# QUASIOPTICAL NbN PHONON-COOLED HOT ELECTRON BOLOMETRIC MIXERS WITH LOW OPTIMAL LOCAL OSCILLATOR POWER

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## Abstract

In this paper, the noise performance of NbN based phonon-cooled Hot Electron Bolometric (HEB) quasioptical mixers is investigated in the 0.55-1.1 THz frequency range. The best results of the DSB noise temperature are: 500 K at 640 GHz, 600 K at 750 GHz, 850 K at 910 GHz and 1250 K at 1.1 THz. The water vapor in the signal path causes a significant contribution to the measured noise temperature around 1.1 THz. The required LO power is typically about 60 nW. The frequency response of the spiral antenna+lens system is measured using a Fourier Transform Spectrometer with the HEB operating in a detector mode.

## Introduction

In the past years the development of low noise receivers for the THz frequency range has focused on superconducting HEB mixers. Predicted feasible noise figures of HEB are close to the quantum limit and their RF frequency bandwidth is not limited by the superconducting energy gap like in SIS mixers [1].

Two different types of HEB mixers have been developed: The phonon cooled HEB and the diffusion cooled HEB. These mixers employ different cooling mechanisms of the electron subsystem. In the phonon cooled HEB the electron energy relaxes through interaction with phonons [1] while in the diffusion cooled HEB hot electrons are predominately cooled by outdiffusion into metal contact pads [2]. The intermediate frequency (IF) bandwidth of a HEB mixer is determined by an electron energy relaxation time. To realize a wide bandwidth in the phonon-cooled HEB one must use a superconductor with a short electron-phonon relaxation time $\tau_{e\text{-}ph}$, e.g. NbN. For the diffusion-cooled HEB a material with rather long $\tau_{e\text{-}ph}$ as Nb can be used, but the bolometer strip must be short enough to enhance the outdiffusion of electrons to dominate over electron-phonon interaction. Recently reported results show that both mixer techniques yield reasonably broad IF bandwidth of several GHz [3-6].

Which type of HEB mixer is more appropriate is not yet clear. The comparison of mixer technologies shows that at the present stage of the development the phonon cooled HEB mixers exhibit larger gain and noise bandwidths, 3.2 and 8 GHz respectively, measured at 650 GHz [3] and a better noise performance at frequencies up to 1.1 THz [7].

The diffusion cooled Nb HEB mixers have shown better noise performance at 2.5 THz [8]. Gain bandwidth measurements at 20 GHz indicate that for this type of HEB it is possible to achieve a bandwidth of 6 GHz for the 0.1 μm long devices [6]. However, at higher RF frequencies measurements were performed only for 0.3 μm long devices and the noise bandwidth does not exceed 2 GHz [8,9].

Taking a look at the recent results obtained for both types of mixers one can see that the main difference in the characterization of these mixers was the amount of absorbed LO power, $P_{LO}$, which is basically determined by the bolometer time constant and its volume. It should be noted that the conversion gain of the HEB mixer does not depend on the bolometer volume [1]. Therefore the dimensions of the strip can be in principle chosen to adjust $P_{LO}$ for a particular application. This freedom is limited by the constraint to match the device impedance to the antenna. Moreover there are other limitations restricting the bolometer dimensions for both types of HEB:

For the diffusion cooled devices the length of the strip must be small to provide a short time constant of the mixer. The need to match the device to the antenna makes it necessary to have a small cross-section of the Nb strip due to the low film resistance. These two requirements reduce the device volume leading to a very small $P_{LO}$. This, in turn, restricts the dynamic range of the mixer.

For the phonon-cooled HEB the film thickness is the only limiting parameter. It must be small enough to provide fast escape of nonequilibrium phonons into the substrate. The strip in-plane dimensions are free parameters. Matching to the antenna requires a certain length-to-width ratio of the strip, but one can scale the strip to adjust the dynamic range of the mixer and meet particular LO power requirements.

In this paper we describe the development of submicron size phonon cooled HEB mixers with low required LO power and present results of heterodyne measurements in the 0.55-1.1 THz frequency range.

**Device fabrication and experimental setup**

Micrographs of the spiral antenna integrated HEB mixer and the center part of the antenna are shown in Figures 1 and 2. The fabrication procedure consists of 4 main steps (illustrated in Figure 3):

1. Deposition of NbN film;
2. Patterning of Au pads for bolometer strip definition;
3. Patterning of antenna, large contact pads and transmission line;
4. Patterning of the bolometer.

The devices are made out of a 3 nm thick NbN film deposited on a high-resistivity Si substrate. A detailed description of the film fabrication process is found in [4].

The obtained films have a sheet resistance of about 1 kΩ/□, a transition temperature around 10 K and a transition width of 0.5 K. After all processing steps the transition temperature drops down to 9 K with a transition width of 1 K. A typical R(T) curve of the device is shown in Figure 4.

In the next process step Au pads are placed in the center of each chip. The spacing between them already defines the dimension of the bolometer, typical is a length 0.2-

0.5 μm and a width of 1-5 μm (depending on the design of the spiral antenna). Applying electron beam lithography for patterning a double layer resist system (Copolymer + PMMA) one gets a lift-off mask which allows metallization of the structure. After evaporating 5 nm titanium (to establish good adhesion) plus by 80 nm Au using e-beam evaporation system the lift-off mask is removed in acetone.

The baseline wiring consists of the spiral antenna and large contact pads. For patterning, the same lithography technique as in the previous step is used with 5 nm titanium plus 200 nm Au.

In the last step the NbN film, which is still left on the whole wafer, has to be removed except between the contact pads. E-beam lithography with negative resist SAL601 is used to define a mask that covers the bolometer part and the Au pads. Etching is done in an argon ion beam system for about 10 min (acceleration voltage 400 V, current 0.2 $mA/cm^2$). The remaining resist is left on the device.

Finally, photo resist is spun on the whole wafer for protection when sawing up into chips of size 2x4 mm (5x5 mm if transmission line is included).

The setup for heterodyne measurements is shown in Figure 5. The mixer chip is clamped to an extended hemispherical silicon lens with a quarter wavelength antireflection coating optimized for 660 GHz. The mixer block is mounted in a LHe-cooled vacuum cryostat equipped with a 380 μm Zitex G115 IR radiation filter. As LO sources we use three BWOs covering the 550-1100 GHz frequency range. The radiation from the LO is focused by a Teflon lens and combined with the signal by a 12-μm-thick Mylar beamsplitter. The noise temperature is measured using the Y-factor technique with hot/cold (295/77 K) loads in the signal path of the receiver.

The device output is connected through a bias-T to a two-stage IF amplifier chain. As a first stage we use a cooled HEMT amplifier with a center frequency of 1.5 GHz, 300 MHz band and a noise temperature of 5 K. The amplified mixing signal is then fed to a scalar network analyzer.

**Antenna design and simulations**

The antenna used in the quasioptical setup is an equiangular spiral with a 90° arm width, which yields a self-complementary design. The antenna shape is specified by a spiral expansion rate and an antenna terminal size. The expansion rate is optimized for smooth and uniform antenna patterns with small variations in beamwidth with frequency and wide bandwidth. Based on previous experience an expansion rate of 3.2 per turn was chosen for a 1.5 turn antenna. A wide bandwidth is needed at the present stage of the mixer development since it allows to perform mixer measurements and comparison of mixer properties over a wide frequency range.

As follows from Babinet's principle the input impedance of a self-complimentary infinite structure should be pure real and equal to $Z_{ant}=Z_0/[2(1+\varepsilon)]^{1/2}$, i.e., 75 Ohm for Si. However, there are several factors like finite antenna arm length, nonideal antenna geometry at the device, finite thickness of the antenna arms, frequency-dependent surface impedance of the metal etc, which in practice influences the impedance of the antenna.

Three-dimensional simulations of the integrated antenna were performed using HFSS (High Frequency Structure Simulator – HP85180A) by Hewlett Packard. The following setup is investigated: The antenna arms are modeled as a three-dimensional structure with finite resistance which is located on the back plane of silicon extended hemispherical lens. The whole structure is placed in a cavity with absorbing boundaries.

The antenna is modeled in a transmit mode. This requires to replace the bolometer by a voltage source parallel to a surface resistor with the same size. Such a feed port does not allow direct impedance calculations but it produces consistent field distributions. Simulations are performed in a frequency range 0.5-1.5 THz for a 200 nm thick Au antenna. The surface resistor dimensions are 2x0.3 μm. The conductivity of the Au film was assumed to be $8\cdot10^7\ \mathrm{Ohm^{-1}\cdot m^{-1}}$ - two times larger than its bulk value at room temperature. The calculation results obtained for frequencies above 1.3 THz show strong spurious mode excitations. At frequencies below 1.3 THz the expected field distribution in spiral arms is observed. We have calculated the spot diameter related to current drop off in the antenna arms and compared that to a first order estimation for the minimum required antenna diameter of the ideal spiral (antenna structure is a perfect electric conductor and scaling invariant) [10]. This predicts that the current fades away at an armlength of about one wavelength. The current spot diameter of the calculated structure decreases with frequency faster than predicted. This is due to ohmic losses in the antenna arms which increase with frequency and the change in antenna curvature in the center. The obtained results are preliminary and further work on integrated antenna simulation (antenna impedance and pattern calculations) has to be done.

The integrated antenna frequency response has been investigated experimentally using Fourier Transform Spectroscopy (FTS) technique. In these measurements the HEB is driven to a temperature close to $T_c$ and operated as a detector. Since the HEB response is frequency independent the obtained spectrum is basically determined by the antenna+lens system response. There are also additional optical losses in the signal path (cryostat Teflon window, Zitex IR filter) which were not taken into account so far.

The signal from the FTS is phase modulated (PM) in order to reduce the background noise and increase the detector signal-to-noise ratio. Due to the fact that PM does not modulate all wavelengths equally the modulation amplitude of a vibrator mirror was chosen in such a way to make the spectral power distribution within 50% variations in the frequency range of interest 0.7-2.5 THz. The maximum of FTS output power measured with a Golay cell was found at about 1.5 THz.

The FTS spectrum obtained for the device #2 is show in Figure 6. The antenna extends one and a half turns and has an inner radius of 3 μm. This gives a crude short wavelength limit of 30 μm (3 THz in a free space) [11].

The observed lower cut-off frequency of the measured integrated antenna arises because of the wavelength selective nature of phase modulation and spectral emission function of the FTS Hg lamp. The upper cut off frequency is about 1.25 THz. This is considerably lower than the expected value for the above antenna geometry. Possible explanations for this are:

Destructive interference of the antireflection coating of the lens optimized for a maximum transition at 660 GHz; minimum transition occurs at a double frequency – 1.3 THz;

Chromatic aberration of the lens leading to a shorter focal length at higher frequencies which deteriorates the antenna coupling efficiency. This can be avoided employing elliptical or smaller hemispherical lenses.

**Results and discussion**

Several mixers made by e-beam lithography have been tested. Most of them have shown excellent noise performance. The noise temperature of three best mixers are plotted as a function of LO frequency in Figure 7. The in-plane dimensions of the bolometer strip are 0.2x4 μm for the device #1 and 0.2x2 μm for the devices #2 and #3. The best Y-factor of 1.4 dB was measured for the device #1 at 630 GHz, corresponding to 500 K DSB noise temperature. Note that all reported results are not corrected to account for losses. The measurements are performed at 4.5 K ambient temperature, cooling the mixers down to 2.5 K leads to an insignificant drop of the noise temperature.

The optical losses in the signal path are estimated to be at least 3 dB. This includes absorption losses in the cryostat teflon window, Zitex IR filter, beamsplitter and Si lens, and antenna losses (backside radiation and sidelobe losses). Eliminating this from the receiver noise temperature gives the intrinsic mixer noise temperature of about 300 K for all mixers presented in this work.

The observed smooth frequency dependence of the noise temperature for all mixers is probably determined by the antenna-lens system, as discussed above. Another possible reason could be the change of the RF impedance of the superconducting film near the gap frequency. This effect influences the RF matching of the device to the antenna.

A considerable contribution to the measured receiver noise temperature at THz frequencies comes from atmospheric absorption. It can been seen distinctively at 1.1 THz, where the sharp rise in the noise temperature is due to a strong water absorption line. Moving the cold load forth and back in front of the cryostat window at this LO frequency causes the substantial change of the measured Y-factor.

In Figure 8 we plot the pumped IV-curves of the device # 2 as well as results of noise temperature measurements vs. position of the operating point at 0.75 THz. It can be seen that in a quite wide range of the LO power and dc bias variations the noise temperature of the mixer is not changing drastically. This is a special benefit for THz frequency applications where one still has to refer to laser systems as LO sources often suffering from output power instability.

The absorbed LO power was estimated using the isotherm technique assuming that the response to dc and RF power is the same. It is derived from two pumped IV curves with different amounts of LO power which are crossed far from the unstable region by a constant resistance line [7]. This technique gives about 100 nW absorbed LO power for the device #1 and about 60 nW for the devices #2 and #3. These numbers correlate well with the in-plane dimensions of the bolometer. It is important that there is no fundamental limitation to further decrease the bolometer volume and assure even smaller amount of LO power.

## Conclusions

A quasioptical phonon-cooled HEB mixer with submicron in-plane dimensions of the superconducting strip has been fabricated and tested in the 0.55-1.1 THz frequency range. The results of the noise temperature measurements show that these mixers have excellent performance, comparable to SIS mixers at frequencies about 1 THz. The small amount of coupled LO power, about 60 nW, is needed to pump the mixer to the optimal operating point.

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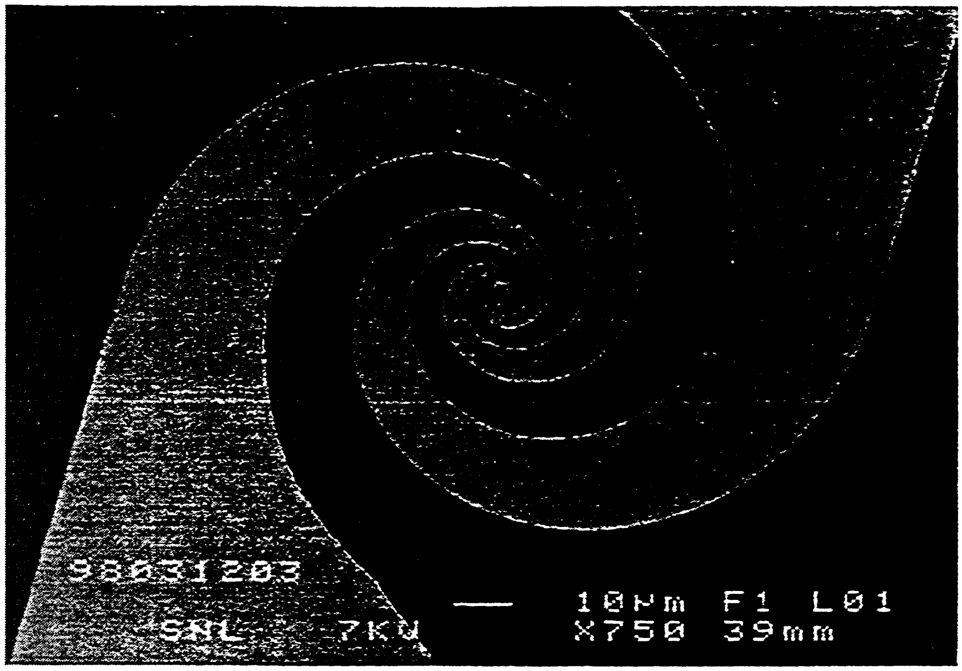


Fig.1. Micrograph of the spiral antenna integrated HEB mixer.

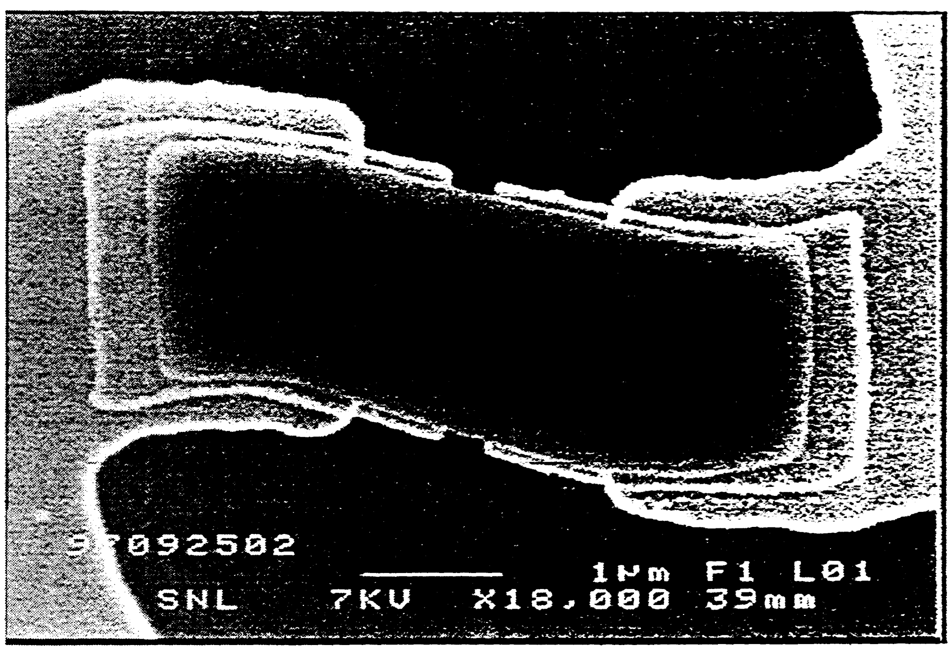


Fig.2. Micrograph of the antenna gap.

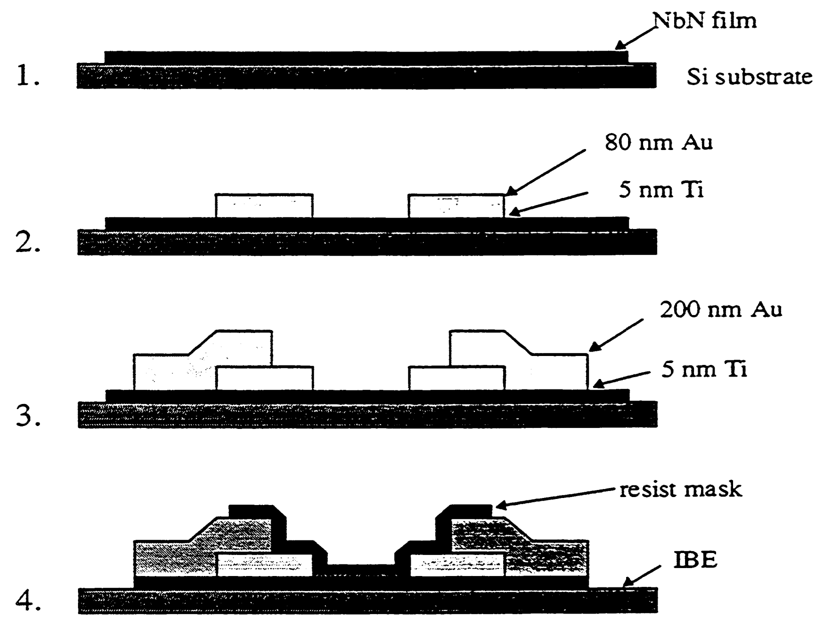


Fig.3. Schematic top of the fabrication process.

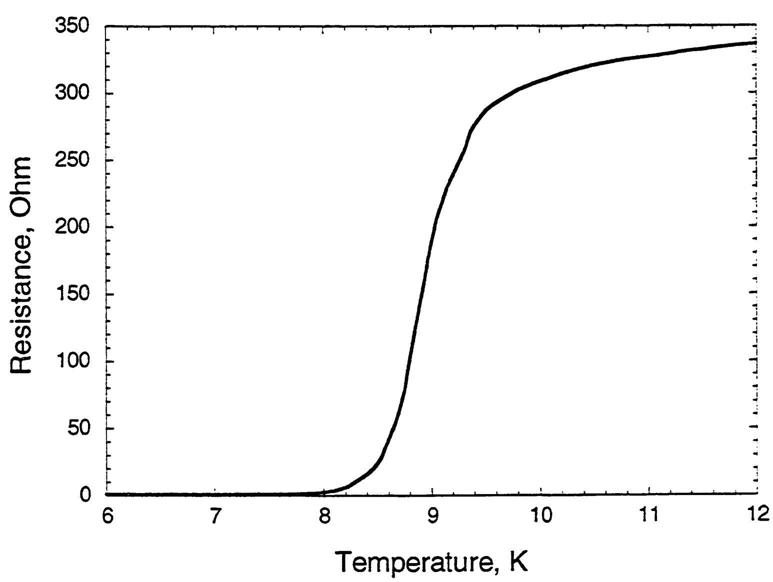


Fig.4. Typical R(T) curve of mixer with submicron dimensions of the bolometer strip.

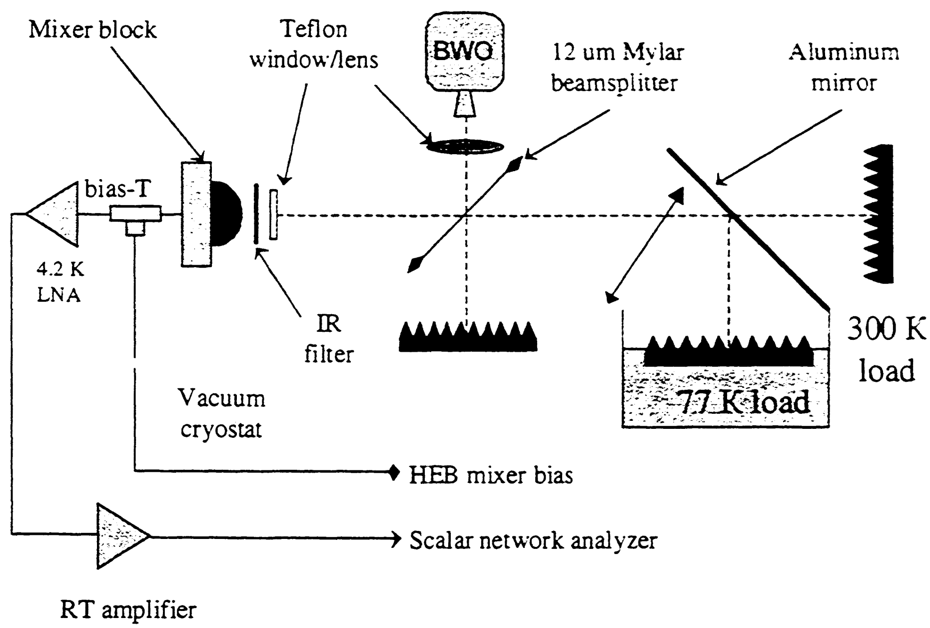


Fig.5. Setup for noise temperature measurements.

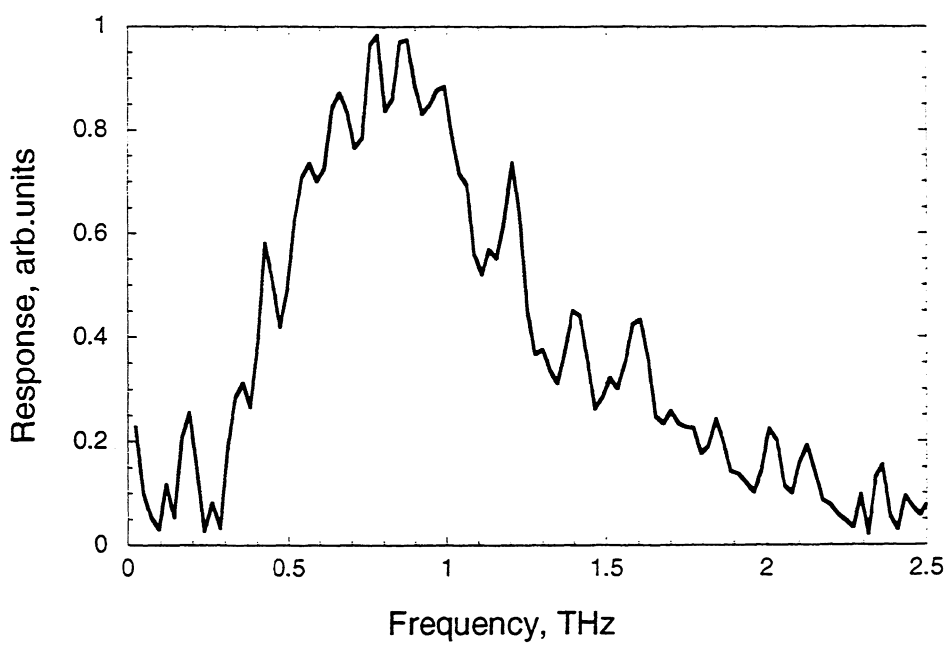


Fig.6. FTS spectrum measured for the device #2. The antenna extends one and a half turns and has an inner radius of 3 μm. The Si lens has an antireflection coating optimized for 660 GHz.

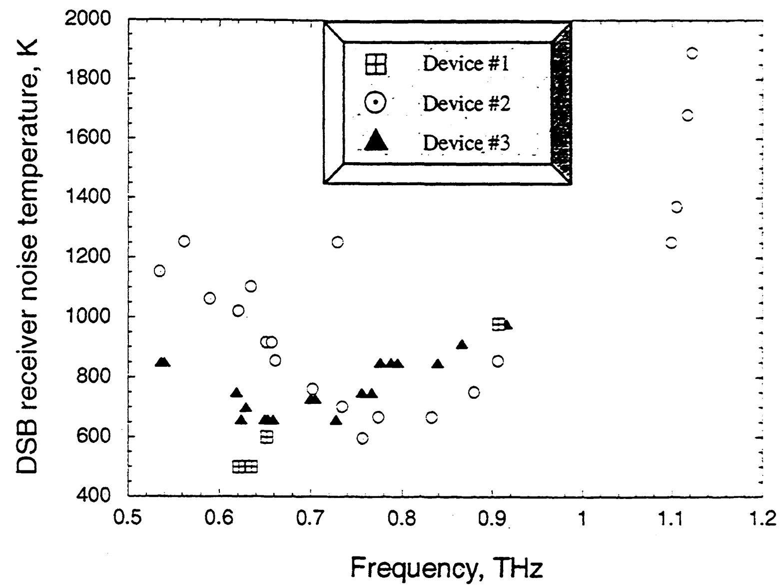


Fig.7. DSB receiver noise temperature as a function of LO frequency for three mixers.

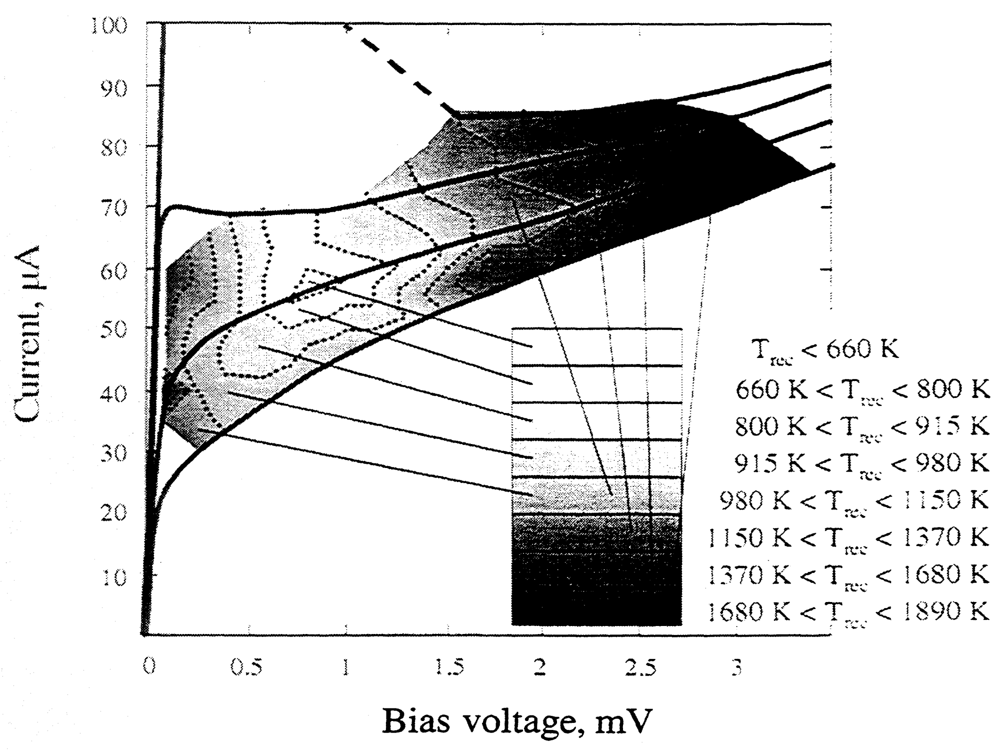


Fig.8. Pumped IV-curves of the device # 2 and results of noise temperature measurements for different positions of the operating point.