Receiver Measurements at 700 GHz with a Niobium Diffusion-Cooled Hot-Electron Bolometer Mixer

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Abstract

We report on heterodyne measurements with a Nb diffusion-cooled hot-electron bolometer in a fixed tuned waveguide mixer at 700 GHz. The device is a 300 nm long and 12 nm thick Nb microbridge, with a normal state resistance of 31 Ω. We have measured the DSB receiver noise temperature using a standard Y-factor method with a 300 K and 77 K blackbody load. At 700 GHz, a bath temperature of 4.3 K, and an intermediate frequency of 1.25 GHz, the receiver noise temperature $T_{rec,DSB}$ is 1690 K after correction for the losses in the beamsplitter. Reducing the bath temperature to 3.3 K decreases $T_{rec,DSB}$ to 1100 K. Careful inspection of the pumped differential I(V) characteristics does not reveal any influence due to direct detection. From the data we extract a maximum value of −17.8 dB for the conversion gain of the mixer at 4.3 K. The minimum mixer noise is determined to be 1170 K by applying a noise breakdown calculation. We expect significant improvement of the receiver noise performance upon further reduction of the bath temperature.

I. Introduction

Since the suggestion of using superconducting HEBs as mixer elements in heterodyne receivers [1], there has been a wealth of experimental results using these devices. An HEB mixer roughly consists of a superconducting microbridge, which is operated in a resistive state by dc biasing and irradiation with THz radiation generated by a local oscillator (LO) power. Heterodyne mixing occurs when a small RF signal is applied, leading to a modulation of the dissipated radiation in the microbridge at the intermediate frequency (IF). This leads to a length variation of the resistive region, called a hotspot, and consequently to a modulation of the resistance [2]. Based on the way in which the thermal energy of the hot electrons is removed, they can be divided into two classes.

The first class uses outdiffusion of the hot electrons as a cooling mechanism [3]. Nb based diffusion-cooled hot-electron bolometers have been tested successfully in heterodyne experiments and the results have clearly confirmed the

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expected advantages of HEBs at frequencies between 533 GHz and 2.5 THz [4-6]. They have shown a low-noise, low LO power consumption, and a reasonable IF bandwidth. Further improvement of diffusion-cooled HEBs is expected by using Al instead of Nb for the microbridge [7]. A disadvantage of using Al, however, is the need of cooling the mixer well below a bath temperature of 1 K.

The second class uses electron-phonon coupling as a cooling mechanism for the hot-electrons. Commonly, the superconducting material in phonon-cooled devices is NbN. In order to achieve a very fast phonon escape time, the film is made very thin, ~ 3 nm. Experiments with NbN HEB mixers have been performed up to 3.12 THz [8-11].

In this paper we report on heterodyne receiver measurements with a Nb diffusion-cooled HEB at 700 GHz in a *fixed-tuned* waveguide. In section II we give a short overview of the technology used to fabricate the devices. In section III we describe the RF experiments, consisting of a FTS measurement and heterodyne measurements with hot and cold loads.

II. Device fabrication

The essential part of the fabrication process of Nb HEBs is the definition of the Nb microbridge and cooling pads. In order to let diffusion-cooling dominate over electron-phonon cooling, the length of the bridge should be shorter than ~ 400 nm. Also, to achieve a reasonable match between mixer and the IF load, the resistance should be about 50 Ω. This can be achieved by making the film thin (~ 12 nm) to get a high sheet resistance (± 20-30 Ω) and by choosing a proper length-width ratio. Thus, to define the microbridge, electron-beam lithography (EBL) is required.

The process starts off with the deposition of a 12 nm thick Nb film by dc sputtering over the whole area of a 300 μm thick fused quartz wafer. Then the Au cooling pads are defined by EBL using a standard lift-off process with PMMA. The RF choke structure and electrical contacts are defined by optical lithography and lift-off. In the last step, the etch-mask to pattern the microbridge via reactive ion etching (RIE) is defined using a combination of deep-UV photolithography and EBL. Before heterodyne measurements, devices are diced and polished so that the substrate has a width of 90 μm and a thickness of 50 μm. A more detailed description of the process can be found in [12]. Note that the devices used for the measurements in this paper have been fabricated in June 1997 and have not shown any significant degradation upon storage in ambient atmosphere.

III. Experimental results

III.A FTS measurement

Before mounting a HEB in the mixerblock, the devices are characterized by a dc I(V) measurement on a dipstick and by inspection under the scanning electron microscope (SEM). A SEM picture of the device that has been used for the measurements described in this paper is shown in Fig. 1. Typically, the microbridges have a critical temperature of 5.9 K and a critical current density of ~ $4x10^{10}$ A/m^2. The device that has been used for the measurements described in this paper has a normal state resistance R_n of 31 Ω. The device is mounted in a fixed-tuned (tunerless) waveguide[1] which is designed for frequencies around 700 GHz. Photographs of the complete mixermount and the substrate channel are shown in Fig. 2a and Fig. 2b. The mixer is placed in a dewar and cooled down with liquid helium to a temperature of 4.3 K.

The frequency response of the HEB mixer with the waveguide is measured by operating the device as a direct detector in a Fourrier Transform Spectrometer (FTS) using a broadband source. Fig. 3 shows the measured spectra with and without a vacuum between the source and dewar. During the measurement the device is biased in a resistive state close to the dropback point in the I(V) characteristic (see inset). The peak response is of the waveguide is at 690 GHz, and the bandwidth is 120 GHz. The dip around 560 GHz in the measurement without vacuum is due to water absorption. The exact shape of the spectrum is not well understood at this moment and is still under investigation.

III.B Measurement of the receiver noise temperature

We have measured the receiver noise temperature using a standard Y-factor method. LO power is provided by a carcinotron-doubler combination, with a frequency range from 660 GHz to 760 GHz. All experiments described here are performed at exactly 700 GHz. To couple enough LO power to the device, we used a thick beamsplitter (55 μm mylar), because, due to a technical problem, the LO source did not allow to pump the device with a thinner beamsplitter. This causes an extra 2.3 dB loss in the RF path. The IF chain consists of a Berkshire HEMT cryo-amplifier and two room temperature amplifiers with a total gain of 68.7 dB, a center frequency of 1.4 GHz, and a gain bandwidth of 0.6 GHz. The intermediate frequency is tuned with a narrow bandpass filter. The measurements described here are performed at an IF of 1.25 GHz in a 65 MHz band. The IF output power was measured with a HP power meter. A schematic picture of the experimental set-up is given in Fig. 4.

The maximum measured Y-factor by manual switching between the hot (300 K) and cold load (77 K) is 0.29 dB, which corresponds to a DSB receiver noise temperature of 1690 K, after correction for the beamsplitter loss. Fig. 5a shows the IF output power of the pumped mixer with hot and cold load. The corresponding pumped I(V) curves are shown in Fig. 5b, together with the unpumped I(V). In order to exclude contributions of direct detection to the receiver noise temperature, we have performed a careful inspection of the pumped I(V) curves with hot and cold close to the optimum operating point (inset Fig. 5a), as well as a calculation the differential resistance of the I(V) curves (Fig. 5b). Both do not show any significant differences upon switching between the blackbody loads, indicating that the measured signal is truly heterodyne. The observed peaks in the dV/dI curves are not well understood at this moment. They are device specific and usually not observed. Possibly they are related to (electronic) inhomogeneities in the microbridge.

The noise of the receiver decreased to 1100 K upon reducing the bath temperature to 3.3 K. A further reduction of the bath temperature was not possible

[1]waveguide and mixermount developed at SRON by H. van de Stadt and H. Schaeffer

due to the limited capacity of the pump for the helium bath. However, it is reasonable to expect a receiver noise well below 1000 K at about 2 K.

IV. Calculation of the mixer gain and mixer noise temperature

We have extracted the mixer gain G_{mix} and mixer noise T_{mix} of the bolometer at 4.3 K from the measured IF output powers with hot and cold load. The gain is calculated according to

$$G_{mix} = \frac{\Delta P_{out}}{\Delta P_{in} G_{IF}} = \frac{\Delta P_{out}}{2k_B (T_{eff.h} - T_{eff.c}) G_{IF}}. \qquad [1]$$

Here, ΔP_{in} and ΔP_{out} are the RF input power from the blackbody loads (USB and LSB) and IF output power of the HEB mixer, respectively. G_{IF} is the gain of the IF chain. $T_{eff.h}$ and $T_{eff,c}$ are the effective input and output temperatures of the hot and cold load at the mixer input, corrected for the loss in the RF optics. Here, the waveguide is assumed to couple the radiation without loss to the bolometer.

Calibration of gain (and noise temperature) the IF chain is performed by using a SIS tunnel junction as a calibrated shotnoise source. The values for $T_{eff.h}$ and $T_{eff.c}$ are calculated using the known transmission coefficients and physical temperatures of the beamsplitter (55 µm mylar, 300 K), dewar window (125 µm mylar, 300 K), and heatfilter (115 µm black poly-ethyleen, 77 K). The values for the gain and noise temperature of the RF optics and IF chain are summarized in table 1. The high noise contribution of the RF optics is mainly due to the high loss in the 55 µm beamsplitter. Once the gain of the mixer is calculated, the mixer noise follows from

$$T_{rec} = T_{RF} + \frac{T_{mix}}{G_{RF}} + \frac{T_{IF}}{G_{RF} G_{MIX}} \qquad [2]$$

Figure 6 shows the calculated gain and noise of the HEB mixer as a function bias voltage, together with the pumped I(V) curve. Close to the dropback point of the I(V) characteristic, a gain of –17.8 dB is observed, whereas the corresponding mixer noise is 1170 K. It was not possible to do the same calculation for the Y-factor measurements at 3.3 K, because the IF chain is not calibrated at this temperature. Therefore, on the basis of our measurements, we cannot conclude whether the strong decrease in receiver noise temperature on decreasing the bath temperature is due to an increase of the mixer gain, a decreased mixer noise, or a combination of both. In the near future, we hope to answer this question by performing a systematic measurement of the mixer gain and noise as a function of the bath temperature.

Table 1 : *Gain and noise contribution of the IF chain and RF optics.*

	IF chain	*RF optics*
Gain (dB)	68.7	-2.5
Noise Temperature (K)	7.1	214

V. Conclusions

In summary, we have presented receiver measurements with a Nb diffusion-cooled HEB mixer in a fixed-tuned waveguide. At an IF of 1.25 GHz and a bath temperature of 4.3 K, the DSB receiver noise temperature is 1690 K. This value decreases to 1100 K upon reduction of the bath temperature to 3.3 K. The maximum mixer gain at 4.3 K was –17.8 dB and the corresponding mixer noise is 1170 K. On the basis of our measurements, we cannot resolve what the origin is of the strong decrease in receiver noise temperature after reducing the bath temperature.

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Figures

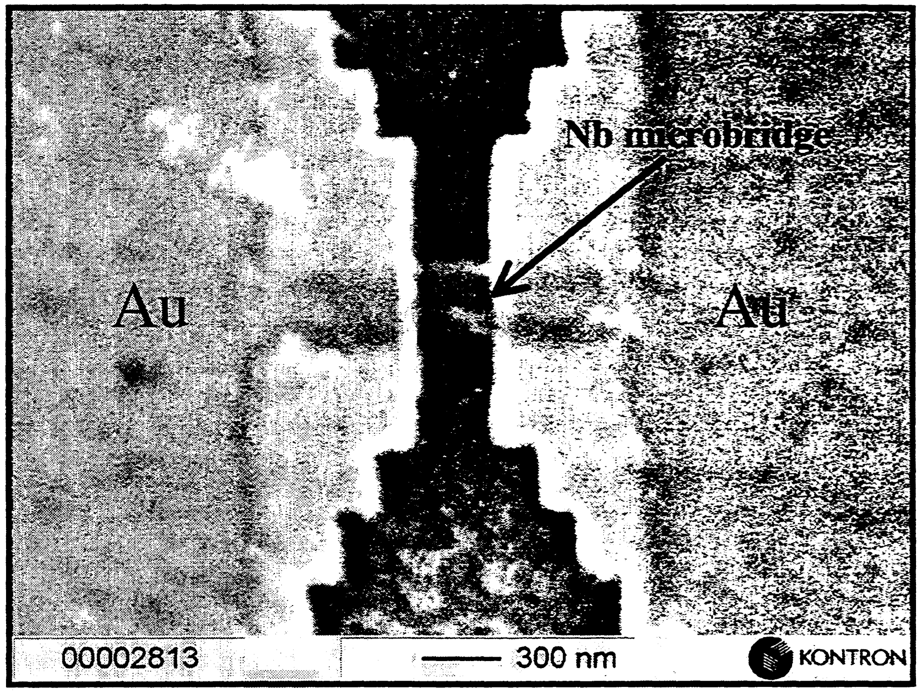

Fig.1 : SEM picture of the device that has been used for the measurements described in this paper. The length and width of the device are approximately 300 nm.

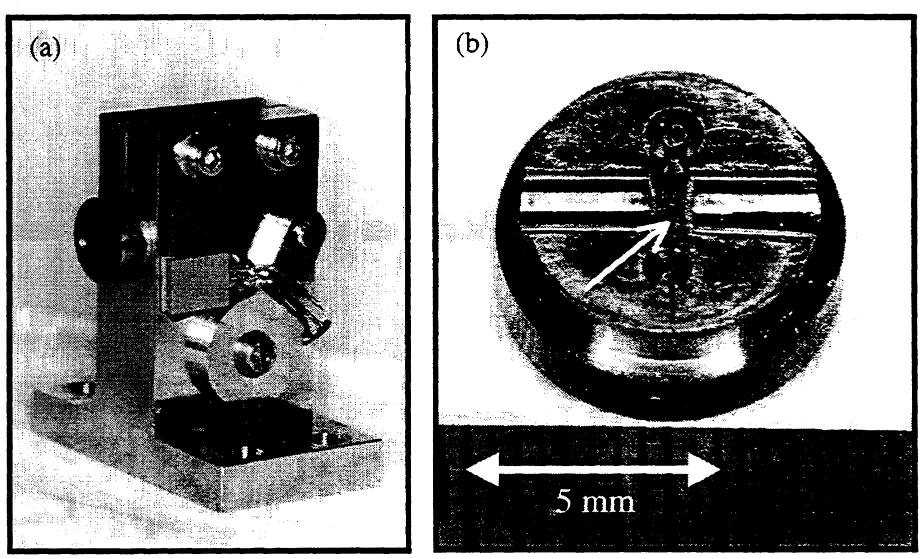

Fig.2 : (a) Photograph of the mount of the fixed-tuned mixer in combination with a diagonal horn.
(b) Part of the mixerblock where the device is mounted. The arrow indicates the substrate channel.

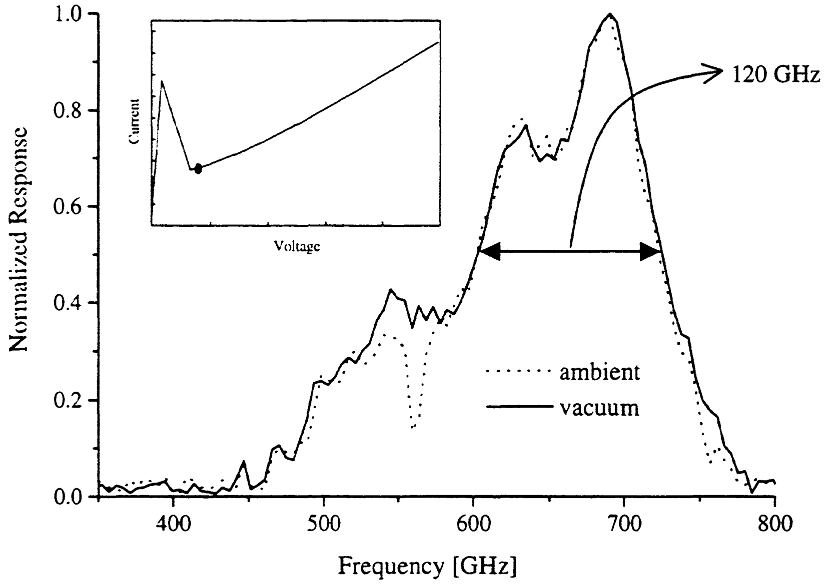

Fig.3 : FTS response of the HEB-waveguide combination. The measurement is performed with (solid line) and without (dotted line) vacuum between dewar and source. The inset shows the I(V) characteristic of the device. The dot indicates the bias point during the measurement of the spectra.

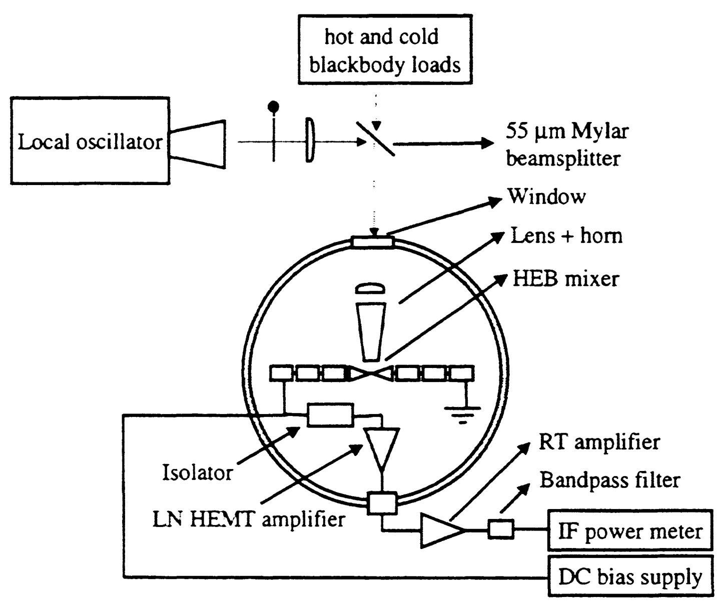

Fig.4 : Schematic representation of the experimental set-up used for the receiver noise measurements.

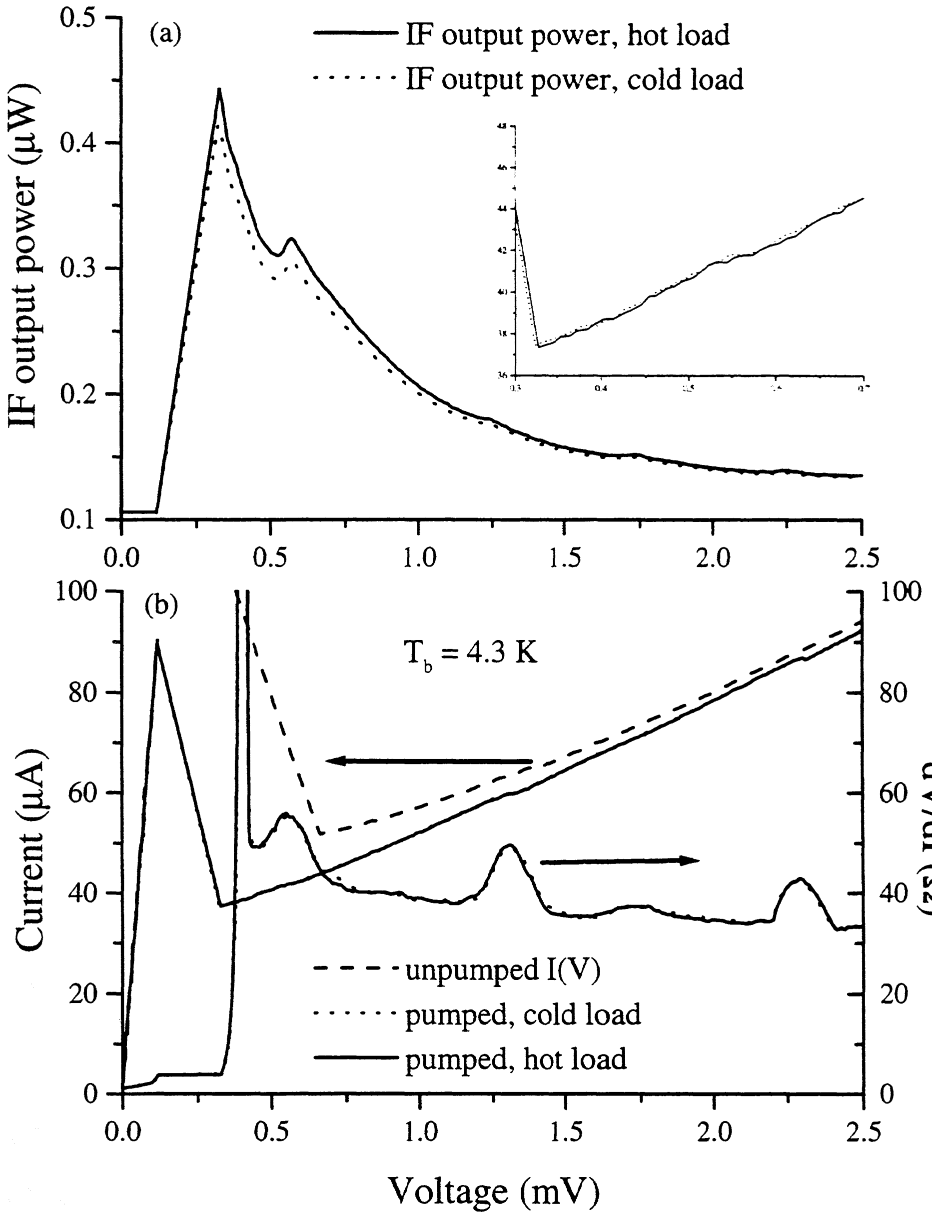

Fig.5 : (a) IF output power of the mixer with hot and cold load as a function of bias voltage. The inset shows the pumped I(V) with hot and cold load close to the optimal operation point.
(b) Measured pumped and unpumped I(V) curves together with the calculated differential resistance as a function of bias voltage.

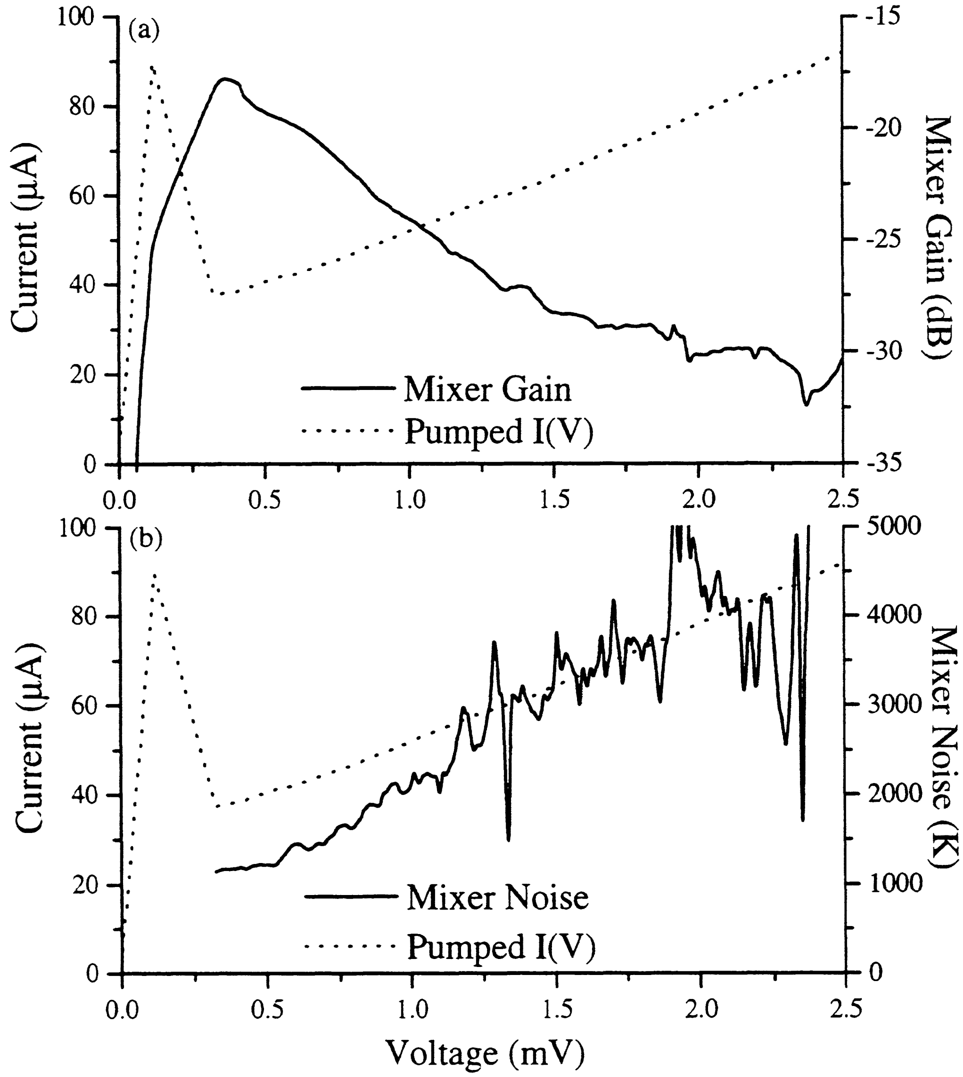

Fig.6 : Calculated mixer gain (Fig. 6a) and mixer noise (Fig. 6b) as a function of bias voltage at a bath temperature of 4.3 K. Also shown in each graph is the pumped I(V) characteristic.