DIFFUSION-COOLED ALUMINUM HOT-ELECTRON BOLOMETER MIXERS AT SUBMILLIMETER WAVELENGTHS

Anders Skalare, William R. McGrath,
Pierre M. Echternach, Henry G. LeDuc

Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Irfan Siddiqi, Aleksandr Verevkin, Daniel E. Prober

Dept. of Applied Physics, Yale University, New Haven, CT 06520-8482

Abstract

We report on the first mixing experiments at submillimeter wavelengths with superconducting diffusion-cooled hot-electron bolometers (HEB's) made from aluminum. The measurements were carried out at frequencies around 618 GHz, and showed conversion bandwidths of up to 3 GHz, and absorbed local oscillator (LO) powers of 0.5 to 6 nW. The highest mixer conversion efficiency was found to be about -21.5 dB single-sideband. A mixer noise temperature of about 1000 K DSB (double sideband) and a receiver noise temperature of about 3100 K DSB can be inferred from measurements of conversion efficiency and intermediate frequency output noise. The ratio of RF power coupled into the electrons to the power at the input of the mixer, that is the RF coupling efficiency, was found to be similar to that of our niobium HEB mixers. This demonstrates that despite the long electron-electron interaction time as measured near the Fermi energy in Al, the "hot" electrons thermalize efficiently in response to the RF power.

1. Introduction

During the last five years superconducting hot-electron bolometer (HEB) mixers [1,2] have increasingly come to be regarded as the most promising technology for extremely low-noise molecular spectroscopy observations at frequencies above about 1 THz. This is because unlike competing SIS mixers these devices are not limited to operation around or below the gap frequency of available superconductors. Compared to the more noisy Schottky diode mixers they also require low enough local oscillator (LO) power levels, so that operation with solid-state multiplied sources may be feasible even at terahertz frequencies. This combination of useful properties have made HEB mixers prime candidates for spaceborn, aircraft, or balloon-borne instrument platforms. The spaceborne ESA/NASA FIRST mission, NASA's SOFIA aircraft observatory, and a Long-Duration Balloon instrument all plan to employ HEB receivers. These HEB instruments will focus on low-background astrophysical observations of emission lines in the frequency regime from 1-3 THz.

Aluminum diffusion-cooled HEB devices are expected to have significant advantages over Nb devices, namely lower local oscillator (LO) power requirements and lower mixer noise temperatures with equal or higher intermediate frequency (IF) bandwidths. The lower LO power needs are significant since the solid-state tunable LO sources that are preferred for most applications do not yet exist, and when they do become available in the near future it is not certain that they will produce a sufficient amount of power to operate other HEB mixers As we will demonstrate for the first time, Al HEB devices require absorbed LO power levels of only a few nW, while Nb diffusion-cooled HEB mixers need about 20-80 nW absorbed in the device [3, 4]. It should be pointed out that Nb devices requiring less LO power can be fabricated, but that they will have reduced IF bandwidths. In this way the aluminum technology gives an increased flexibility to the diffusion-cooled bolometer approach that is not present in the phonon-cooled devices used by other groups. Previously published material shows that the actual amount of LO power required scales as Tc^2, where Tc is the critical temperature of the superconductor [5, 6]. In addition, [5, 6] predicts that the mixer input noise temperature should scale in direct proportion to Tc, which should eventually lead to even lower noise temperatures than those already reported for other HEB mixers. The purpose of this paper is to present the first submillimeter wave measurements with a diffusion-cooled aluminum HEB mixer, and provide experimental data for the conversion efficiency, intermediate frequency bandwidth, and LO power.

2. Fabrication and DC properties

The aluminum HEB devices were fabricated using a shadow mask technique, previously described in [7], which allows the device and its contacts to be fabricated using a room temperature process in a single run without breaking the vacuum. This is critical to avoid contamination and/or oxidation of the Al films. The device films were about 13 to 17 nm thick, with contacts of 63 nm Al, 28 nm Ti and 28 nm Au. This is a robust contact design that avoids diffusion of normal metal contact material into the Al microbridge. The devices were 0.1 µm wide with lengths of 0.3, 0.6, and 1.0 µm. The HEB devices are fabricated together with a microstrip or coplanar waveguide circuit that connects to a planar double-slot antenna. The different circuit types require that the aluminum films are fabricated either directly onto the silicon wafer or on the silicon monoxide dielectric used for the microstrip, and it appears that the device process works about as well for both cases. The microstrip circuit requires a few extra process steps, but avoids one of the difficult steps in the CPW process, which is to pattern the narrow gaps required to give the CPW lines the correct characteristic impedance. Fig.1 shows a 0.3 micron long Al HEB device on SiO.

Measurements show that the transition temperatures of the devices are about 1.6 to 1.8 K, while the thicker aluminum of the connecting pads has a reduced transition of about 0.6 to 1.0 K, see Fig.2 . The ends of the devices have an apparent suppressed Tc as shown schematically in Fig.3 . In fact, for the shortest 0.3 micron most of the device has its transition close to the Tc of the pads. This critical temperature is too low to operate the device efficiently as a bolometric mixer since it is only barely above the operating temperature of the helium-3 system (~400 mK), which does not allow enough local oscillator power to be applied.

3. Mixer Measurement Set-Up

In the experiments the device chips were attached to the plane back side of an elliptical silicon lens of 12 mm diameter using cyanoacrylate glue. The lens was held in a copper fixture, where the devices were connected with an intermediate frequency microstrip circuit on Duroid 6010 with several aluminum bond wires. The intermediate frequency output signal from the mixer was either connected via a low-noise cooled L-band HEMT amplifier at 4 K [8] or, for bandwidth measurements, via a 0.5 to 18 GHz FET at 77 K [9]. Stainless steel coaxial cables were used in several places to reduce heat conduction between different components in the receiver. The mixer was attached to the cold plate of a helium-3 cryostat system that allowed operating temperatures down to about 400 mK [10]. The optical path used to couple in the RF power to the mixer had Zitex and black polyethylene filters on a 77 K heat shield, and a black polyethylene / diamond dust filter on a 4 K heat shield that enclosed the He-3 tank and the mixer. In measurements of mixer conversion and conversion bandwidth, the local oscillator (LO) power was supplied by a broadly tunable backward-wave oscillator (BWO) [11] and the signal was provided by a a Gunn oscillator driving 2 cascaded frequency-multipliers [12]. The output power from the multiplier chain was coupled into the optical path using a Mylar beamsplitter. Most of the measurements were done with the multiplier providing a signal frequency of about 618 GHz, which was determined by measuring the Gunn oscillation frequency with a counter. A spectrum analyzer was used to detect the IF output signal.

4. RF coupling and LO Power Requirements

The RF coupling to the bolometer can be estimated by switching the receiver input beam between two broadband calibration targets that are maintained at different temperatures, and observing the effect this known difference in broadband thermal emission has on the DC characteristics of the device. In this method, the shift in DC heating that is required to maintain a constant device resistance is considered a measure of the difference in coupled RF power from the two targets. Such a measurement was made with device #6 (see Table 1), and showed a coupling efficiency from the targets of –4.7 dB. This value is similar to those seen earlier for our niobium HEB mixers, that usually fell in the range of –5 dB to –8 dB [4,13] The conclusion that can be made from this is that the 600 GHz RF power appears to couple about as well to this aluminum device as it would to a niobium HEB.

The amount of local oscillator power that is absorbed in the device can also be calculated from the effect on the DC IV curve, which is how the power estimates in Table 1 were deduced. The amount of LO power that is actually incident on a device is harder to estimate, since the mode matching between the source and the device chip is not accurately known. It is possible to calculate an upper limit, however. In one experiment device #6 was pumped strongly enough by a Gunn oscillator/multiplier to cause it to become completely normal conducting. The source gave less than 100 μW of power at 618 GHz, and about –7 dB of this power was coupled into the receiver beam with a beam splitter. A further 20 dB of coupling loss was due to losses in the cryostat window and filters, and to the diverging multiplier output beam. This leads to an upper estimate of the LO power that acually reaches the silicon lens in the mixer of about 200 nW, and most likely the power that is acually coupling into the chip antenna is substantially less due to the poor focussing. Even this upper limit shows that predictions for devices much shorter than the electron-electron inelastic time, where LO power requirements in the μW regime have been predicted [14], are not applicable to the devices used here

5. Mixer Measurements

The mixer conversion efficiency and its dependence on frequency have been measured for several devices and the data are summarized in Table 1. The conversion efficiency was determined from measurements with a monochromatic signal source, and was calculated as the ratio of the coupled IF output power to the input signal power absorbed in the device. This means that losses in the RF optical path as well as losses in the mixer embedding circuit are not included. The –4.7 dB value for the RF coupling loss that was mentioned earlier refers to device #6 in Table 1, but the losses for the higher resistance devices should be considerably higher due to the larger impedance mismatch.

The highest mixer conversion efficiencies measured were about –20 to –21 dB single sideband (SSB) for several of the devices, with bandwidths up to 3 GHz. It should be pointed out, that in all the measurements shown in the table, except device #5, the LO power was optimized for maximum conversion.

The dependence of IF conversion bandwidth on bias voltage is shown in Figs. 4 & 5 for the 1 μm long device #1. At the highest bias voltage the bandwidth is at its largest, 2.7 GHz, but at the same time the conversion is quite low, -33 dB (SSB). When the bias voltage is reduced into the regime where self-heating is evident in the IV curve, the conversion increases and the bandwidth is suppressed, which is consistent with the behavior of other superconducting HEB's. At the lowest bias point (V1 in Fig.4) the maximum conversion is at about –21 dBm and the IF bandwidth at 1 GHz. This clearly demonstrates one of the key advantages of Al since even this IF bandwidth is several times larger than the value obtained for Nb devices of this length [3, 15]. Device #3 is 0.6 μm long and gave the largest bandwidth of 3 GHz, for a similar conversion efficiency of –20 dB. This increase is consistent with the L^{-2} dependence of the IF bandwidth for diffusion-cooled HEB mixers, and demonstrates that the *entire* length of the Al bridge determines the IF bandwidth despite the presence of the apparently normal conducting ends (discussed below).
While the DC characteristics of the 1 μm long Al devices tested so far have resistance vs. temperature (RT) and current vs. voltage (IV) curves that are qualitatively similar to the ones seen for diffusion-cooled niobium devices, this is not quite the case for the 0.6 μm long devices. The end effect in the bridge extends to about 0.15 μm from the contacts and appears to have a significant impact on the IV curves. This can be seen in Fig.6, which shows such an IV curve with varying amounts of local oscillator power applied. One possible interpretation of Fig.6 is that with increasing amounts of LO power first one, then the other end region become normal conducting at low voltages where the central region of the bridge is still superconducting. Marker "a" in the Fig.6 indicates where one end region is normal conducting, while the other is still superconducting. At marker "b"

both ends are normal. At the higher LO levels required to achieving higher conversion, both ends are normal conducting. This situation is almost the reverse of that which usually gives the best mixer conversion efficiency in niobium devices, where the center of the bridge is normal conducting and the ends are superconducting.

Fig. 7 shows the bias dependence of the mixer output for three different input signal levels. The highest power, which corresponds to a conversion efficiency of –21.5 dB SSB (device #6 in Table 1) occurs when the bridge ends are normal and the central part of the device is at its transition temperature. A separate measurement of output noise and Y-factor was made with the same device under similar conditions. It was found that the output thermal fluctuation noise from the device was about 3 K, the Johnson noise (including noise generated elsewhere and reflected against the device) was about 2 K, and the IF amplifier noise was about 10 K. With the total IF noise thus estimated at 15 K, the conversion efficiency at –21.5 dB, and the RF coupling at about –4.7 dB, the receiver noise temperature can be estimated at about 3100 K double sideband (DSB) of which two thirds is IF amplifier noise and the contribution from the mixer is about 1000 K (the noise temperatures are thus referred to the input window of the cryostat). Although the directly measured Y-factors do indeed show a similar response, they are unfortunately also affected by direct detection of the broadband radiation from the calibration targets, and are not currently used as a verification of these noise estimates.

6. Device End Effects

The measurements show that the device is affected by end effects that appear to be extending to about 120 to 150 nm from the contact pads at each end. The precise mechanism behind this is not fully understood at this point, but the cause may be proximity effect from the contact pads, and be further complicated by charge imbalance [16]. The end regions have several non-trivial effects on the HEB mixer, especially for devices that are shorter than 1 µm. To maximize the mixer conversion efficiency and/or minimize the mixer input noise temperature, a sufficient amount of DC and LO power needs to be dissipated so that the electron temperature in the central part of the device is close to the local critical temperature (about 1.8 K). Under these conditions the end regions will be heated to a temperature higher than their local critical temperature (about 0.6 to 1.0 K), since the temperature provided by the He-3 system is only marginally lower (about 0.4 K), and since the temperature distribution inside the device has a parabolic shape that is determined by the Wiedemann-Franz law and the diffusion-cooling mechanism. One effect of the normal conducting end regions is to change the effective load line of the central part of the device. If the end regions have a combined resistance of 45 Ω, for example, the effective load impedance in the IF band will be a total of 95 Ω instead of the 50 Ω provided by the IF system by itself. This makes it harder to maintain a stable DC bias point close to the Tc of the central device region, which can cause oscillations and which prevents the mixer from being operated at its optimum bias point. Another effect is dissipation of intermediate frequency output power in the end regions. In the example just given, this would result in almost 3 dB of additional conversion loss. The end effects also define the length of the shortest device that can be efficiently operated as a mixer, since shorter devices appear to have the Tc lowered significantly by the contact pads, so that only very small amounts of LO power can be applied. Previous estimates of intermediate frequency bandwidths were based on the assumption that devices could be made very short. An example given in [5] assumes a film diffusivity of $D=10\ cm^2/s$ and a device length of 100 nm, resulting in an IF bandwidth of 157 GHz. With an effective minimum length of 300 nm, the maximum bandwidth is reduced to $\Delta f = \pi D/(2L^2) = 17$ GHz.

There are a few different ways to reduce the consequences of the end effect, and increase the IF bandwidth of the device: One would be to lower the operating temperature of the mixer so that the device ends do not go completely normal conducting, and maybe also reduce the Tc of the device film itself. This approach would require a more complex cryocooler than the He-3 system used by us, such as a dilution refrigerator. Another approach would be to modify the geometry of the bolometer, for example by making the device film much wider at the ends, so that the wider (but still affected) regions have lower normal resistance and can act as heat sinks for the central part of the device. Also, the sheet resistance of the device can be lowered, which would reduce the losses associated with having the resistance of the normal conducting end regions in series with the IF system impedance. Such devices have already been fabricated, and will be investigated in the near future.

7. Summary

In summary, we have measured the local oscillator power requirements, the conversion efficiency and the IF bandwidth of several diffusion- cooled aluminum HEB mixers at frequencies around 618 GHz. We found that the LO power needed was indeed about 10 to 20 times lower than that required for niobium HEB mixers as would be expected from the ratios of the squares of their critical temperatures. The conversion efficiency was relatively low compared to that achieved for niobium, about –21.5 dB SSB. There are several possible explanations for this, including some relating to the end effects in the device. IF bandwidths of up to 3 GHz were measured, but since the data for different devices were recorded under varying bias and LO pump conditions, the precise dependence on film diffusivity and device length cannot be determined yet. Since these dependencies are primarily low-frequency properties of the device, they can be expected to be similar to the D/L^2 trend found for the 30 GHz measurements in [17]. The conversion efficiency, RF input coupling efficiency and the output noise in the IF band leads to a rough estimate of 3100 K (DSB) receiver temperature, of which about 1000 K (DSB) would be mixer noise. These noise temperatures were not, however, measured directly through a well-calibrated Y-factor measurement. The end effects in the devices were found to be significant, especially in the shorter 0.3 µm and 0.6 µm devices, and future work should clearly be devoted to minimizing the consequences. An estimate of the required input local oscillator power, as well as direct detection measurements using broadband blackbody radiators, show that there are no severe losses in the RF coupling to the device.

Acknowledgments

This work was performed jointly by the Jet Propulsion Laboratory and Yale University, and was supported by the Space Science Enterprise of the National Aeronautics and

Space Administration (NASA) and by the National Science Foundation. Funding for Irfan Siddiqi was provided by a NASA Graduate Student Fellowship.

References

[1] E.M. Gershenzon, G.N. Gol'tsman, I.G. Gogidze, Y.P. Gusev, A.I. Elant'ev, B.S. Karasik, A.D. Semenov, "Millimeter and submillimeter range mixer based on electronic heating of superconducting films in the resistive state," Sov. Phys. Superconductivity, Vol.3(10), pp.1582-1597, 1990

[2] D.E. Prober, "Superconducting Terahertz Mixer using a Transition-Edge Microbolometer," Appl. Phys. Lett., Vol.62(17), pp.2119-2121, 26 April 1993.

[3] R.A. Wyss, B.S. Karasik, W.R. McGrath, B. Bumble, H. LeDuc, "Noise and bandwidth measurements of diffusion-cooled Nb hot-electron bolometer mixers at frequencies above the superconductive energy gap", Proc. Tenth Int. Symp. Space Terahertz Tech., pp. 215-228, University of Virginia, Charlottesville, Virginia, March 16-18, 1999

[4] B.S. Karasik, M.C. Gaidis, WE.R. McGrath, B. Bumble, H.G. LeDuc, "Low noise in a diffusion-cooled hot-electron mixer at 2.5 THz", Appl. Phys. Lett. **71** (11), 15 September 1997, pp.1567-1569.

[5] B.S. Karasik, W.R. McGrath, R.A. Wyss, "Optimal Choice of Material for HEB Superconducting Mixers", IEEE Trans. Applied Superconductivity, Vol.9, No.2, June 1999, pp.4213-4215.

[6] B.S. Karasik, A.I. Elantev, "Analysis of the noise performance of a hot-electron superconducting bolometer mixer", Proc. Sixth Int. Symp on Space Terahertz Tech, California Institute of Technology, Pasadena, California, March 21-23, 1995, pp.229-246

[7] P.M. Echternach, H.G. LeDuc, A. Skalare, W.R. McGrath, "Fabrication of an aluminum based hot electron mixer for terahertz applications", Proc. Tenth Int. Symp. Space Terahertz Tech., pp. 261-268, University of Virginia, Charlottesville, Virginia, March 16-18, 1999

[8] The cryogenic HEMT amplifier was supplied by Berkshire Technologies.

[9] Broadband coolable 05-18 GHz FET by Miteq Inc.

[10] The 8-inch baseplate He-3 cryostat was supplied by Infrared Laboratories, Inc.

[11] The BWO tube was manufactured by Istok.

[12] Both the Gunn oscillator and the x6 multiplier by Radiometer Physics GMBH

[13] A. Skalare, W.R. McGrath, B. Bumble, H.G. LeDuc, "Measurements with a diffusion-cooled Nb hot-electron bolometer mixer at 1100 GHz," , Proc. Ninth Int. Symp.

Space Terahertz Tech., pp.115-120, Jet Propulsion Laboratory, Pasadena, California, March 17-19, 1998.

[14] A.D. Semenov, G.N. Gol'tsman, "Nonthermal mixing mechanism in a diffusion-cooled hot-electron detector", J. Appl. Phys., Vol.87, No.1, Jan.1, 2000, pp.502-510.

[15] P.J. Burke, R.J. Schoelkopf, 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., Vol. **68** (23), pp.3344-3346, 3 June 1996

[16] D. Wilms-Floet, J.J.A. Baselmans, T.M. Klapwijk, Appl. Phys. Lett. **73**, 2826 (1998)

[17] I.Siddiqi, A. Verevkin, D.E. Prober,,A. Skalare, B.S. Karasik, W.R. McGrath, P. Echternach, H.G. LeDuc, "Aluminum sub-micron superconducting hot-electron bolometer mixers", These proceedings

Tables and Figures

Device	L	R	η SSB	BW	LO Power
	(μm)	(Ω)	(dB)	(GHz)	(nW)
#1	1.0	448	-21 to –33	1 to 2.7	0.5
#2	1.0	285	-21	3	1.3
#3	0.6	255	-20	3	3.7
#4	0.6	330	-----	1.7	0.9
#5	0.6	100	-29	3	2.7
#6	0.6	106	-21.5	----	5.7

Table 1; Measured results for Al HEB devices. The conversion efficiency does not include losses in the optical coupling to the mixer embedding circuit. The absorbed LO power was estimated by the effect on the DC IV curves of the HEB's.

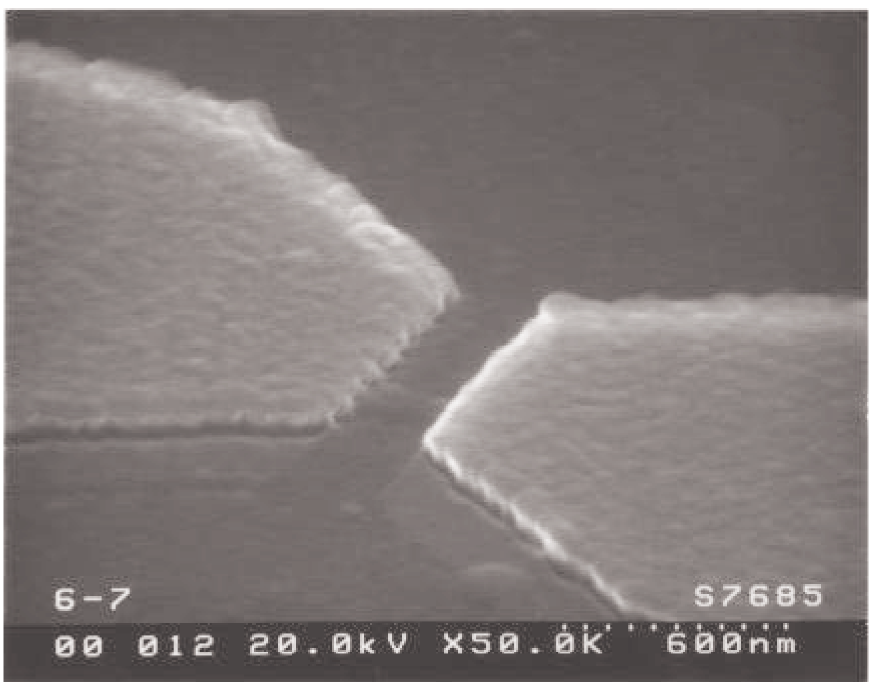

Fig.1; SEM of an Al microbridge. The Al device is faintly visible between the Al-Ti-Au contacts.

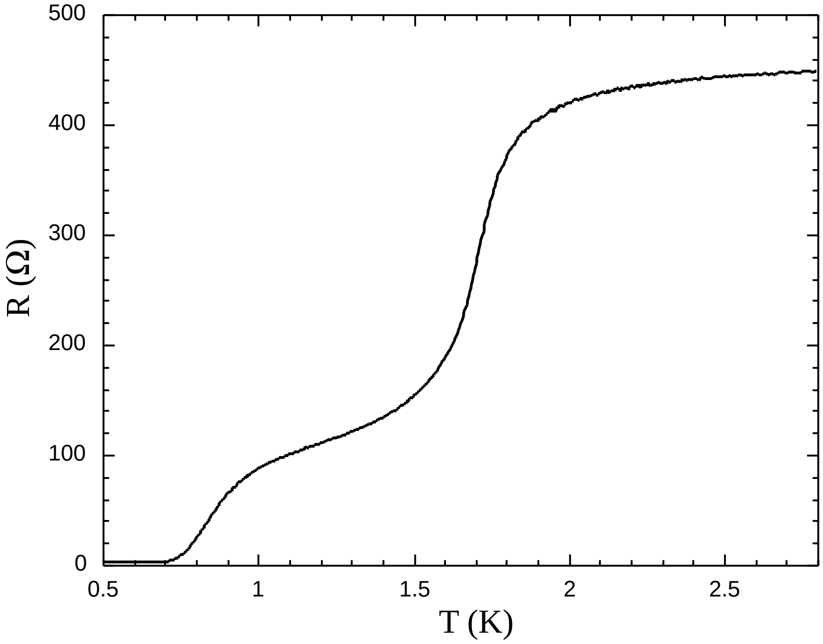

Fig.2; Resistance vs. Temperature characteristic for device #1 in Table 1. The first resistance drop occurs at the transition temperature of the microbridge, the second drop near 0.7 K is due to the transition of the Al contact pads.

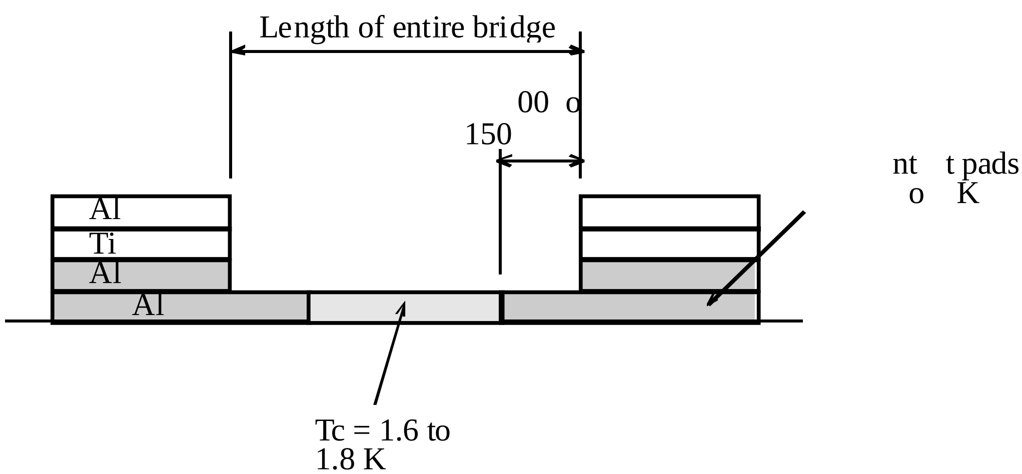

Fig.3; Schematic cross section of the microbridge and contact pads (not to scale).

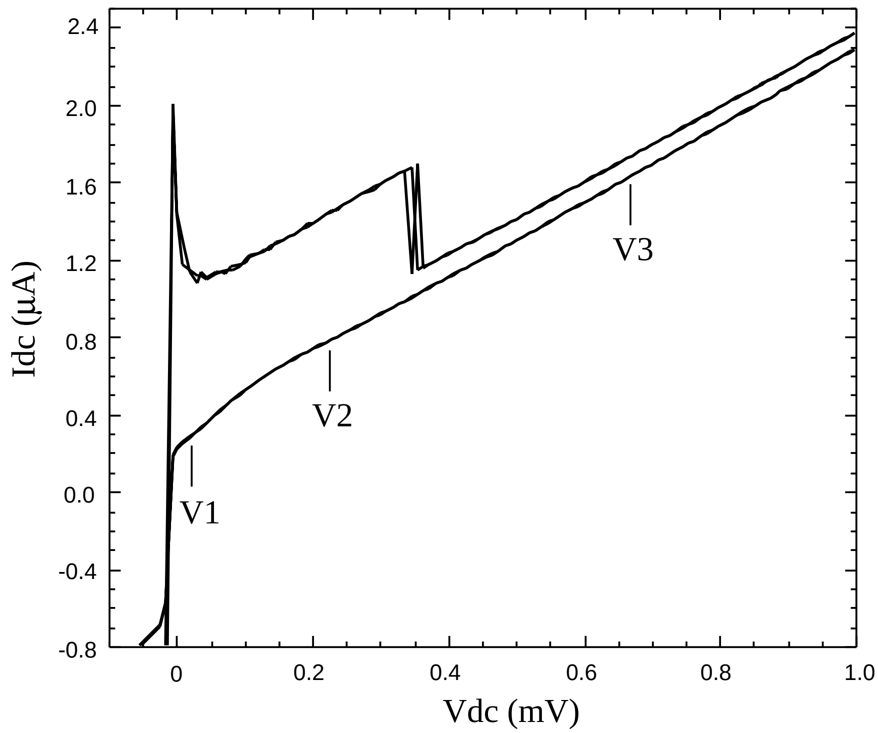

Fig.4; Unpumped and LO-pumped IV curves of device #1 at 0.42 K. The marked points correspond to the bias voltages used for the IF bandwidths shown in Fig. 5.

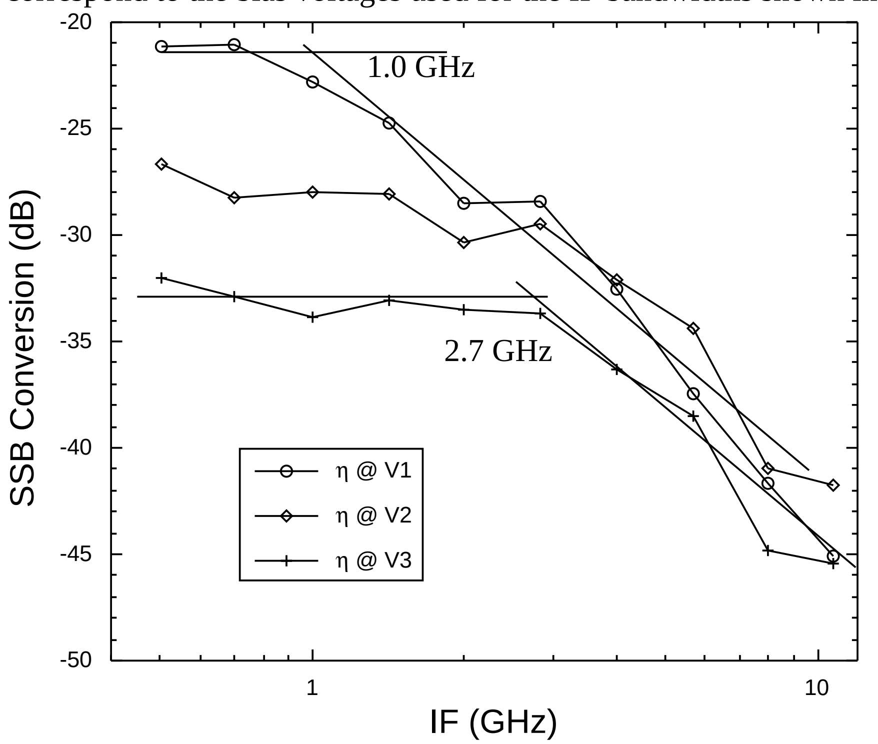

Fig.5; Conversion efficiency vs. intermediate frequency for device #1. The different curves correspond to the marked bias voltages in Fig.4 . The signal was kept at a constant frequency of 618 GHz in the lower sideband, while the local oscillator frequency was varied.

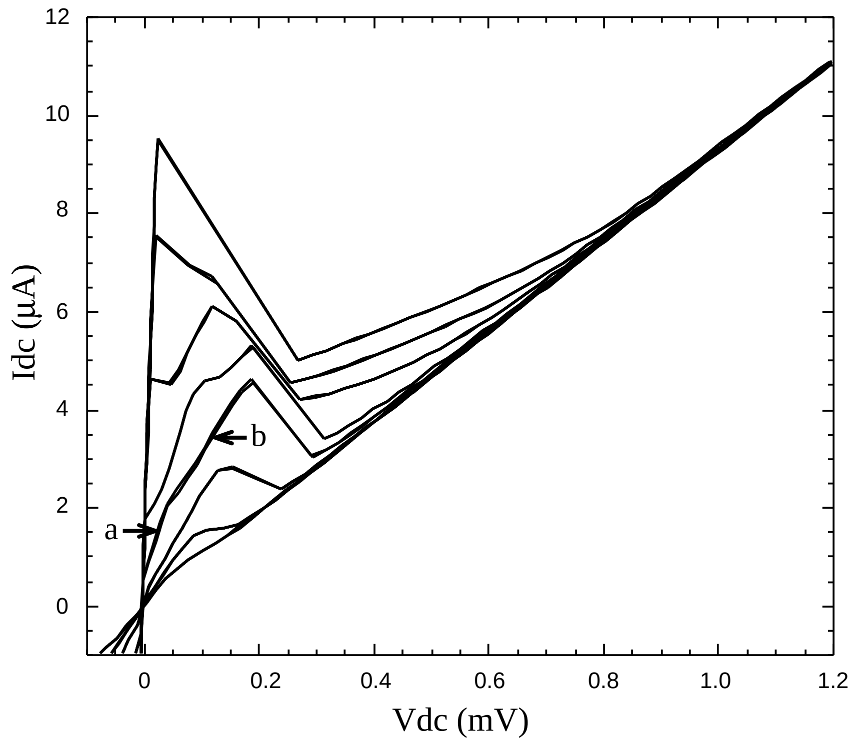

Fig.6; IV curves of the 0.6 micron long device #6 at 0.44 K. One curve is unpumped and the others are local oscillator pumped at varying power levels at 620 GHz. The labels “a” and “b” are explained in the main text.

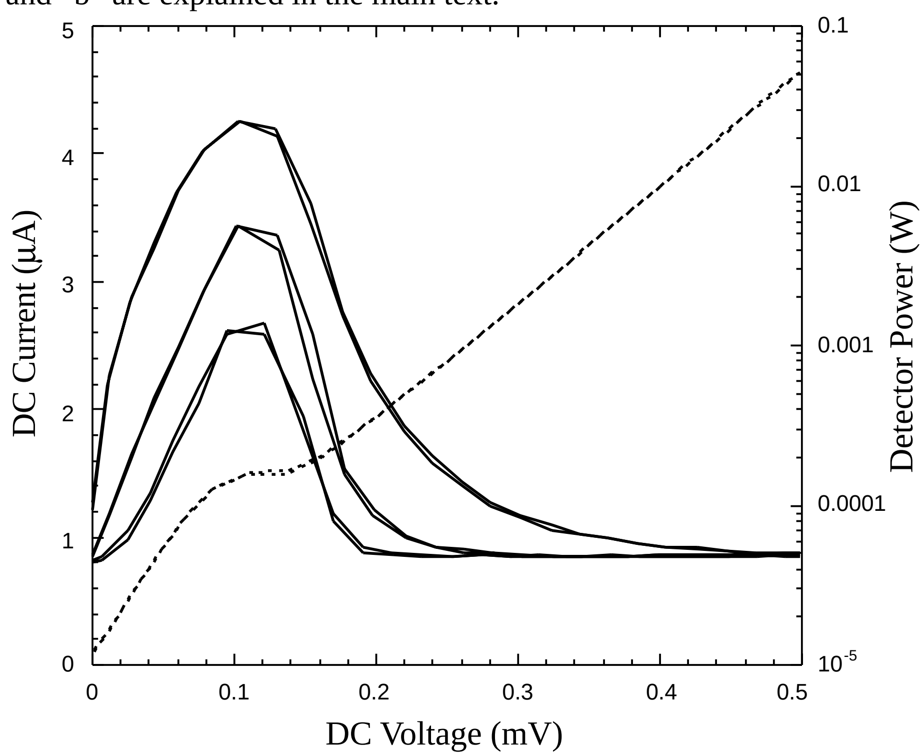

Fig.7; IF output power vs. bias voltage for device #6 for three different RF signal power levels at 618 GHz. Also shown is the pumped DC IV curve. The temperature was 0.44 K.