NOISE AND RF BANDWIDTH MEASUREMENTS OF A 1.2 THz HEB HETERODYNE RECEIVER

A.Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc

Center for Space Microelectronics Technology
Jet Propulsion Technology, California Institute of Technology
Pasadena, CA 91106

Abstract

Receiver noise and RF coupling bandwidth have been measured for a quasioptically coupled diffusion-cooled hot-electron bolometer mixer at a local oscillator frequency of 1267 GHz and an intermediate frequency of 1.4 GHz. A lowest receiver equivalent noise temperature of 1880 K double-sideband was measured, with an upper limit for the mixer noise temperature of 950 K double-sideband. The amount of absorbed local oscillator power in the bolometer device was approximately 6 nW. The effective instantaneous RF bandwidth measured with a Fourier transform spectrometer was 730 GHz.

Introduction

In the last few years, superconducting transition-edge hot-electron bolometers (HEB's) have emerged as prime candidates for use in low-noise heterodyne receivers at frequencies exceeding 1 THz [1,2,3,4,5,6]. The reason is that their performance does not degrade above the superconducting gap frequency, as is the case for SIS mixers, since bolometers operate through heating of the electron gas in the device. The most urgent need for these receivers is within the field of astrophysics, where the strong requirements on detector sensitivity justify the use of cryogenic temperatures below 10 K. Conventional bolometers have traditionally not been considered for such applications, as their intermediate frequency bandwidth has been limited to less than the 500 MHz to 1 GHz that would be required. Recent measurements have shown that superconducting HEB's can satisfy both the sensitivity and IF bandwidth requirements of molecular spectroscopy in astrophysics [2,3,4,5,6,7].

Two varieties of superconducting HEB's have been reported. The phonon-cooled variety studied by other research groups [3,4,8] uses interaction between the hot electrons and the lattice as a cooling mechanism, and will not be treated here. The diffusion-cooled superconducting HEB, which is the topic of this paper, instead relies on electron out-diffusion as the main cooling mechanism for the heated electrons. This requires that the device is very short, less than 1 μm [1,2,7], since the thermal response time and therefore also the intermediate frequency bandwidth depend on the time required for the heated electrons to escape via the ends of the bolometer. This type of HEB requires normal metal contacts, which suppress the superconducting energy gap at the device ends, thereby ensuring that Andreev reflection will not slow down the escape of the electrons.

In this paper we present measurements of receiver noise and RF bandwidth of a quasioptically coupled diffusion-cooled superconducting HEB at 1267 GHz. Additional details of the device operation are discussed elsewhere [6].

Bolometer Device & Experimental Setup

The device is a 150 nm wide and 300 nm long strip, that is e-beam patterned and etched from a 10 nm thick Nb film using a recently developed self-aligned fabrication technique [9]. This process provides a robust thermal and electrical contact between the Nb microbridge and the gold contact pads, which is important for the mixer operation. Fig. 1 shows an SEM of a completed bolometer. It is integrated with a gold double-dipole antenna [10,11,12] on a crystal quartz substrate to form the planar mixer circuit, see fig.2. A $\lambda/4$ thick quartz plate with a gold reflector is placed on top of the device substrate which is then glued to a hyperhemispheric lens of crystal quartz. An additional plastic lens is used to create an essentially parallel beam in front of the mixer assembly. This mixer assembly, together with a HEMT intermediate frequency amplifier is cooled to an operating temperature of about 2 K in a vacuum cryostat. Y-factor measurements were performed in an evacuated box that was attached to the vacuum cryostat, as shown in fig.3, thereby eliminating the need for atmospheric corrections to the measured Y-factors, and thus allowing for accurate measurements of receiver noise. The box contains a 10 μm thick polyethylene beamsplitter to couple in the local oscillator power, and a rotating mirror to switch between the hot (295 K) and cold (85 K) loads. The 1267 GHz local oscillator is a submillimeter gas laser using a difluoromethane (CH_2F_2) line, that is pumped by a CO_2-laser operating at the 9R6 line. Two Zitex filters at 77 K and at 2 K are used to reduce the amount of infrared radiation coming in through the cryostat window. The intermediate frequency chain consists of a cooled isolator, a cooled 1.4 GHz HEMT amplifier, two FET amplifiers operating at room temperature, and a crystal direct-detector. A bandpass filter outside the cryostat sets the IF bandwidth for noise measurements to 300 MHz. The entire chain has an equivalent noise temperature of 6.3 K and a total gain of 85 dB.

Measurements

The frequency dependence of the RF power coupling to the bolometer was measured using a Fourier transform spectrometer (FTS) with the bolometer operated as a direct detector. The measured coupling center frequency was approximately 1 THz, with an effective coupling bandwidth of 730 GHz as shown in fig.4. This is in good agreement with the antenna design frequency, which was 1100 GHz, and with the one octave 3 dB bandwidth that has been measured for this type of antenna at lower frequencies [12]. This indicates that the coupling bandwidth is defined by the antenna rather than the bolometer. The dip near the center of the coupling band (see fig.4) corresponds to a third-order Fabry-Perot resonance between the quartz lens and the plastic lens in the mixer block, which we believe is enhanced by the mismatch between the f/6 beam of the spectrometer and the high focal number beam of the mixer.

A measurement of the direct detection response of the bolometer when switching between a hot (295 K) and a cold (77 K) blackbody load in the receiver signal beam indicates that the coupled broadband RF power is of the order 0.4 nW. In combination with the 730 GHz bandwidth this indicates that the total beam-path loss between the loads and the bolometer is approximately 7 dB.

Figure 5 shows the measured data for heterodyne receiver measurements. The best Y-factor response occurs in the resistive branch of the device IV curve at bias levels just above the instability point where the device switches into the superconducting state. The largest Y-factor value, measured at a constant DC bias voltage of 0.345 mV was 1.084, giving a receiver noise temperature of 2430 K double-sideband (DSB). This value does, however, contain a systematic error due to a slight shift in the electron temperature of the device from the broadband thermal radiation coupled from the calibration hot and cold loads. The temperature shift causes a change in the DC resistance and in the amount of thermal fluctuation noise generated by the device. This temperature shift can be avoided by maintaining constant resistance during the measurement instead of constant voltage, since the device resistance is a unique function of the electron temperature. This gives a slightly higher DC bias current, and therefore a higher mixer conversion [13] for the "cold" data point than for the "hot" one, leading to a conservative (slightly underestimated) value of the real Y-factor. The Y-factor measured in this way at a constant resistance of 54 Ω is 1.107, corresponding to an equivalent noise temperature of 1880 K DSB. It should be pointed out that the shift in temperature is not the same as a saturation of the mixing process; in fact the effect occurs also when no local oscillator is present. Due to the thermal response time of the device, only broadband power coupled within a few GHz of bandwidth around the LO frequency can actually take part in the mixing process. This power is only a few pW, which is not enough to cause saturation.

An upper limit estimate for the mixer noise temperature can be calculated by subtracting the IF amplifier chain noise, and by taking into account that the antenna is operating at 1267 GHz where the coupling is 1.6 dB lower than optimum (see fig.4). Other coupling losses such as reflections at lens surfaces, losses in the infrared filters and ohmic losses in the antenna are less accurately known to us, and are therefore not taken into account. This upper limit for the mixer noise is 950 K DSB.

The absorbed LO power in the device can be estimated from the direct detection response of the bolometer to be approximately 6 nW. This very low number is a result of the fairly high sheet resistance of the niobium film; the two-squares long device has a resistance of 140 Ω. The sheet resistance is linked via the Wiedemann-Franz law to the thermal conductivity of the electron gas, and therefore affects the bolometric response. Lower resistance devices generally require higher amounts of LO power, see [2,5,7]. In addition, for lower resistance devices (20-30Ω) than the one described here the broadband thermal radiation from the hot and cold loads has a negligible effect in Y-factor measurements [2,5], since the higher thermal conductance effectively reduces the temperature shift of the electrons.

Planned measurements

We are currently preparing to do two types of measurement with the devices described in this paper:

The first is a gas cell measurement using a rather strong absorption line of deuterized ammonia (NH_2D) at 1268 GHz, with either a backward wave oscillator (BWO) or the 1267 GHz CH_2F_2 laser line as a local oscillator. This measurement is warranted since it is the is the best way of conclusively verifying that the detector is operating in a 100 % heterodyne mode.

The second experiment is a measurement of resistance and IF output noise from the bolometer as a function of ambient temperature and the amount of LO pump power. Preliminary measurements have shown that an unpumped device can generate a significant amount of thermal fluctuation noise when biased thermally right at the superconducting transition temperature. The amount of noise generated appears to be higher than what an LO-pumped device produces when operated as a mixer. This may indicate that only a portion of the microbridge is operating precisely at the transition, and that the mixer can therefore be further optimized. This is reasonable, since the diffusion-cooled microbridge must operate with a temperature gradient along its length. A local oscillator that is stable over an extended period of time is required for this experiment because of the time constants involved in varying the temperature of the fixture that holds the mixer. We will therefore use either a BWO or a lower-frequency (630 GHz) solid-state source rather than a gas laser.

Summary

We have made the first measurements at terahertz frequencies with a diffusion-cooled hot-electron bolometer. A receiver noise temperature of 1880 K (DSB) was measured at 1267 GHz, with a mixer noise temperature below 950 K (DSB). The amount of local oscillator power absorbed in the device was approximately 6 nW, which is the lowest amount reported for any heterodyne receiver operating above 1 THz. The RF coupling bandwidth was 730 GHz, as measured with a Fourier transform spectrometer.

Acknowledgments

We acknowledge D. Prober, P. Burke and R. Schoelkopf of Yale University and B. Karasik of the Jet Propulsion Laboratory for many useful discussions. We are also grateful to T. Crawford, M. Gaidis and M. Shumate for supporting our laser LO system, and to H. Pickett for the use of the Fourier Transform Spectrometer. In addition, we appreciate the loan of a quartz lens and mount from J. Zmuidzinas. The research in this paper was performed by the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration, Office of Space Science.

References

[1] D. E. Prober, “Superconducting Terahertz Mixer using a Transition-Edge Microbolometer”, Appl. Phys. Lett. **62** (17), pp. 2119-2121, (1993).

[2] A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, P.J. Burke, A.A. Verheijen, R.J. Schoelkopf, D.E. Prober, “Large bandwidth and low noise in a diffusion-cooled hot-electron bolometer mixer”, Appl. Phys. Lett. 68 (11), pp.1558-1560, (1996)

[3] P. Yagubov, G. Gol'tsman, B. Voronov, S. Svechnikov, S. Cherednichenko, E. Gershenzon, V. Belitsky, H. Ekstrom, E. Kollberg, "Quasioptical phonon-cooled NbN hot-electron bolometer mixer at Thz frequencies", Proc. 7th Int'l. Symp. on Space Terahertz Technology, University of Virginia, Charlottesville, VA, March 1996, pp. 303-317.

[4] J. Kawamura, R. Blundell, C.-Y. E. Tong, G. Gol'tsman, E. Gershenzon, B. Voronov, J. Appl. Phys. **80**, p. 4232 (1996).

[5] B. S. Karasik, M.C. Gaidis, W.R. McGrath, B. Bumble, H.G. LeDuc, "A Low-Noise 2.5 THz Superconductive Nb Hot-Electron Mixer", To appear in IEEE Trans. Applied Superconductivity.

[6] A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, "Receiver measurements at 1267 GHz using a diffusion-cooled transition-edge bolometer", To appear in IEEE Trans. Applied Superconductivity.

[7] P.J. Burke, R.J. Shoelkopf, D.E. Prober, A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, "Length scaling of bandwidth and noise in hot-electron superconducting mixers", Appl. Phys. Lett. **68** (23), pp. 3344-3346 (1996)

[8] G.N. Gol'tsman, A.I. Elant'iev, B.S. Karasik, E.M. Gershenzon, "Antenna-coupled superconducting electron-heating bolometer", Proc. Fourth Int. Symp. on Space Terahertz Technology, p. 623, University of California, Los Angeles, March 30-April 1, 1993.

[9] B. Bumble, H.G. LeDuc, "Fabrication of a diffusion cooled superconducting hot electron bolometer for THz mixing applications", To appear in IEEE Trans. Applied Superconductivity.

[10] D. B. Rutledge, D. P. Neikirk, D. P. Kasilingam, "Integrated Circuit Antennas", *Infrared and mm Waves*, K. J. Button (Ed.), Vol.10, Ch.1, Academic Press, New York, 1983

[11] P.T. Parrish, T.C.L.G. Sollner, R.H. Mathews, H.R. Fetterman, C.D. Parker, P.E. Tannenwald, A.G. Cardiasmenos, "Printed Dipole-Schottky Diode Millimeter Wave Antenna Array," *SPIE Millimeter Wave Technology*, pp.49-52, Vol.337, 1982

[12] A. Skalare, Th. de Graauw, H. van de Stadt, "A planar dipole array antenna with an elliptical lens", Microwave and Optical Tech. Lett., Vol.4, No.1, Jan 5, 1991.

[13] F. Arams, C. Allen, B. Peyton, E. Sard, "Millimeter Mixing and Detection in Bulk InSb", Proc. IEEE **54**, 308 (1966)

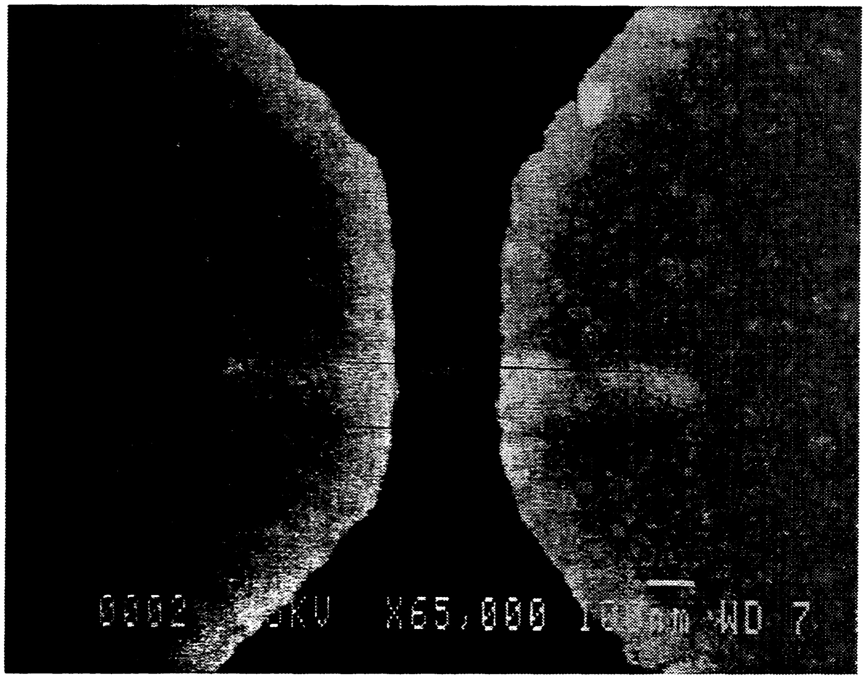

Fig. 1: SEM photo of a submicron Nb HEB.

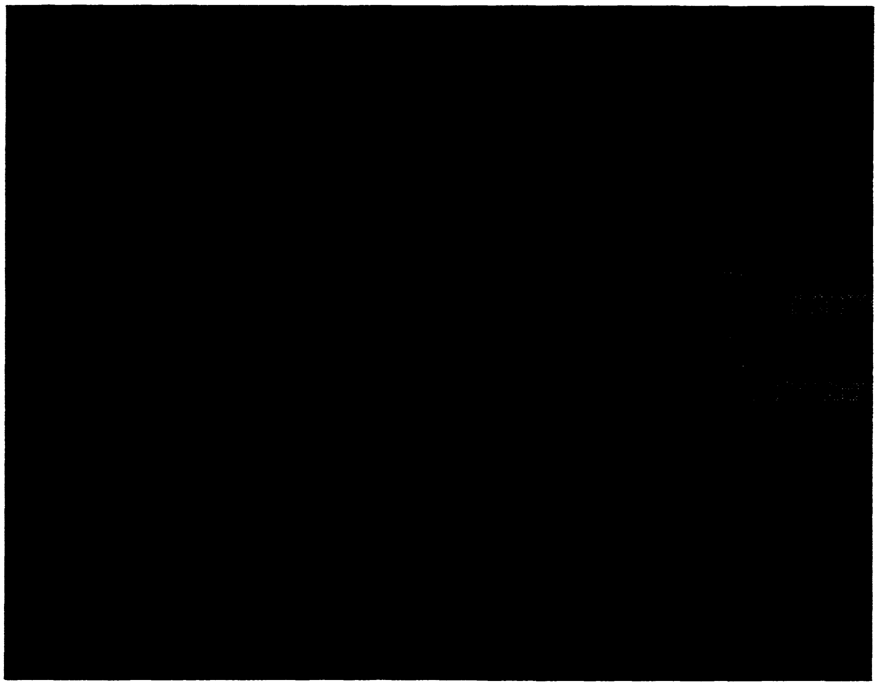

Fig.2: Double-dipole antenna and coplanar transmission line embedding circuit and RF bandstop filter. These elements are fabricated in gold. The Nb microbolometer is located in the center of the antenna circuit.

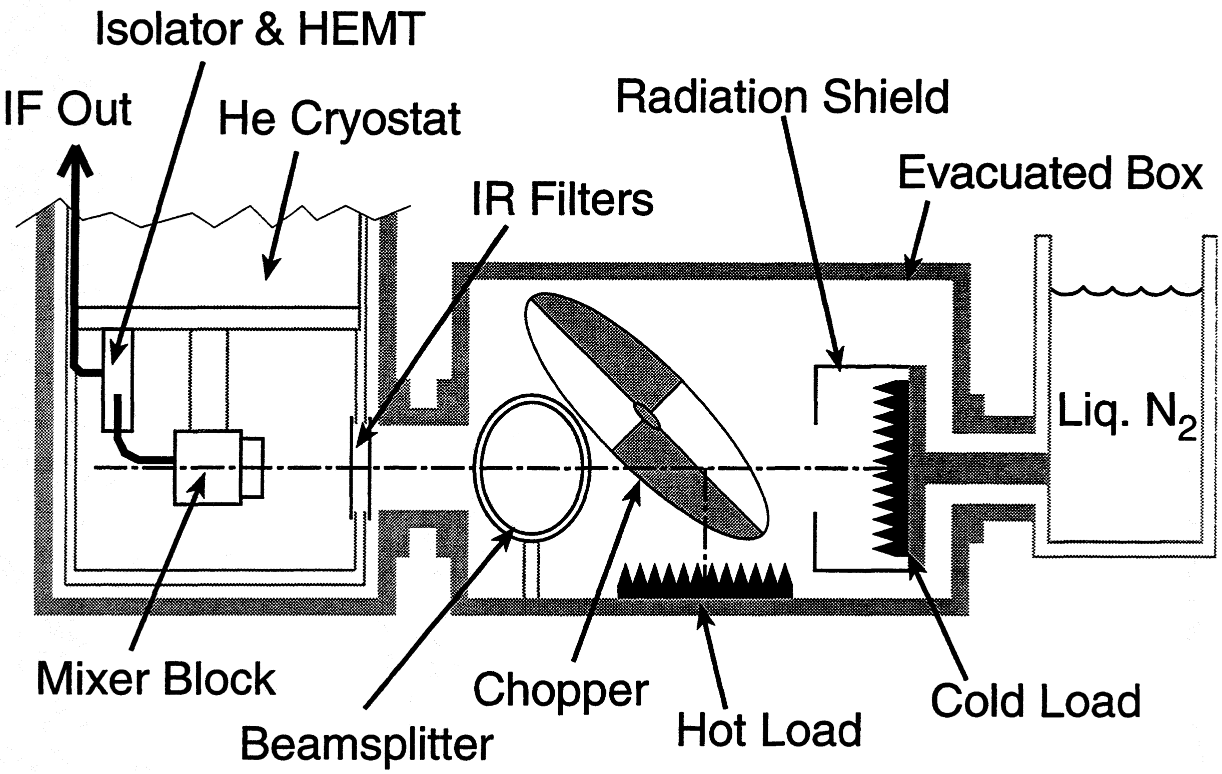

Fig.3: Schematic of the vacuum cryostat and the evacuated Y-factor measurement box.

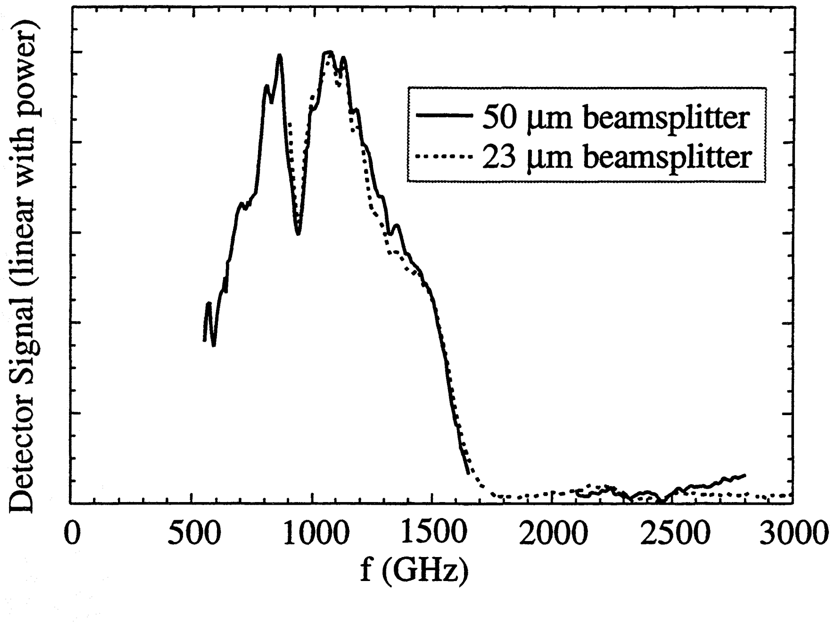

Fig.4: Relative coupled rf power versus frequency as measured with a Fourier transform spectrometer. To first order, the frequency dependence of the FTS itself has been calibrated away. Two different beamsplitters were used in the spectrometer which shows that there were no systematic errors due to this particular element.

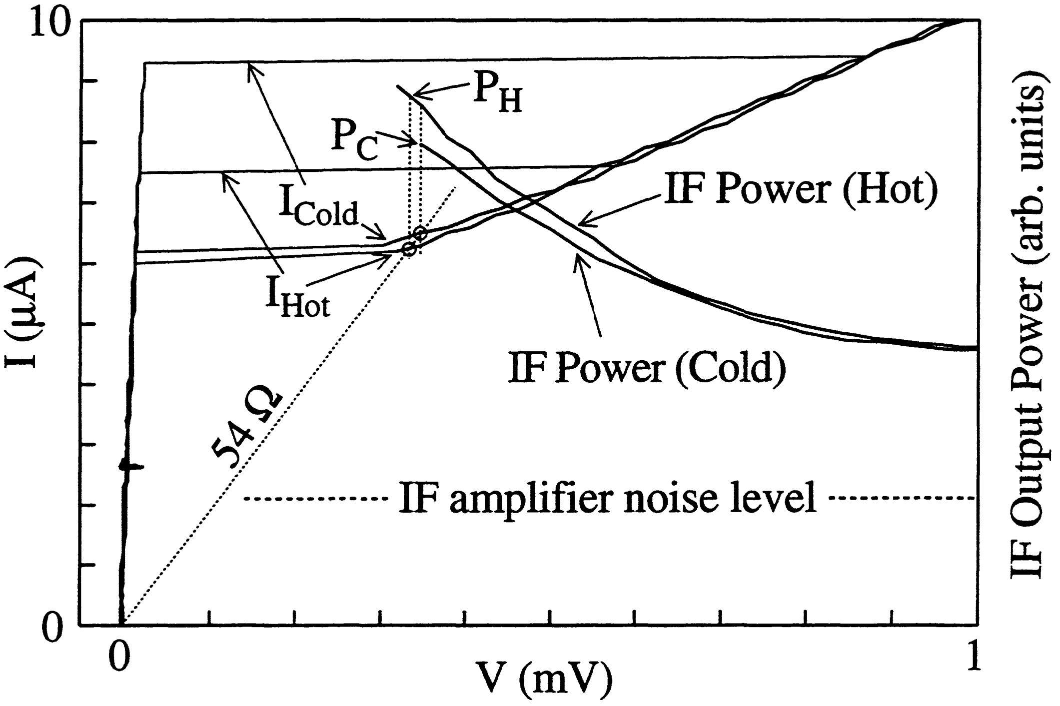

Fig.5: A pumped IV-curve at 1.2 THz and the output intermediate frequency power when coupling to a hot and a cold blackbody radiator. The periodic "wiggles" in the IV-curves are due to numerical truncation in the digitized data and are not present in the actual device. The integration time used in acquiring the IF power data was fairly low, which causes some point-to-point variation in the power readings shown. At high enough bias currents both IF power curves increase linearly with the dc current (not shown here), which is a result of the diffusion cooling mechanism in conjunction with the Wiedemann-Franz law for the thermal conductivity.