oscillator (LO) and a chopped 77 K blackbody signal, strong modulation of the 1 GHz IF noise power is observed. However, certain features of the modulated IF power signal strongly suggest that a large fraction of it is not true heterodyne detection. The spurious component is probably due to direct detection of the broadband hot load/cold load signal. We believe that reliable measurement of heterodyne performance will require narrowband signal sources.

I. Introduction

The importance of investigating high-critical temperature (high-T_c) Josephson junction mixers arises chiefly from the possibility of approaching quantum-limited noise performance at frequencies far higher than is possible with conventional quasiparticle mixers. Higher frequency performance can be reasonably hoped for because the energy gaps of high-T_c superconductors, though not measured (and perhaps not well-defined), would be expected to lie >10 times higher than those of low-T_c materials, based on the respective critical temperatures and the relation $E_{gap} = C\,kT_c$, ($C = 3.52$ for classic BCS superconductors). The possibility of mixer operation at higher temperatures is also an important secondary motivation for investigating high-T_c mixers, particularly for applications in remotely operated or spaceborne receiver systems. For these reasons, as techniques for fabricating Josephson junctions from the high-T_c materials have been developed, a number of groups[1,2] have been examining their characteristics at high frequencies ($\geq$ 100 GHz) and their suitability as terahertz-frequency mixers.

All high-T_c Josephson junctions fabricated to date are in the "shunted", or low capacitance regime, defined by a dimensionless capacitance $\beta_c = 2\pi(2e/h)\, I_c R_n{}^2 C \ll 1$, where I_c is the critical current, R_n the normal-state resistance, and C the capacitance of the junction, and $(2e/h) = 1/\phi_0 = 483$ GHz/mV is the Josephson constant. This gives them non-hysteretic current-voltage (I-V) characteristics with no sharp feature at the gap voltage. Conventional low-T_c tunnel junctions, because of their trilayer or "sandwich" geometry are in the $\beta_c \gg 1$ regime, which gives them a hysteretic I-V curve with a sharp non-linearity at the gap voltage due to the onset of quasiparticle tunneling. Mixing in conventional low-T_c junctions is based on this resistive non-linearity in the quasiparticle tunneling; mixing in non-hysteretic junctions ("Josephson mixing") on the other hand, is based on the non-linearity in the tunneling of Cooper pairs. In the late 1970's and early 1980's, low-T_c quasiparticle and Josephson mixers for millimeter wavelengths were developed in parallel, and a considerable body of knowledge about the physics of Josephson mixers was acquired,[3] much of it based on the standard "resistively-shunted junction" (RSJ) model. Although a vague opinion arose that Josephson mixers always show large "excess" noise, the chief reason for the eventual predominance of quasiparticle mixers over Josephson mixers was that, at that time, the only experimental realization of Josephson mixers was in point contacts, which are mechanically and electrically extremely unstable and irreproducible. The theoretical properties of Josephson mixers are now being carefully re-examined[4] and compared with experiment using well controlled (low-T_c) lithographic junctions. In fact, the "excess" noise of optimized Josephson mixers should be only a factor of a few (~10 or less) above the thermal noise level.

The natural or characteristic frequency f_c for any superconducting junction is set by the junction's $I_c R_n$ product via the definition $f_c = (2e/h)\, I_c R_n$. The characteristic frequency can never exceed the energy gap frequency of the superconducting material forming the

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[1] J. P Hong, H. R. Fetterman, R. J. Forse, and A. H. Cardona, "Double Step-edge Weak Links Integrated with Spiral Antenna Structure in Epitaxial $Tl_2CaBa_2Cu_2O_8$ Films for Millimeter Wave Mixing", Appl. Phys. Lett., 62, pp 2865-2867 (1993)

[2] R. Gupta, Q. Hu, D. Terpstra, G. J. Gerritsma, and H. Rogalla, "Near-millimeter-wave Response of high T_c Ramp-type Josephson Junctions, Appl. Phys. Lett. 62, pp.3351-3353 (1993)

[3] J. H. Claasen and P. L. Richards, "Performance Limits of a Josephson-junction Mixer", J Appl. Physics, 49, pp. 4117-4129 (1978)

[4] R. J. Schoelkopf, T. G. Phillips, and J. Zmuidzinas, "A 100 GHz Josephson Mixer Using Resistively Shunted Nb Tunnel Junctions", IEEE Trans. Appl. Supercon., in press

junction. In the low-T_C junctions used in conventional SIS mixers, the full energy gap-limited characteristic frequency is attained. However, in all high-T_C junctions fabricated to date, the characteristic frequencies lie well below any reasonable estimate of the gap frequency. Indeed, all high-T_C Josephson junctions yet reported, except ours, have characteristic frequencies which are only comparable to, or less than, those of the low-T_C junctions. About a year ago however, we developed a technique for producing high-T_C junctions with characteristic frequencies as high as 5 THz.[5] In addition to high f_C, a low-noise Josephson mixer requires a normal state resistance that is at least comparable to the impedances of quasi-optical or waveguide RF coupling structures and to the impedance of the microwave IF circuits. Our high-f_C junctions typically have resistances of 10-30 Ω, which is quite reasonable for both RF and IF matching. They are therefore excellent candidates for low-noise mixers at THz frequencies. In the original work, these junctions were integrated with lithographic antennas and illuminated with far-infrared (far-IR) laser radiation. The resulting DC current-voltage characteristics showed Shapiro steps up to 17 mV, corresponding to locking of the internal Josephson currents with harmonics of the laser radiation to >8 THz.[6] These results were described at the last Space Terahertz Symposium.

Since then, we have modified our device layout and the measurement apparatus to allow the coupling of 1 GHz intermediate frequency (IF) signals from the junction off the chip and into a low noise amplification and measurement system. Using this, we have directly measured mixer noise, both in the dark and with far-IR laser illumination. We have also performed heterodyne mixer measurements using the conventional hot load/cold load (H/C) technique. Although the noise of a related type of high-T_C Josephson junction has been examined indirectly through the rounding of Shapiro steps in the DC current-voltage characteristic,[7] the work reported here is, to our knowledge, the first describing direct measurement of the IF-frequency noise in high-T_C junctions, and the first describing H/C load response from a high-T_C mixer at submillimeter frequencies.

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[5] P. A. Rosenthal, E. N. Grossman, R. H. Ono, and L. R. Vale, "High Temperature Superconductor-Normal-metal-Superconductor Josephson Junctions with high Characteristic Voltages", Appl. Phys. Lett., 63, pp. 1984-1986 (1993)

[6] P. A. Rosenthal and E. N. Grossman, "Terahertz Shapiro Steps in High Temperature SNS Josephson Junctions", IEEE Trans. on Micr. Theory and Tech, in press

[7] R. Gupta, Q. Hu, D. Terpstra, G. J. Gerritsma, and H. Rogalla, "A Noise Study of a High-T_C Josephson Junction under Near-millimeter-wave Irradiation", Appl. Phys. Lett. in press

II. Mixer Fabrication, Experimental Setup, and Calibration

A. Mixer Fabrication

The technique for fabricating our high I_cR_n junctions has been described in detail elsewhere.[5,6] Briefly, the mixers are fabricated on 1 cm square substrates of either single-crystal lanthanum aluminate (LAO) or neodymium gallate (NGO). An 80-100 nm deep step is formed by ion-milling, in some cases milling directly into the substrate, but in most cases, milling into a previously deposited 300 nm thick film of strontium titanate (STO) (see table 1.) YBCO is then deposited by laser ablation at a 40° angle to the chip normal, from the high side toward the low side of the step, so that the YBCO film breaks at the step. The difference between the step height and the YBCO film thickness is thought to be crucial in determining the critical current density of the junction. Then, Au is sputtered in-situ from the opposite angle so as to fill in the break and create the SNS structure. This YBCO/Au bilayer is the basic building block for our mixer circuits. The bilayer is patterned into a strip as it crosses the step in order to define the junction width, which is 4 μm for all the mixer junctions described here (as opposed to 6 μm for the junctions in refs. 5,6). The crucial fabrication step for raising the junction's characteristic frequency and normal-state resistance is performed at the end. A small window directly above the junction is opened in photoresist and an angled ion-mill (from high side to low side) is performed to remove the Au of the bilayer that remains directly atop the YBCO, but not to remove the Au that lies in the shadow of the step and which forms the normal section of the SNS bridge. Removing this Au eliminates a large parasitic shunt conductance, and typically raises the junction resistance from ~.5 Ω to >10 Ω.

Table 1

	Substrate	I_c(4K)	R_N	f_c	T_n(max), 4K
THz 3	LAO/STO	145 μA	1.25 Ω	87.5 GHz	-
THz 4	LAO/STO	32 μA	37 Ω	520 GHz	-
THz 5	NGO/STO	25 μA	20 Ω	242 GHz	36 ± 4 K
THz 6	NGO	4 μA	150 Ω (!)	290 GHz	100 ± 20 K
THz 9	NGO/STO	315 μA	14 Ω	2.13 THz	850 K

For all our mixer chips except THz 9, the lithographic antenna was formed from electron-beam evaporated Ag, patterned by liftoff. This was done in a separate step, after patterning the bilayer but before the final angled ion-mill. For THz 9, the antenna was formed from the same YBCO/Au bilayer. The rationale for a separately fabricated Ag antenna was that the antenna efficiency would be higher, because the ohmic loss in a high conductivity normal metal is substantially lower than in superconducting YBCO at high frequencies. However, since we recently directly measured a respectable optical coupling efficiency of 25 % over a 0.2 - 3 THz bandwidth from a YBCO/Au bilayer antenna of very similar design,[8] we adopted a bilayer antenna for THz 9 for the sake of the simpler fabrication. The antenna used for our mixer junctions is of the same toothed log-periodic design[9] as was used in refs. 5 and 6. The only difference is in the innermost tooth size - in the present case its inner radius is 10 μm. The outer radius of the outer tooth is 1000 μm. This results in an antenna bandpass of approximately 0.027 - 2.7 THz.

B. Experimental Setup

The overall layout of our experiments is illustrated in Fig. 2. A homemade, optically pumped, far-infrared molecular gas laser serves as our local oscillator (LO). In these experiments, the laser was operated on either the 404 or 992 GHz line of formic acid, on which it produces 1 - 4 mW. The substrates were mounted, circuit side up, against a 1 cm diameter hyperhemispherical Si lens.[10] In general, 0.65 of Si spacer plates were placed between the chip substrate and the lens surface, placing the mixer somewhat behind the aplanatic hyperhemispherical focus. The mixer block was mounted on a thermally isolated platform whose temperature could be varied with a heater and monitored on a Ge resistance thermometer. A cooled low-pass filter with a measured 3 dB cutoff frequency of 3.3 THz and a measured passband insertion loss of -1.55 dB was used to reduce the thermal IR background to a manageable level. The total insertion loss due to the dewar window, low-pass filter, and reflection off the Si substrate lens was -4.7 dB. For most of the measurements, the LO and signal beams were focused into the cryostat and onto the mixer with a 90° off-axis paraboloidal mirror (40 mm on-axis focal length). Loss due to mismatch between the antenna beam and the focused signal beam is unknown, but we have measured an efficiency of 18 % for coupling the focused far-IR laser beam onto a room-temperature bolometer at the feed of an identical log-periodic antenna. Si wafers of various thicknesses were used as beamsplitters to combine LO and signal beams for heterodyne

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[8] J. P. Rice, E. N. Grossman, and D. A. Rudman, "Antenna-coupled High-T_c Microbolometer on Silicon", submitted to Appl. Phys. Lett.

[9] R. H. DuHamel and D. E. Isbell, "Broadband Logarithmically Periodic Antenna Structures", IRE Natl. Conven. Rec. Pt. 1, p. 119-128 (1958)

[10] D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz, "Double-slot Antennas on Hyperhemispherical, Elliptical, and Extended Hemispherical Dielectric Lenses, IEEE Trans. Mircr. Theory and Tech. June 1992

mixing experiments. At 404 GHz, one of our standard thickness wafers is almost exactly 1 dielectric wavelength thick, providing >98 % transmission for the signal beam. For devices with high critical current (i.e. THz 9, see table 1), this beamsplitter did not couple sufficient LO power into the mixer, and a thicker beamsplitter was used, whose transmission for the signal beam was only 30 %. For H/C load measurements, we found the drift in the laser power was too great to allow reliable measurements of the H/C difference in IF power, ΔP_{IF}, to be made at DC. Therefore, the signal beam was mechanically chopped at 17 Hz and the signal of interest, P_{IF} or V, synchronously detected.

Both the DC and microwave frequency contacts to the chip are made by Au-plated, BeCu circuitboard traces. The mixers are DC biased by a battery powered, 1 kΩ output impedance supply (i.e. approximately a current bias). The microwave contacts are patterned into 50 Ω coplanar waveguide (CPW) on both the circuitboard and chip. A short length of semi-rigid coaxial cable is soldered at one end to the circuitboard's CPW and at the other to an SMA connector, which defines a convenient reference plane for the output of the mixer block. From there, the microwave signals pass through a DC block and isolator to an ultra-low noise 0.7 - 1.4 GHz HEMT amplifier. These three components remain at 4 K, even when the mixer block platform is raised to higher temperatures. For the measurements on THz 3 and Thz 4, the cryogenic isolator was omitted. The output of the HEMT amplifier then passes through futher room temperature amplification and a 50 MHz wide bandpass filter centered at 1 GHz. The filtered signal is then measured by a commercial microwave power meter.

In order to obtain 4-terminal DC contact to the mixer junction without series resistance from normal metal CPW and coax, the CPW ground return is broken to allow a DC current and voltage line to pass through. A primitive crossover is formed by patterning photoresist into a patch covering the DC lines, then overlaying the photoresist with In foil to complete the CPW ground return. The (room-temperature) 1 GHz return loss of the mixer block, as measured from the output reference plane, on a commercial microwave network analyzer, with an open circuit at the chip contacts, was -0.35 dB. The mixer block return loss with a chip in place, and with the In foil crossover arrangement, but an open circuit at the junction position, was -1.3 dB.

C. Calibration

In order to perform quantitative measurements of microwave mixer noise, it is essential to accurately calibrate the gain and noise of the IF system. We do not have a system of cryogenic microwave switches, directional couplers, etc. incorporated into the cryostat that would allow the injection of calibrated signals into the IF system during the course of a measurement run. Therefore, we have performed our calibration by disconnecting the IF system input from the mixer block output, and connecting it instead to a 50 Ω termination mounted on the variable-temperature platform. Then, during a separate cooldown, we measure the IF system output power as a function of the platform temperature. The dependence is linear, with the slope yielding the IF system gain and the intercept yielding the IF system noise : $P_{out} = kB(G_{IF}T_{50} + T_a)$, where B is the 50 MHz system bandwidth, T_{50} is the temperature of the 50 Ω termination, and G_{IF} and T_a the desired gain and noise temperature of the IF system (the latter being essentially that of the HEMT amplifier). The accuracy of this calibration method is limited by the IF system's stability and reproducibility from cooldown to cooldown. Independent calibration runs done two weeks apart yielded gains which agree within 0.15 dB (3.4 %), and noise temperatures which agree within 0.8 K.

For converting system output powers to junction noise temperatures, the impedance mismatch between the mixer and 50 Ω IF system needs to be accounted for. This can be a very large effect as the junction's dynamic resistance $R_d = dV/dI$ can vary from 0 (in the 0-voltage state) to » 50 Ω. We use a relation[11] expressing the scattering matrix formulation of the dependence of amplifier output noise on input match :

$$T_{out} = P_{out}/kB = G_{IF}\left[\left(1-|\Gamma_1|^2\right)T_1 + T_a + T_{rev}|\Gamma_1 - \beta|^2\right] \qquad (1)$$

where T_{rev} is the temperature of the reverse wave emitted from the amplifier input, and β the complex reflection coefficient for optimum amplifier noise match. Using an isolator effectively sets β to 0 and T_{rev} to the physical temperature of the isolator, 4 K. T_1 and Γ_1 are the noise temperature and complex reflection coefficient at the mixer block reference plane. If the IF line from the junction to the reference plane were perfectly lossless, then T_1 would just be the junction noise temperature T_j, and if, in addition, its impedance were exactly 50 Ω, then Γ_1 would just be the reflection coefficient of the junction $\Gamma_j = (R_d - 50\Omega)/(R_d + 50\Omega)$. In the remainder of this paper, we will make these assumptions and set $T_1 = T_j$ and $\Gamma_1 = \Gamma_j$. Experimentally however, we know the IF line has some loss because T_{out}/G_{IF} does not exactly reduce to T_a + 4 K in the 0-voltage state, independant of the junction's physical temperature. Rather, we find T_{out}/G to have a small linear dependance on temperature, with $\frac{d}{dT}(T_{out} / G) = 0.2$, suggesting approximately 1

[11] D. Wait and G. F. Engen, "Application of Radiometry to the Accurate Measurement of Amplifier Noise", IEEE Trans. on Instrumentation and Measurement, 40, p.433-437, (1991), Eqn. (8)

dB of loss in the IF line, consistent with the 300 K network analyzer measurement of 1.3 dB loss.

III. Results

Five separate mixer chips have been fabricated and tested so far. For various ill understood reasons related to fabrication changes made in the last year, all but one mixer, THz 9, have had characteristic frequencies well below 1 THz (see table 1). For this reason, nearly all of the optical testing was done at 404 GHz. Two of the mixer junctions, THz 3 and THz 6 were clearly anomalous. The former did not receive a proper final angled ion-mill due to imperfect alignment of the milling window; its parasitic shunt conductance was therefore not fully removed. The latter had an exceptionally low critical current and high normal-state resistance, although its I_cR_n product was quite in line with those of THz 4 and 5. We speculate that this junction's effective width was much less than those of all the others. In general, the attainment of reasonably high junction resistances (>10 Ω) has not proven a problem. The difficulty has been in obtaining high and controllable I_c's. We now believe our difficulties are related to accurate measurement and control of the difference between step height and YBCO film thickness. Beginning with THz 9, we expect our junctions to now be fairly close in their electrical characteristics to those described in refs. 5 and 6. Based on the hysteresis observed in those earlier devices, we had derived an approximate value of junction capacitance of 4.5 fF for 6 μm wide junctions. Scaling by the junction width, the current devices should have capacitances around 3 fF, leading to β_c in the range 0.09 - 0.8 (except for THz 3).

At the top of Fig. 3 we show the DC current and dynamic resistance of THz 5 as a function of DC voltage, without laser illumination. The dynamic resistance was measured by superimposing a small (~0.3 μA rms) AC current on the DC current, and synchronously detecting the resulting AC voltage. At the bottom of Fig. 3 is the raw IF system output power as a function of junction voltage on the same scale. There is an obvious correspondance between the peaks and dips in $P_{out}(V)$ and those in $R_d(V)$. This is largely just a manifestation of better matching to the IF system with higher dynamic resistances. The main features of $P_{out}(V)$ are (a) a value in the 0-voltage state that reflects the instrumental noise, as discussed above, (b) an initially linear rise out of the 0-voltage state, (c) a peak at a relatively low voltage, (d) a gradual rolloff at higher voltages, with a small number of peaks and dips superimposed, eventually converging on a constant value not far different from the noise in the 0-voltage state.

Analytic expressions exist for the RSJ model's predictions of junction noise in the regimes of (d) and (b). Specifically, RSJ quantum-noise theory[12,13] yields, for the low-frequency, noise voltage spectral density $S_V(0)$ (in V^2/Hz),

$$S_V(0) = \frac{R_d^2}{R_n}\left[4kT + 2eV\left(\frac{I_c^2}{I}\right)\coth\left(\frac{eV}{kT}\right)\right] \qquad (2)$$

when the following conditions are met : low capacitance, i.e. $\beta_c \ll 1$, low frequency, i.e. $f(= 1\ \mathrm{GHz}) \ll f_J = (2e/h)V$, and current $I > I_c$, so that noise rounding can be neglected. These conditions are well satisfied for our junctions in the regime (d) where the noise gradually rolls off at high voltages. A further implicit assumption made in this RSJ-based noise theory is that the junction is current biased (i.e. embedding impedance $\gg R_n$) at all frequencies at which the Josephson currents are significant, i.e. up to the THz range. This condition is not so well satisfied for our junctions since we have (deliberately) aimed to make the junction resistance R_n comparable to the antenna impedance to obtain good RF coupling. Determining and accounting for finite embedding impedance at the Josephson frequencies is the main obstacle to obtaining a quantitative yet intuitive understanding of Josephson noise, and the issue was never thoroughly explored in the early work on Josephson mixers. Eqn. (2) is applicable to the gradual rolloff in the experimental noise at high voltages. On the other hand, the initial linear rise in the noise coming out of the 0-voltage state, where $I < I_c$ and noise rounding entirely accounts for the finite voltage, can be described[14] by a model of thermally activated phase diffusion. In this case, the noise is the "fluxonic" equivalent of the usual electronic shot noise, and

$$S_V(0) = 2\phi_0 V \qquad (3)$$

where $\phi_0 = h/2e$ is the flux quantum. This again assume $\beta_c \ll 1$. The regime intermediate between these two cases, in which the noise power peaks, and the case of finite capacitance $\beta_c \sim 1$ or $\beta_c \geq 1$, can only be modeled by numerical simulation.

The junction's equivalent circuit is a random voltage generator with voltage spectral density $S_V(0)$, in series with its dynamic resistance R_d. Therefore, the power spectral density delivered to a load resistance $R_L = 50\ \Omega$ is given by

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[12] R. H. Koch, D. J. Van Harlingen, and J. Clarke, "Quantum-Noise Theory for the Resistively Shunted Josephson Junction", Phs. Rev. Lett., 45, p2132-2135 (1980)
[13] K. K. Likharev and V. K. Semenov, JETP Lett., 15, p.442 (1972)
[14] R. F. Voss, "Noise Characteristics of an Ideal Shunted Josephson Junction", J. Low Temp. Phys., 42, pp. 151-163, (1981)

$$P_{del} = (1 - |\Gamma|^2)kT_1 = \frac{R_L}{(R_L + R_d)^2} S_V(0). \qquad (4)$$

In Fig. 4 we show a comparison between the experimental junction noise temperature T_1, (derived from the raw IF system output power via Eqn. (1)), and the theoretical junction noise temperature derived from Eqns. (2)-(4) and the experimental I-V and R_d-V data. The agreement is remarkably good in the voltage regions where the theoretical expressions apply. In the region of the noise peak, the experimental noise is significantly higher than predicted by simply applying Eqn. (2).

This data on THz 5 consitutes an existence proof : it shows that high-T_c Josephson junctions can be experimentally realized that have resistances suitable for matching to ~ 50 Ω microwave and quasi-optical circuits, and which have noise temperatures comparable to the RSJ predictions, namely a few times the physical temperature. The next question is whether low noise temperature and high characteristic frequency ($I_C R_N$ product) can be attained in the same junction. To give a crude idea of the noise level of different junctions, we have tabulated in table 1, along with f_c, the maximum junction noise temperature observed in the $P_{IF}(V)$ data without laser illumination. Unfortunately, we do not have sufficient statistics to answer the question yet. The only legitimate comparison we can make among our junctions that is relevant is between THz 5, which had low noise, but also low f_c (240 GHz), and the most recent device, THz 9, which had high f_c (2.1 THz) but also much higher noise. (THz 6 also had higher noise than THz 5, but this is largely expected due to its extremely small critical current. Its Josephson noise parameter $\Gamma = 2\pi\left(\frac{2e}{h}\right)\frac{kT}{I_c}$ is high enough that significantly higher noise would be expected just from the RSJ model.) We suspect that the correlation between high f_c and high noise suggested by comparing THz 5 with THz 9 is not genuine and general, however, because the I-V curve of THz 9 displays dramatic non-RSJ structure, whereas we already know from the devices described in ref. 6 that high characteristic frequencies can be attained simultaneously with I-V curves much closer to the ideal RSJ type.

There is definite evidence that, in the junctions with higher I_c (THz 3 and THz 9), the junction noise depends strongly on magnetic field. We have taken no special precautions to eliminate or shield the junction from magnetic components (particularly the 1 GHz isolator, in cases when it was used) inside the Dewar. The main manifestation of these effects is asymmetry in the measured junction noise between positive and negative current biases. Fig. 5a, for example, shows 2 sweeps of junction noise versus voltage for THz 3, the first taken in ambient field, and the second taken with the entire cryostat placed inside a magnetic shield. Moreover, for THz 9, we have seen apparent evidence of trapped flux within the junction (Fig. 5b). Independant of whether the measurement was made with the cryostat in ambient field or in a magnetic shield, sweeps of junction noise after the cryostat had been cooled in ambient field showed very large asymmetry, while sweeps made a few days later, after the cryostat was cooled in zero field, were perfectly symmetric. In addition, larger, externally applied magnetic fields strongly modulate the critical current of most of the junctions. THz 6 however, which had anomalously I_c, showed no dependence of either critical current or junction noise with magnetic field. Thus, based on our admittedly limited statistics, there appears to be a strong correlation between critical current and sensitivity of critical current and junction noise to magnetic field.

When the mixer is illuminated with far-IR radiation, strong Shapiro steps appear in the DC I-V curve. Alongside this, the overall shape of the noise sweep versus voltage which is displayed in the dark measurements around zero voltage is reproduced around every Shapiro step voltage when the laser is incident. The height of the noise peak scales with the Shapiro step height. These general features of the $P_{IF}(V)$ dependence when LO radiation is applied are illustrated in Fig. 6. In most cases, we find a minimum in $P_{IF}(V)$ occurs approximately halfway between steps. This would suggest, as has been found in numerical RSJ simulations[4], that approximately halfway between steps is the optimum bias point for heterodyne noise. On the other hand, in some cases, we find a maximum in $P_{IF}(V)$ halfway between steps. We do not presently have an explanation for this. Contrary to our expectation, the extrema in $P_{IF}(V)$ do not always correspond to matching extrema in $R_d(V)$; we have observed strong minima (factor of 2 peak-to-valley) in $P_{IF}(V)$ between steps with very little, if any curvature in the I-V curve at the same point.

Finally, we illuminated the mixer with both the LO beam from the laser and a signal beam from a chopped 77 K black body. Fig. 7 shows the total IF noise power as a function of mixer voltage, $P_{IF}(V)$, and the demodulated difference in IF noise power $\Delta P_{IF}(V)$ due to the chopped signal. Within the context of the usual H/C load measurement technique, the latter is proportional to the receiver's heterodyne conversion gain. If the demodulated signal shown in Fig. 7 is naively interpreted as entirely due to heterodyne detection, then its maximum value, $\Delta P_{IF} = 22\ \mu W$ would correspond to a DSB receiver conversion gain of -12 dB, and the 950 μW total IF noise power at the same point would correspond to a DSB noise temperature of approximately 9000 K. In H/C measurements on THz 4 we have observed demodulated ΔP_{IF} signals corresponding to noise temperatures as low as 3000 K. To our knowledge, these are the first observations of H/C load response of a high-T_c mixer at frequencies above 100 GHz.

Unfortunately, we believe that use of the demodulated ΔP_{IF} signal to derive heterodyne conversion gain and noise temperature is by no means as straightforward as outlined above, even though this H/C measurement technique is the most widely used one for characterizing heterodyne receivers in general, and was used in the Josephson mixer experiments in refs. 1 and 4. Two observations cast the primary doubt on this simple interpretation of the H/C signals. The first is that the demodulated ΔP_{IF} displays large signals of both signs. That is, at certain biases the IF power is larger with the hot load in the signal beam than with the cold load, but at other biases the IF power is larger, by a comparable amount, with the cold load in place than with the hot load. For a true heterodyne signal, the IF power must always increase as the signal power is increased (load switched from C to H). Secondly, in some cases we have observed ΔP_{IF} signals - signals substantially above the noise level - with the laser LO blocked. (This latter effect is common in conventional SIS mixers operated at high frequency. Recall that in the case of Josephson mixers however, there is the possibility of bona-fide "internal-mode" heterodyne mixing, between the junction's internal Josephson oscillations and the signal, which would manifest itself in just this way.)

An effect that would explain both these observations is direct (or "video") detection of the broadband H/C signal. Direct detection produces a small change in the DC I-V curve of the junction; since we use a DC current bias in our setup, this is manifested as a modulation of the junction voltage that is synchronous with the chopping of the H/C signal. Since the IF noise power, with or without laser illumination, varies rapidly with voltage at some voltages (see Figs. 5,6), the small voltage modulation due to direct detection produces a small modulation in P_{IF}. This appears just like a heterodyne signal, except that, since the IF noise power sometimes increases and sometimes decreases with voltage, the modulation in P_{IF} can be of either sign, i.e. $P_{IF}(H) >$ or $< P_{IF}(C)$. A third observation suggests that this effect is indeed likely to be significant. It is that the voltage dependence of $\Delta P_{IF}(V)$ appears by eye to track, at least roughly, that of the derivative of the noise power, $dP_{IF}(V)/dV$. See Fig. 7. In principle, it would be possible to subtract this effect out of the measurements, by directly measuring both $dP_{IF}(V)/dV$ and the demodulated junction voltage ΔV, and subtracting their product from the measured $\Delta P_{IF}(V)$. Indeed, we can detect, and measure with reasonable signal-to-noise ratio, the demodulated junction voltage (not shown), while $dP_{IF}(V)/dV$ can be obtained from plots like Fig. 6. However, in practice, with realistic levels of signal-to-noise ratio, drifts in LO power, etc., we do not believe it likely that this subtraction of the spurious component of $\Delta P_{IF}(V)$ can be done very reliably or accurately. Furthermore, although we have described the effect for the case of a DC current bias, as used in our setup, the use of a DC voltage bias would not materially affect the situation. Therefore, we are presently not at all confident that the H/C load measurement technique can be used with broadband sources to accurately evaluate heterodyne performance of Josephson mixers. This conclusion was also reached by Blaney et al.[15] who did some of the most careful of the early work on point-contact Josephson mixers. The only completely reliable way to measure Josephson mixer heterodyne performance is to use a narrowband source (e.g. a spectral line, or a thermal source with a narrowband filter) as the source.

IV. Conclusions

We have performed a number of experiments directed toward measuring the heterodyne noise performance of high-T_C Josephson mixers at high frequencies. The experiments fall into 2 main categories: measurements of the 1 GHz (IF) noise power of bare, non-illuminated junctions, and H/C load heterodyne measurements with an external laser LO. We have fabricated and performed measurements on 5 devices, although only one of these actually had the high characteristic frequency of which our fabrication technique is capable. Substantial differences between junctions were observed in the non-illuminated noise power, but we do not have sufficient statistics to form general conclusions. In at least one case, the non-illuminated mixer noise temperature is consistent with the predictions of the general, current-biased RSJ noise theory. Most importantly for heterodyne receiver applications, the mixer noise temperature in this case is fairly low - it never rises above 36 ± 4 K (at a physical temperature of 4 K). The celebrated "excess noise" of Josephson mixers is simply not that large. The heterodyne measurements showed strong difference signals in the IF noise power from a chopped H/C load source, and naive interpretation of the signal amplitude would imply a DSB heterodyne receiver temperature of 9000 K (for THz 9) and 4000 K (for THz 4) at 404 GHz. However, observation of the signs of the difference signal at different biases, and of the fact that difference signals in IF noise power are still observable with the laser LO blocked, cast strong doubt on the reliability of the H/C load measurement technique for evaluating heterodyne receiver performance for Josephson mixers. Spurious difference signals in the IF power due to direct detection of the chopped signal are the likely cause of the problem, and are difficult, if not impossible, to subtract from the data. For this reason, we currently believe the only foolproof method for demonstrating low noise Josephson mixer performance with high-T_C junctions will be by using narrowband signal sources, e.g. by the observation of spectral lines.

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[15] T. G. Blaney, N. R. Cross, and R. G. Jones, "The Properties of a Heterodyne Receiver at 450 GHz using a Josephson Point-contact Mixer and an External Local Oscillator", J. Phys. D: Appl. Phys., pp. 2103-2124, (1982)

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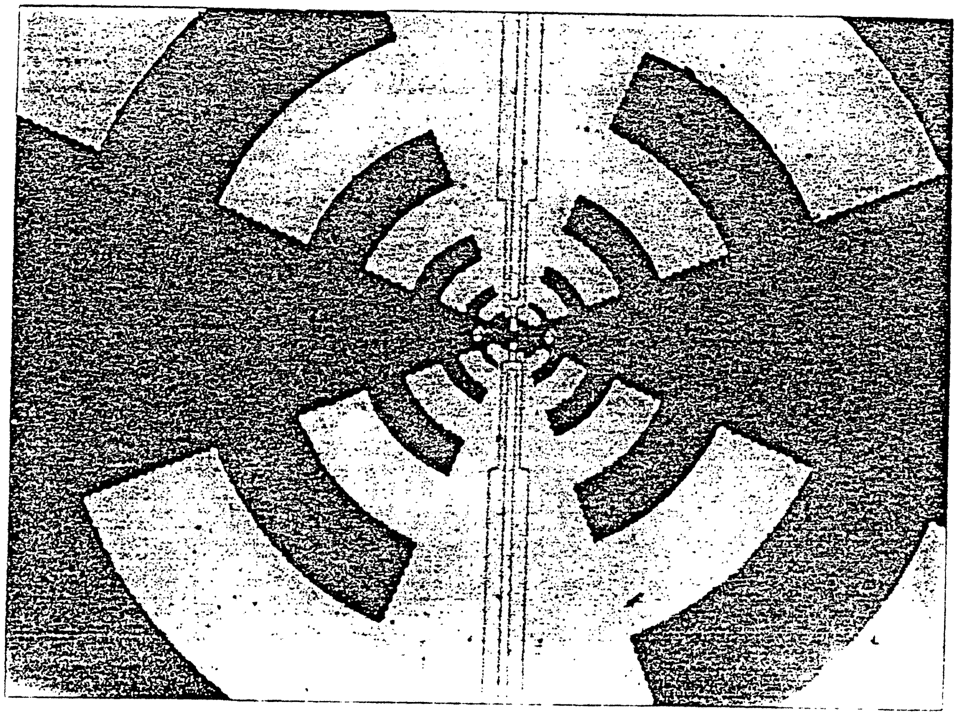

Figure 1. Photograph of THz 6. The step edge runs horizontally through the junction. The dark region at the center is the part of the bilayer which has been ion-milled to raise the junction resistance.

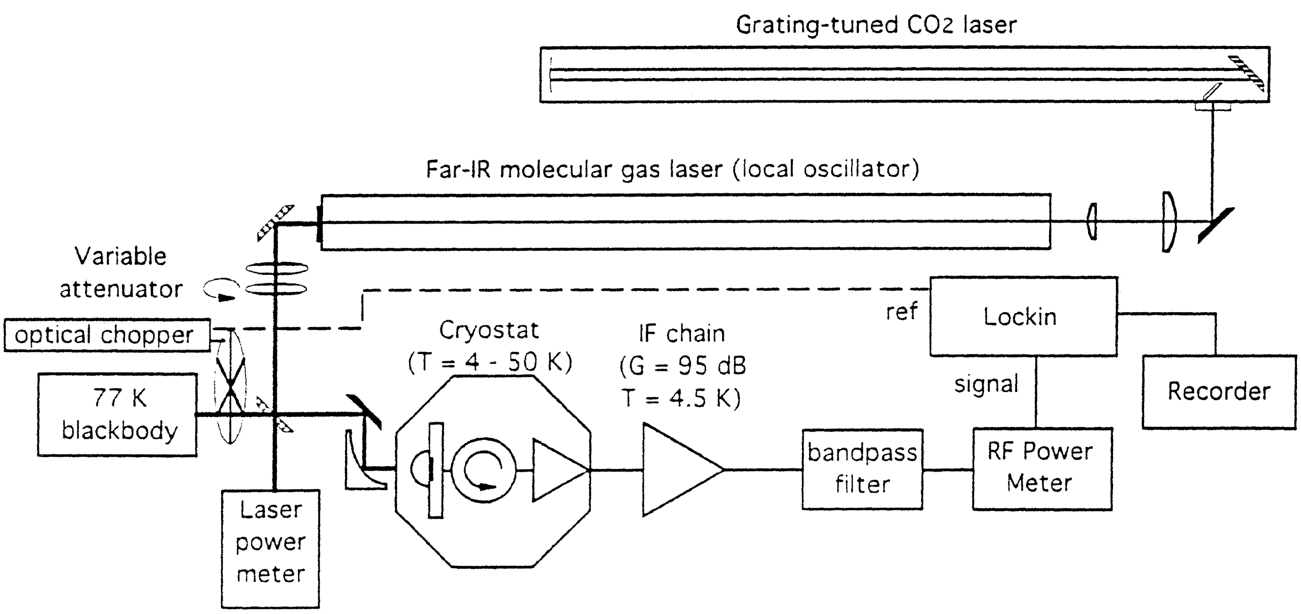

Figure 2. Experimental setup for heterodyne mixer measurements.

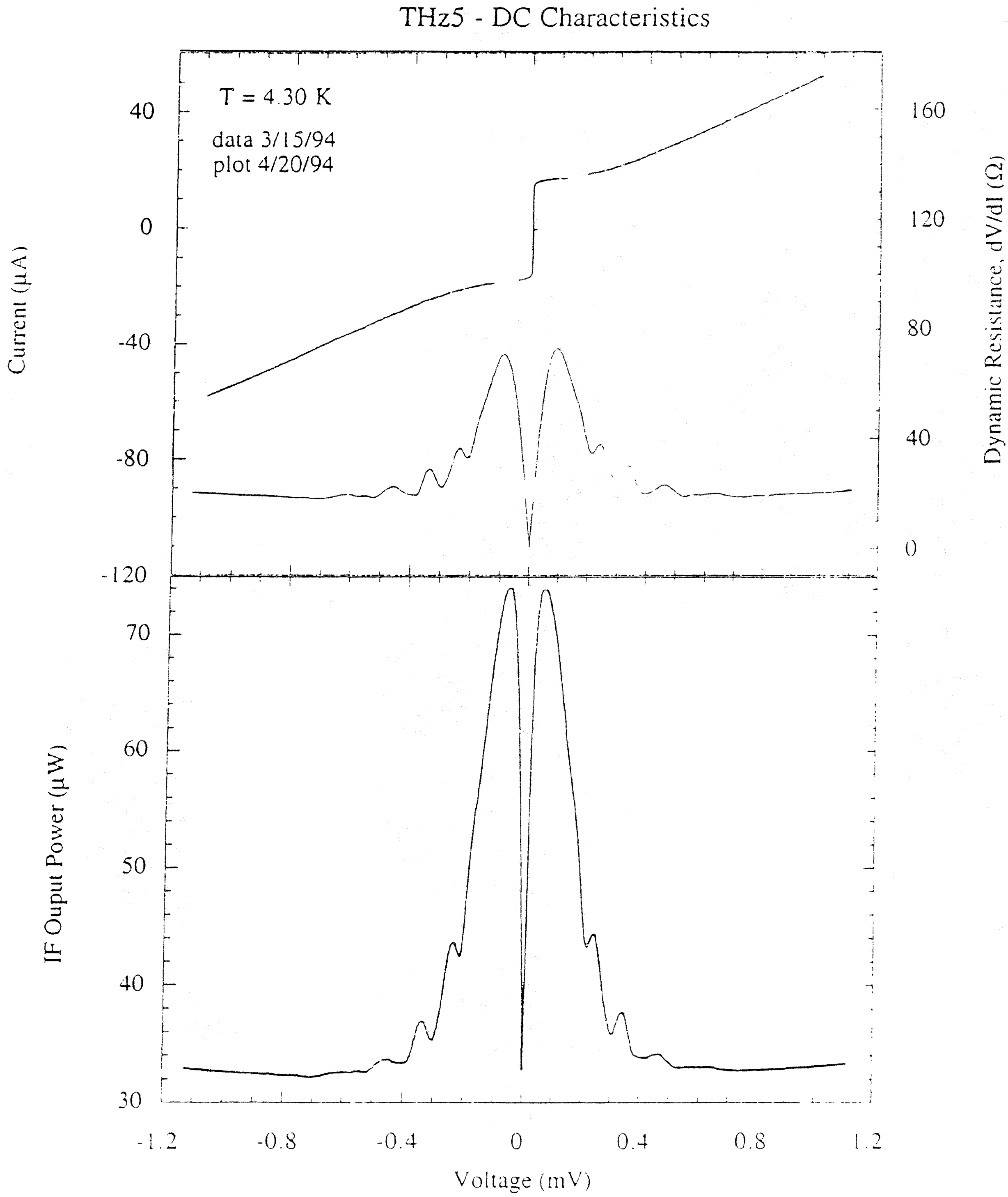

Figure 3. (top) Current-voltage characteristic and dynamic resistance $R_d = dV/dI$ versus voltage for THz 5. (bottom) The raw 1 GHz IF output power versus voltage, on same scale. The gain-bandwidth product of the IF system is $G_{IF}B = 1.76$ μW/K (see text for IF calibration procedure).

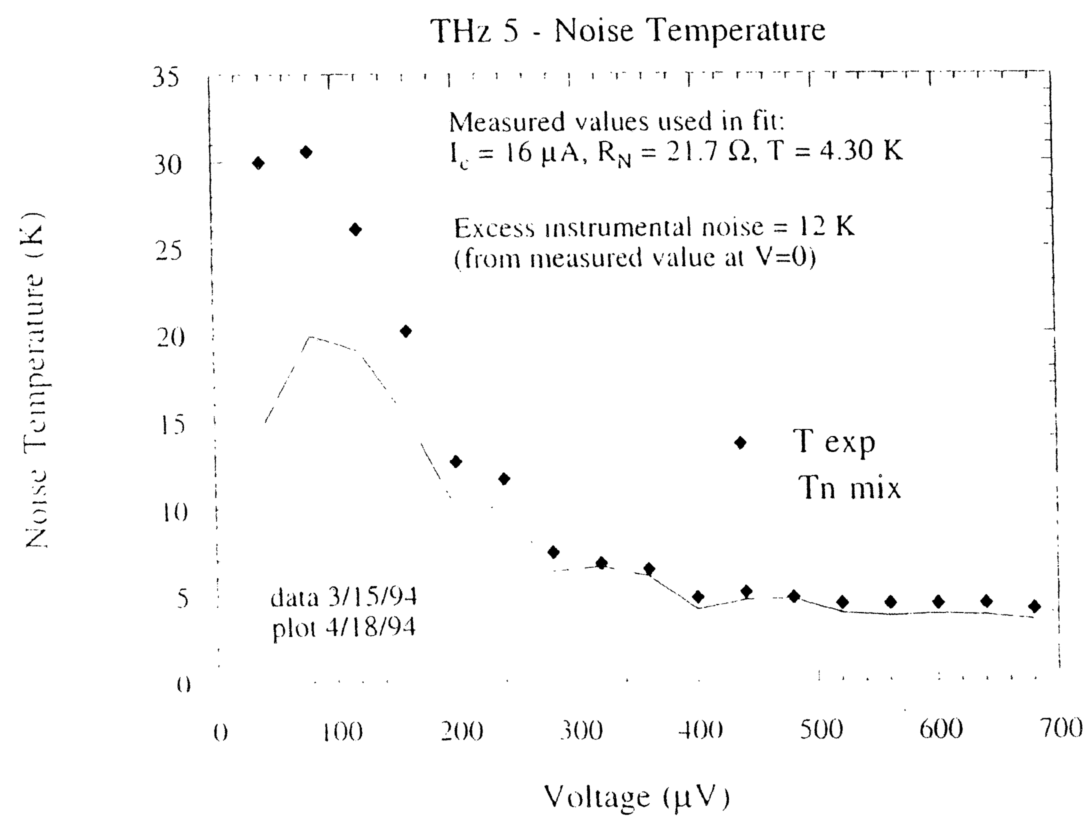

Figure 4. Theoretical junction noise temperature (solid line) using the measured I-V and R_d-V curves shown in Fig. 3, and the RSJ expression Eqn. (2). The solid points are the experimental data.

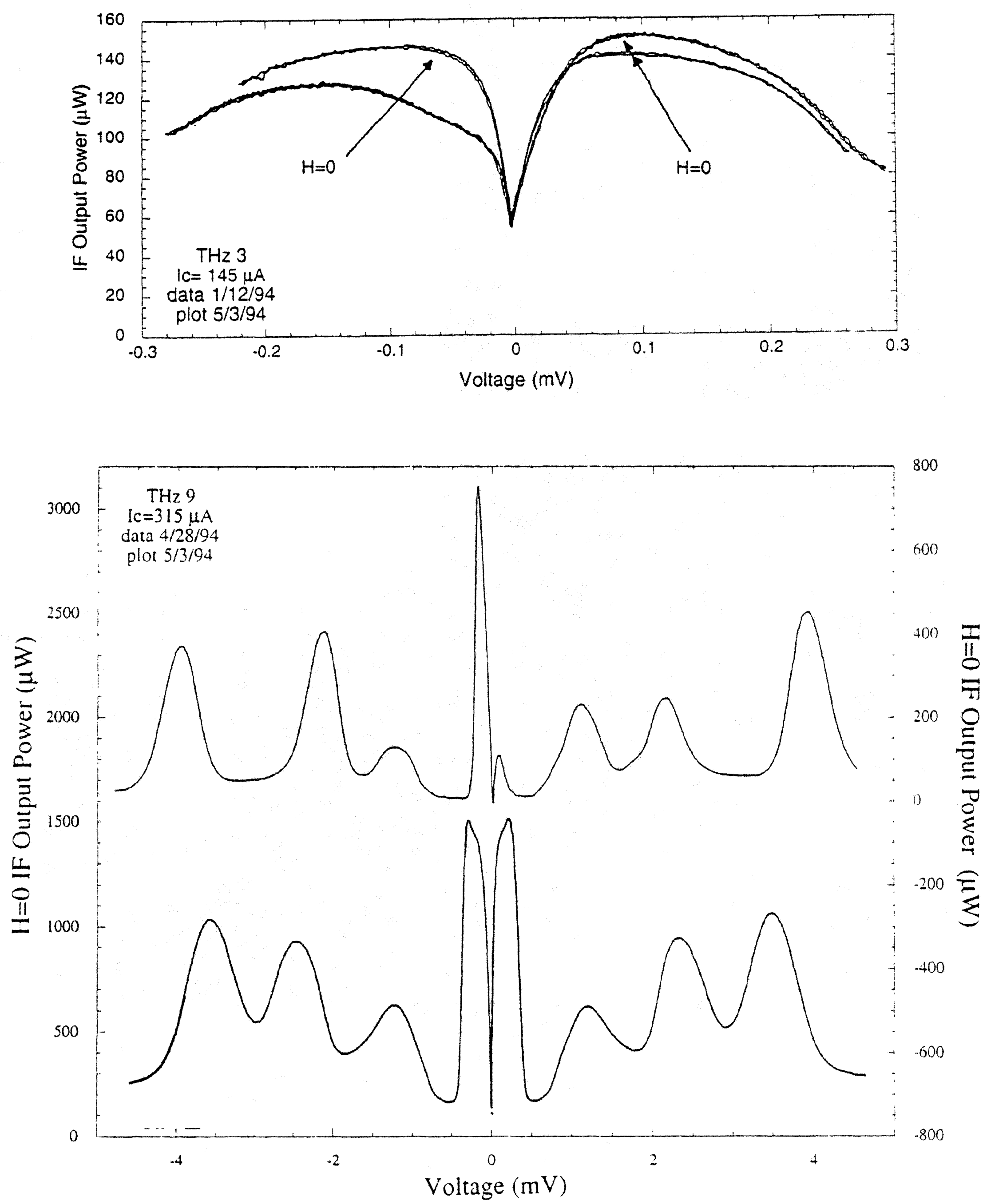

Figure 5. IF output power versus junction voltage for the two highest I_c devices in different magnetic field configurations (see text).

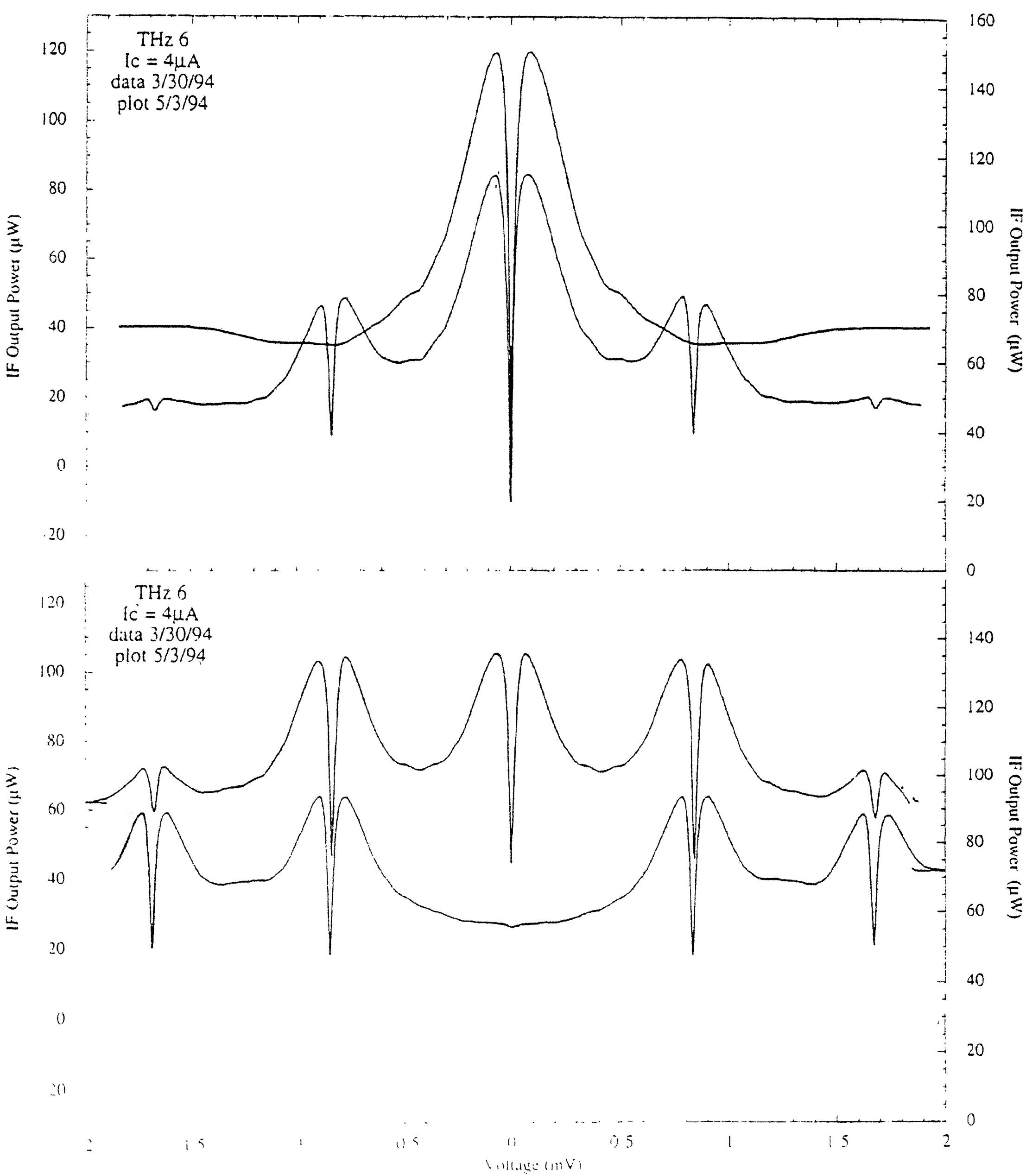

Figure 6. IF output power versus voltage under 404 GHz laser illumination at various power levels. (top) laser off, (second from top) intermediate laser power, (third from top) laser power sufficient to make 1st Shapiro step amplitude equal to I_C, (bottom) laser power sufficient to drive I_C to zero.

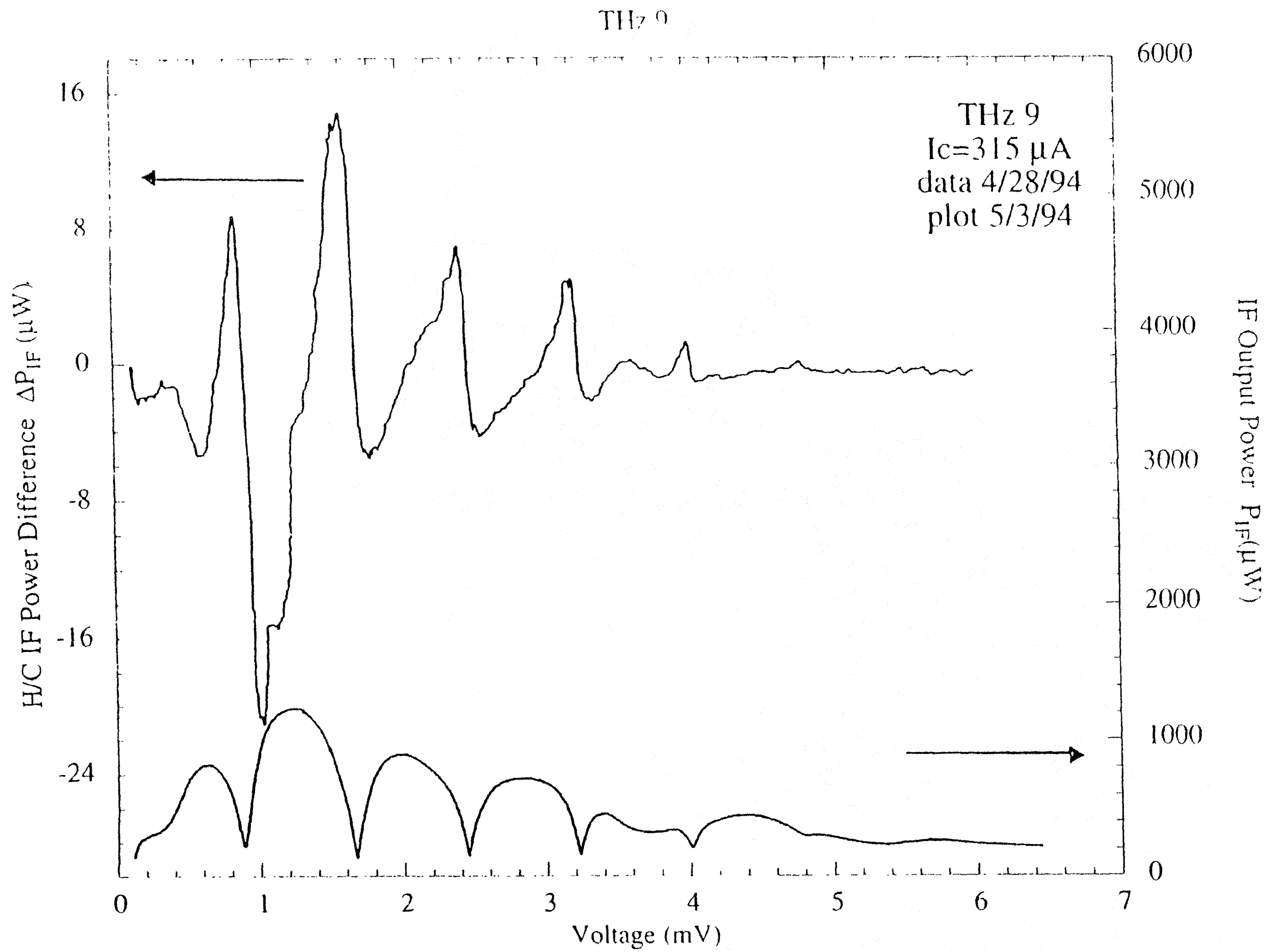

Figure 7. (Bottom) IF output power versus junction voltage, with 404 GHz illumination. (Top) Difference in IF output power ΔP_{IF} with signal beam chopped between 300 K and 77 K blackbody sources. The minima in IF output power occur at the Shapiro step voltages, and line up with zero-crossings in ΔP_{IF}.