Quantum limited responsivity of a Nb/Al_2O_3/Nb SIS waveguide mixer at 460 GHz and first results at 750 and 840 GHz.

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The noise and gain behaviour of a Nb/Al_2O_3/Nb SIS waveguide mixer, with a on chip integrated tuning element, is analyzed at 460 GHz. The receiver sensitivity of the whole system, including the beamsplitter, window and lenses is 116 K DSB. The mixer noise temperature is 35 ± 20 K. Within the experimental error this is as low as the quantum limit at 460 GHz. This is the first measurement of quantum limited sensitivity above 400 GHz. We compare data of the pumped I-V curves with the Werthamer-Tucker theory and demonstrate an excellent agreement at 460 GHz. A comparison of the measured IF-output noise versus bias voltage with the quantum theory of mixing shows a good agreement, indicating for the first time the applicability of this theory, to Nb tunnel junctions up to 500 GHz.

During the last decade the application of heterodyne receivers based on superconducting tunnel junctions shifted from the millimetre into the sub-millimetre range. The high sensitivity and low LO-power requirements make this type of receiver very attractive for ground-based astronomical observations. Several telescopes now use SIS-mixers for observations in the sub-millimetre range. The highest frequency at which SIS-mixers are used is around 500 GHz. Despite the large efforts spent to increase the working frequency of SIS-mixers, relatively little attention is paid to the comparison of measured results with the quantum theory of mixing as developed by Tucker [1,2,3]. In a previous article [4] we showed the performance of a low noise two tuner waveguide mixer in the frequency range 400-500 GHz, using various kinds of mixing elements. An excellent agreement between measured and calculated pumped I-V curves was obtained, and a good qualitative agreement on the noise behaviour of the mixer was shown. In this work the performance of a single junction mixer with an integrated matching circuit is analyzed at 460 GHz. This frequency is close to the resonance frequency of the stripline, and therefore we find a nearly perfect broadband matching of the LO, USB and LSB signals, resulting in a mixer noise temperature on quantum limit level.

The mixer block used in the 400-500 GHz work is a scaled version of the 345 GHz receiver described by Honingh et al.[3] This waveguide system has two moving shorts (backshort and E-plane tuner) as tuning elements, each with a quarter wave choke section to improve the quality of the short. The signal and LO-power are combined by a 15 μm Mylar beamsplitter and enter the cryostat via a 1 mm thick HDP (High Density Polyethylene) window of 3 cm diameter. On the 77 K radiation shield a 200 μm thick quartz plate serves as a heat filter. A diagonal horn with an aperture size of 3.18 mm, a length of 12 mm and a flare angle of 11 degrees is used. Laboratory tests of this horn showed a good Gaussian beam-coupling (side lobes <-15db), equal beamwidths in E-,D- and H- planes and a low

cross-polarisation (<-15 dB). A diagonal horn and a F=31.4 mm HDP lens is used. The lens is mounted in a holder which can be directly mounted on the mixerblock. The mixer block is cut in OFHC. The full height waveguide has dimensions 0.44×0.22 mm. The substrate, containing the junctions and RF-filter, is glued parallel to the sidewalls of the waveguide in a substrate channel of dimensions 0.1×0.165 mm. The E-plane tuner is placed half a guide wavelength (at 492 Ghz) in front of the junction position. A magnet coil with 10,000 turns of 0.1 mm Nb wire is placed around the horn, in front of the mixer block.
The cooled IF-chain consists of a Radiall R443533 T-bias, a Pamtech LTE 1290 isolator and a Berkshire Technologies L-1.4-30H IF-amplifier (40 dB). Outside the dewar a further 47 dB amplification of the IF-signals is provided. The IF power is measured with a HP 8481A powersensor at a center frequency of 1.4 GHz and a bandwidth of 80 MHz. The LO-power in the 400-500 GHz range is supplied by a Thomson carcinotron or a Radiometer Physics Gunn and multipliers system. The noise temperature of the system is measured by using a piece of "ECCOSORB" foam at two different temperatures as a calibrated broadband black-body signal source ("Y-factor" method).

The Nb tunnel junctions are fabricated with the use of a novel process (SNOEP Selective Niobium Over-Etch Process). Junctions with area's as small as .8 um^2 can routinely be made with a high processing yield. The details of this process are described elsewhere [5]. The junctions are fabricated (together with the RF-filters) on a 200 micron thick fused quartz wafer. After the fabrication process the wafer is diced in widths of 150 μm and polished down to 65 μm thickness. The results in this work are obtained on a single junction with an area of 1 μm^2 and a resistance of 31 Ω. The width of the open ended stripline integrated

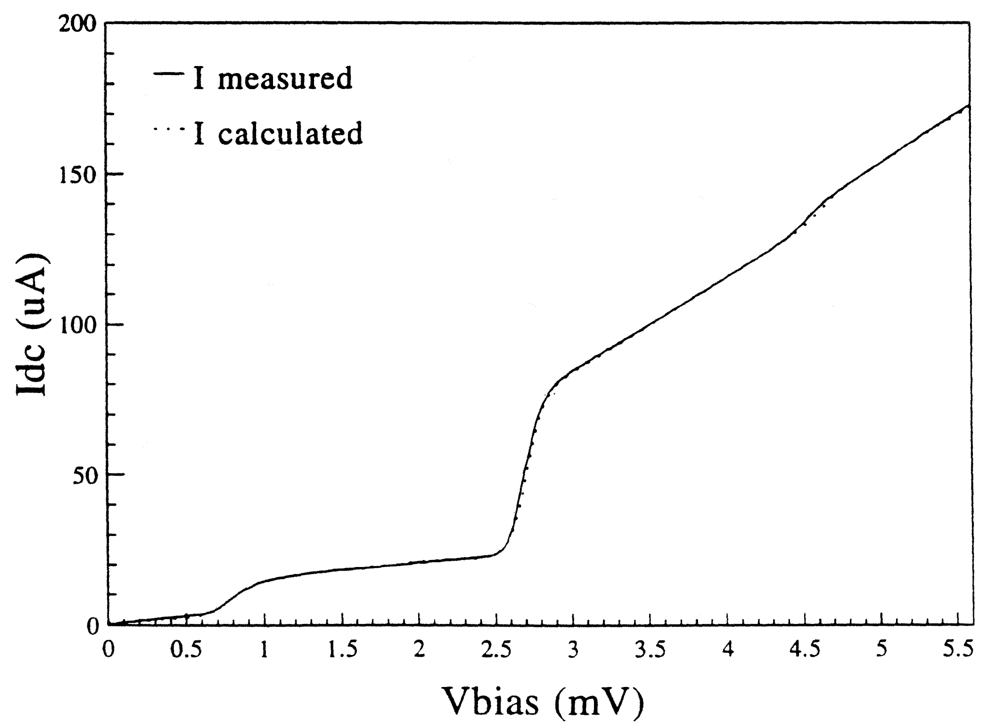

Figure 1. Measured and Calculated IV-curve at 460 GHz and LO-power giving minimum noise temperature.

matching is 5 µm, the length is 86 µm and the thickness of the SiO_2 dielectric layer is 290 nm.

The tuned bandwidth of this mixer is below 140 K in the frequency range 430-495 GHz. At 460 GHz the receiver noise temperature, including the losses of the beamsplitter, window and lens, has a minimum of 116 K. The instantaneous bandwidth of the mixer, measured with fixed tuner settings, is approximately 40 GHz. This is 10 times larger than the bandwidth of a comparable junction without integrated tuning, indicating the large influence of the integrated tuning element.

The pumped IV-curve measured at the 460 GHz LO-frequency and at optimum LO-power is shown in Fig.1, together with a calculated pumped IV-curve, using the Tucker theory. The values of the embedding parameters used in this calculation are G=0.87 and

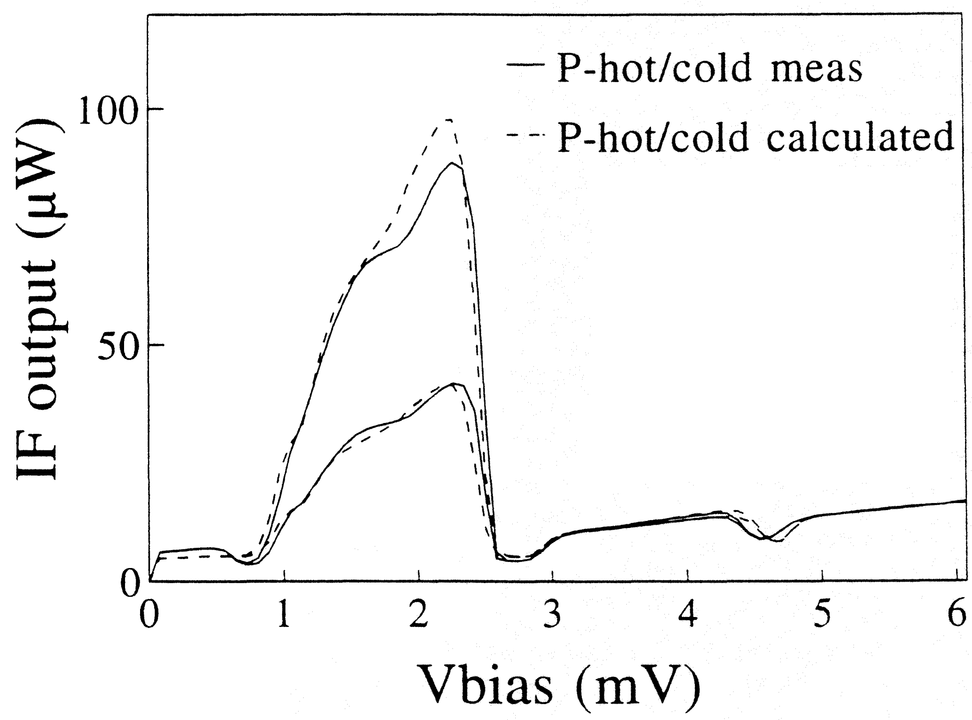

Figure 2. Measured and calculated IF output power at hot and cold input load, as a function of bias voltage

B=0.25 (normalized to the normal state conductance of the junction $G_N = 31^{-1}$ Mho). The embedding parameters for the USB and LSB frequencies are found by tuning the RF-source 1.4 GHz above or below the LO-frequency and performing the same analysis. The fits are of the same quality as shown in Fig. 1 and the values for the USB and LSB admittance are Y_{USB}=0.87 + 0.70j, Y_{LSB}=0.83 +0.31j respectively. The bias voltage dependence of the IF-output is shown in Fig. 2. The figure displays the IF-output with both a hot (293 K) and a cold (77 K) input signal. The gain and noise parameters of the system are found by respectively subtracting and dividing these two curves. The results are shown in Fig. 3. The gain curve in Fig. 3 shows a large conversion on the first photonstep below the gap and almost no conversion above or below this step. Fig. 3 also shows the division of the hot and the cold IF output (the Y-factor) on a linear scale. The nearly constant value of the Y-factor

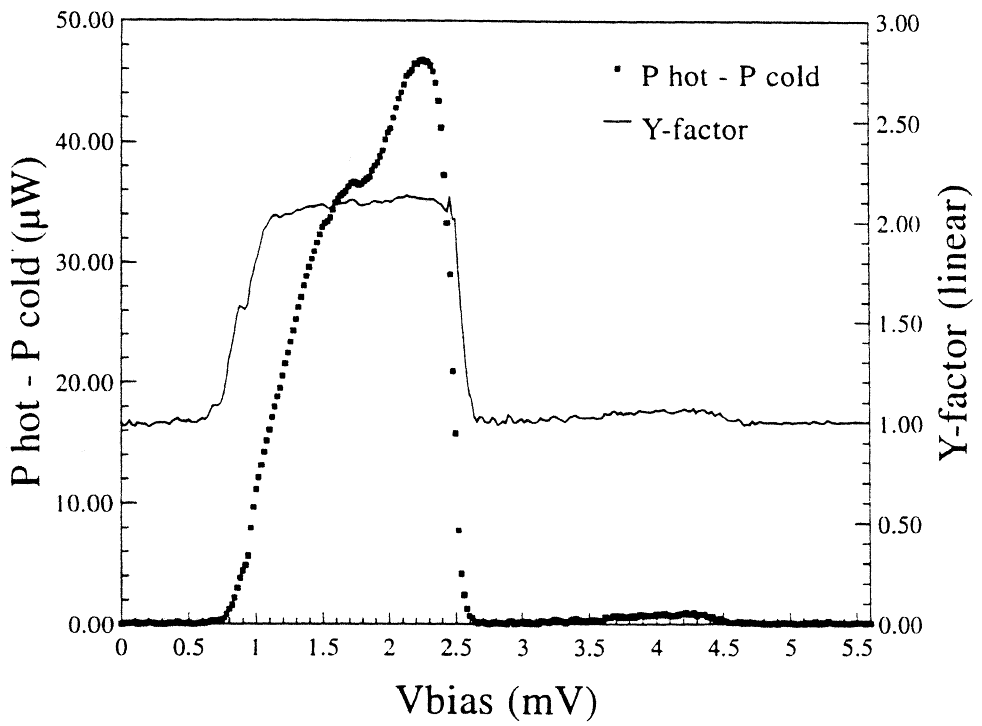

Figure 3. Measured gain and Y-factor as a function of bias voltage

on the fist photon step below the gap indicates that the influence of Josephson effects is sufficiently suppressed.

In the analysis of the mixer noise, the noise contributions of the RF-input and the IF-output have to be taken into account. The gain and noise parameters of the IF-chain (T-bias, isolator, IF-amplifier) are measured by using the unpumped junction as a calibrated noise source at the input of the IF-chain. The values thus found are: G_{IF}=85.7 ± 0.1 dB, T_{IF}=4.8 ± 0.2 K. The total gain and noise contributions of the RF-input are G_{RF}=0.77 ± 0.1, T_{RF}=56 ± 20 K (based on transmission measurements of the beamsplitter, HDP window and quartz filter).

The mixer noise and gain are calculated using the measured output powers shown in Fig. 2. The values for the mixer gain and noise are: G_{mix}=-4.6 ± 0.6 dB, T_{mix}=35 ± 20 K. The value of the measured mixer noise is within the errors equal to the quantum noise limit of 23 K at this frequency.

The measured data on the bias voltage dependence of the mixer gain (as shown in Fig. 2) are compared with the quantum theory of mixing in the three port, low IF approximation. The result of the calculated IF-gain is also shown in Fig. 2. The maximum gain thus found is G_{calc}=-3.6 dB, 1 dB higher than the measured gain.

First results of the 750 GHz mixer (last minute addition)

The measurements at 750 and 840 GHz are performed in the same dewar as the 460 GHz measurements. The 750 GHz mixerblock has a full height waveguide with dimensions 150 x 300 μm (cut-off frequency 500 GHz) and only one tuner element (backshort). This block uses also a diagonal horn and the dimensions of the substrate channel are 50 x 100 μm. The LO-power at 750 GHz is supplied by a Thomson 340-390 GHz carcinotron in combination with a doubler of Radiometer Physics. The measurements at 840 GHz are performed with a 840-930 GHz Thomson Carcinotron.

The junctions are implemented with different kinds of integrated tuning elements, including open ended, quarter lambda shorted and end loaded striplines. The results shown in this paper are obtained with a structure where the junctions are placed at the outer edge of the stripline (end loaded).

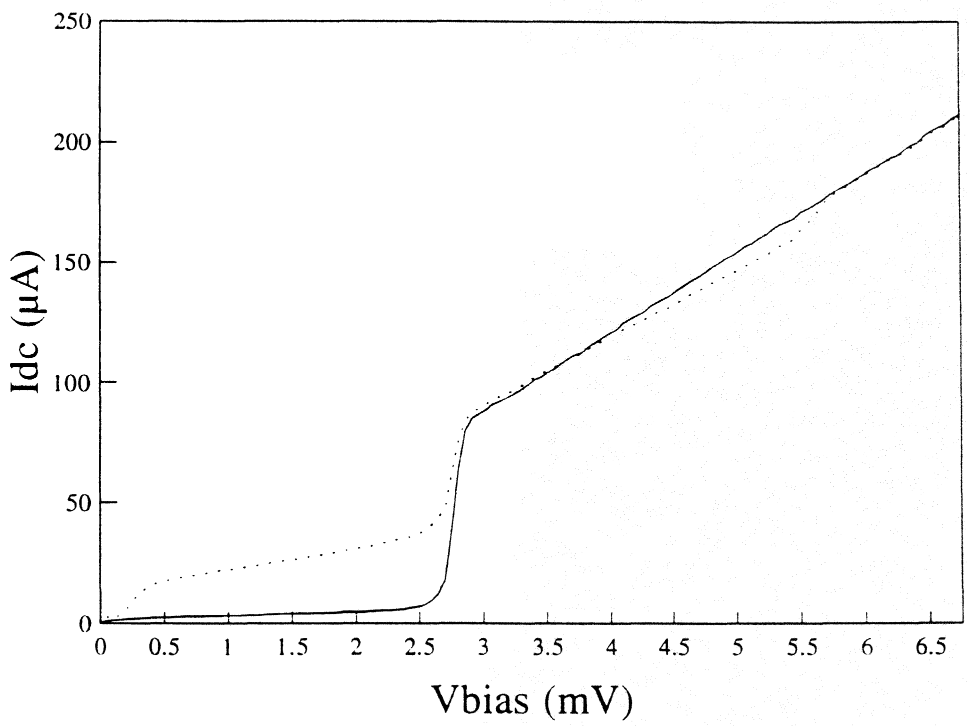

Figure 4. Pumped and unpumped curve with 750 GHz LO frequency. This measurement was performed with the 400-500 GHz mixerblock.

As a test of the 750 GHz doubler, it was placed in front of the 490 GHz receiver. The results of this measurement are shown in Fig. 4. Due to the bad coupling of the 750 GHz radiation in the 490 GHz mixer, a mirror (instead of a beamsplitter) is used to couple in the radiation. Therefore a hot/cold measurement could not be performed. Fig. 4 shows a clear developed 750 GHz photonstep, both above and below the gap. The photon energy at this frequency is above the gap-energy and the first photonsteps below the positive and negative gap voltage start overlapping each other near the zero voltage bias region. In this bias region part of the (positive) DC-current induced by photon assisted tunnelling from the left to the right superconducting electrode is cancelled by a (negative) DC-current from the induced current from the right to the left electrode. Therefore the photonsteps below the gap seems to be less wide than the value hf/e = 3.1 mV. The gap voltage of the junctions shows only a slight decrease, probably due to heating. This indicates that, although the total amount of power reflected at the junction is of the order of several microwatts, exceeding the gap-frequency does not dramatically influence the photon assisted tunnelling.

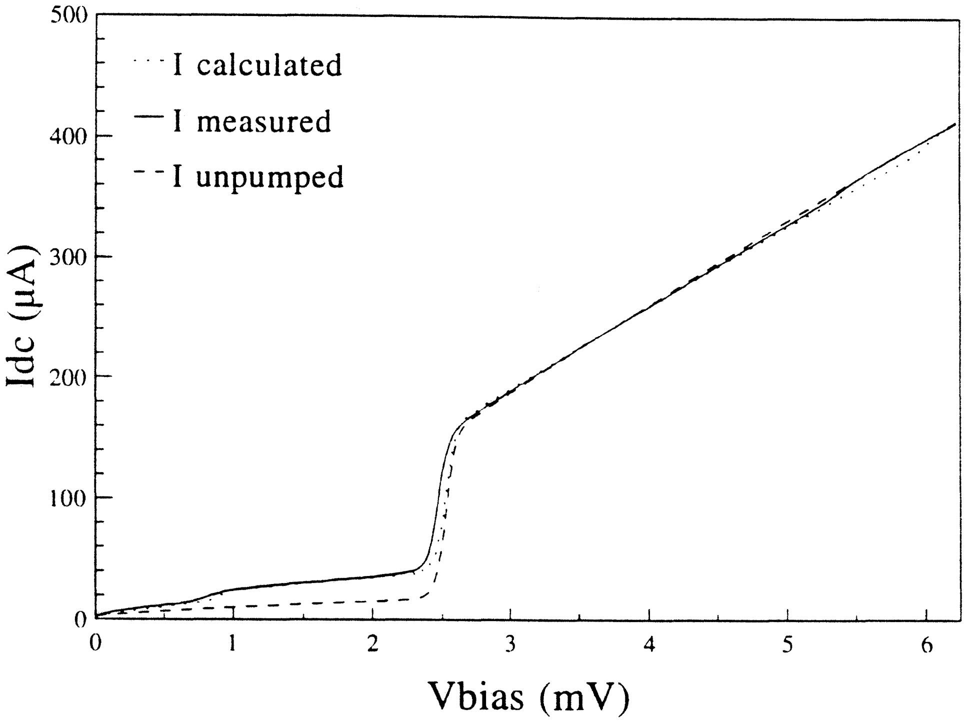

Figure 5. Measured pumped and unpumped I-V curve at 840 GHz and calculated I-V curve.

After this initial test the doubler broke down and was not available at the time the junctions for 750 GHz became available. The 750 GHz mixer was therefore tested with the 840-930 carcinotron. Two single junctions are tested with end loaded striplines with dimensions 10x40 μm and 10x43 μm. The first measurement with the longest stripline resulted in a noise temperature of 3000 K DSB, corrected for the loss of the 90 μm beamsplitter used in this measurement (55 % transmission). The second junction with the 40 μm long stripline showed a hot/cold response of 0.3 dB. Corrected for the beamsplitter loss this gives a 1500 K DSB noise temperature. The gain of the mixer is -17 dB. These values are better than the state of the art Schottky receivers at this frequency. The difference between the two measurements shows that the striplines still improve the RF-coupling at frequencies far above the gap frequency.

The measured I-V curve and the hot/cold response are shown in Figs. 5 and 6. The junctions have a relatively large subgap current and low gapvoltage (2.55 mV). In the DC I-V curve measured without a magnetic field, a self resonant peak was observed at a voltage corresponding to a resonant frequency of 720 GHz. The 840 GHz LO is thus far above the frequency where optimum performance is expected. The 2.55 mV gap corresponds with a 640 GHz gap frequency. The LO frequency is in this case 1.3 times the gap frequency.

In Fig. 5 the measured pumped and unpumped curves are shown, together with a calculated pumped curve. The measured and calculated curves show a good agreement below the gap. The effect of the overlap of photonsteps is more pronounced than at the 750 GHz measurement and this effect is well described by theory. Near and above the gap voltage the theoretical curve deviates from the measured one. In the measured curve the photonstep above the gap is nearly visible and a decrease in gap voltage is observed. These effects are probably

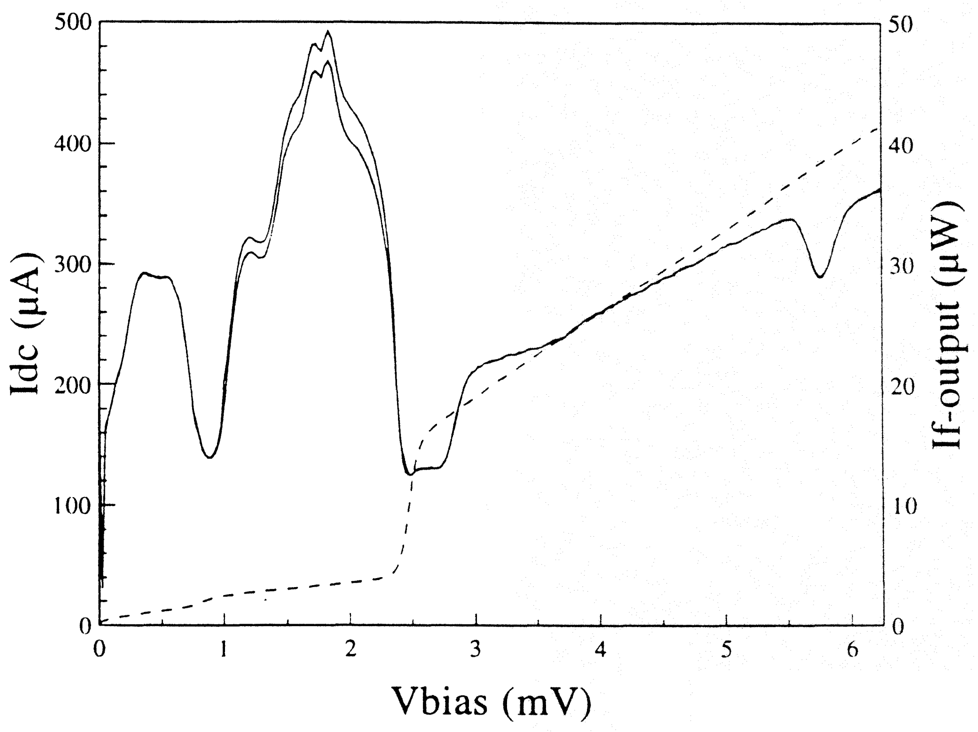

Figure 6. Measured IF-output power at 840 GHz with hot and cold input load. Also shown is the pumped I-V curve.

due to heating. The fact that the incident power on the junction is much larger than the actually coupled power and the relative poor quality of the Nb layer will enhance heating effects.

Fig. 6 shows the measured IF-output power with a hot and cold input load. Subtracting these curves results in a qualitative figure of the gain, as shown in Fig. 7. As can be seen in Figs. 6 and 7 the bias voltage region with hot/cold response (gain) is reduced to the region between the gap voltage and the bias voltage were the 840 GHz photonsteps start to overlap. This behaviour is well described by theory. Preliminary calculations show a good qualitative agreement between the measured and calculated gain curve. The power dependence of the mixergain also shows a qualitative agreement with theoretical predictions. From theory it is known that maximum gain is achieved at a pump power resulting in a pump parameter α of approximately 1. At higher pump levels the gain starts to decrease. This behaviour is observed in the experiments. The measured IF-output power shows some reminiscent Josephson effect at 1.8 mV (giving a dip in the measured gain), but qualitative agreement between calculated and measured gain and the power dependence of the gain (and noise temperature) indicate true heterodyne quasi-particle mixing.

Summary

In summary we have measured the performance of a Nb SIS mixer with an integrated tuning element in the 400-500 GHz range and at 840 GHz. The minimum receiver noise temperature of the 400-500 GHz mixer is 116 K DSB at 460 GHz. The mixer noise temperature is 35 ± 20 K which is at the quantum limit level at this frequency. We show a nearly perfect

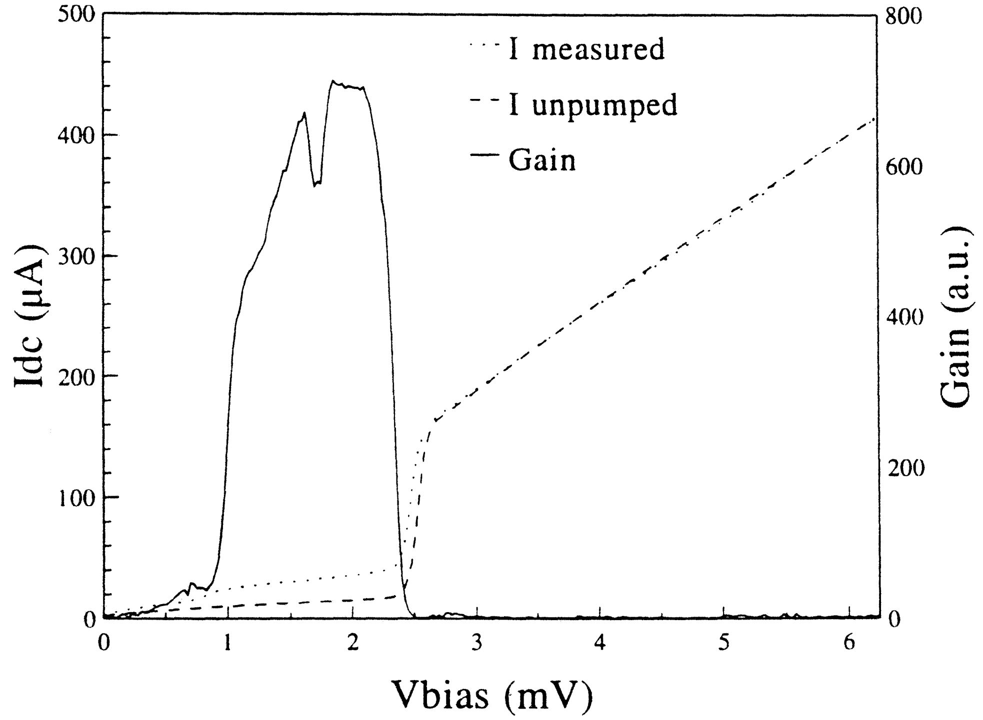

Figure 7. Measured (qualitative) gain of 840 GHz measurement, obtained by subtracting the curves shown in Fig. 6. The region of gain agrees with the theoretical calculated region (not shown).

agreement between the measured pumped I-V curves and the Werthamer-Tucker theory. The measured and calculated bias voltage dependence of the IF-output noise also show a good agreement, indicating for the first time the applicability of the quantum theory of mixing for Nb tunnel junctions up to 500 GHz.

The receiver noise temperature at 840 GHz (corrected for the 55 % loss) is 1500 K DSB. The gain of the mixer is -17 dB. This is the first succesfull measurements of Nb SIS mixers at a frequency above the gap frequency. First comparisons with theory show a good quantitative agreement between the measured and calculated pumped IV-curve.

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