A 1 THZ Nb SIS HETERODYNE MIXER WITH NORMAL METAL TUNING STRUCTURE.

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1. Introduction.

The use of niobium SIS mixers with integrated tuning structures for frequencies above the gapfrequency is described. From model calculations for integrated striplines one can predict lower losses at high frequencies if one replaces a niobium tuning structure by one of normal metal. This idea has been tested in waveguide mixers for frequencies between 0.5 and 1.1 THz.

2. Model Calculations.

Superconductive striplines have shown to be of major importance in the coupling of high frequency signals to SIS quasiparticle mixers. Räisänen et al. [1] proposed the use of on chip superconductive striplines as tuning elements at 100 GHz and several groups now successfully employed niobium integrated tuning elements at frequencies up to 800 GHz [2,3].

In principle an SIS junction can be used for mixing at frequencies up to twice the gap frequency, which lies around 700 GHz for niobium. However, already at frequencies just above the gap frequency the sensitivity of the device decreases due to losses in the integrated tuning structure and to a lesser extent, losses in the antenna and the junction itself.

To calculate the losses and the effect on the behaviour of the entire mixer, the mixer is modelled by an equivalent RF circuit. For the case of an endloaded stripline this consists of the stripline impedance in series with the parallel circuit of the junction's nonlinear tunnel resistance and its capacitance. If we define the total incident power as P_{in}, the reflected power as P_r and the absorbed power in the junction and the tuning as $P_{abs}=P_J+P_{tun}$, then we have $P_{in}=P_r+P_J+P_{tun}$. The relative power coupled to the junction and the stripline, $\{P_J+P_{tun}\}/P_{in}$, is shown as the dashed lines in figures 2.1 and 2.2, the fraction of the absorbed power coupled to the junction, $\{P_J/(P_J+P_{tun})\}$, is represented by the dotted lines and the fraction of incident power coupled to the junction, $\{P_J/P_{in}\}$, is given as the continous lines. Results for Nb and Al striplines are shown in figures 2.1 and 2.2, where we assumed striplines of 43 μm length and 10 μm width. For the case of a normal metal stripline we assumed a conductivity of $3 \cdot 10^{10}$ $(\Omega m)^{-1}$. From the figures it can be seen that the fall-off of the efficiency of the Al stripline at high frequencies is less severe than in the case of the Nb stripline. The expected higher transmission of power to the junction is the reason that we decided to implement aluminum striplines.

Fig 2.1: RF power coupling into a Nb SIS junction with Nb stripline.
Fig 2.2: RF power coupling into a Nb SIS junction with aluminum stripline.

3. Measurements.

3.1: Waveguide mixers.

For our measurements we use two waveguide mixers based on the original design by C.E. Honingh et al.[4] for 345 GHz. One mixer is scaled to a center frequency of 700 GHz and has been tested extensively by G. de Lange et al.[3] up to a frequency of 760 GHz. This mixer was successfully used in airplane campaigns by J. Mees et al.[5] to measure atmospheric ClO, HCl, N_2O and O_3 lines at frequencies between 625 and 650 GHz. The other mixer is scaled to a center frequency of 900 GHz. Both mixers use a contacting mechanical backshort tuner. Instead of an E-plane tuner we use integrated tuning elements to achieve the desired matching between the junction and its environment. Characteristics of the two mixers are summarized in the following table:

	0.7 THz mixer	1 THz mixer
waveguide size	150x300 µm	120x240 µm
cut-off frequency	500 GHz	625 GHz
substrate channel	100x100 µm	90x75 GHz
substrate thickness	50 µm	40 µm

An impression of the waveguide losses in the 1 THz mixer can be obtained by measuring the LO coupling as a function of backshort position. This was done at a frequency of 1013 GHz by moving the backshort over a distance of 3.0 mm. This covers more than 13 half periods of the guide wavelength. There appeared to be no strong decrease of the coupling efficiency. In figure 3.1 we show data taken at 912 GHz over a distance of about 1.0 mm together with a sinusoidal best fit to the data. These measurements suggest that waveguide losses are small, even for a crosssection as small as 120 x 240 micrometer.

Fig 3.1: Coupling as a function of backshort position.

3.2. Optics.

Both mixers use diagonal horns with a plastic lens in front. Our lenses have one flat and one curved, aspherical surface, where the asphericity is used to compensate for spherical aberration of the high focal ratio lens. The 1 THz mixer uses essentially the optics as described by G. de Lange et al.[3] with a horn of 11° cone angle and a HDP lens. The antenna beam pattern is shown in figure 3.2; it shows good symmetry, sidelobes lower than 15 dB and good Gaussian behaviour. But the measured beam angle is larger than the expected value by about 10%. The horn-lens combination of the 0.7 THz mixer uses a horn with 7° cone angle and a PTFE lens.

For injection of the LO beam we do not use an interferometer-diplexer, but a thin beamsplitter under 45° angle of incidence. We use mylar sheets of different thicknesses and the inherent loss in the signal beam for various thicknesses and frequencies is calibrated with good accuracy. Therefore we present not only our actually measured noise temperatures but also the values after correction for the beamsplitter loss.

Fig 3.2: Antenna beam pattern of 1 THz mixer.

3.3. Local oscillators.

For the various frequencies we use different carcinotrons and BWO's (Backward Wave Oscillator), sometimes in combination with a doubler, as local oscillators. In this way we can cover a nearly continuous range from 520 to 1090 GHz. The only gap in the frequency range, where we have no suitable LO available, runs from about 760 to 840 GHz,

3.4. Nb SIS junctions with aluminum striplines.

For the fabrication of Nb junctions with aluminum striplines we use a modification of the SNOEP process described by Dierichs et al [6]. In the usual SNOEP process the trilayer is defined by lift-off and the junctions are made via an overetch (the letters OE in SNOEP) process. In this way the junctions are formed in the top layer of the trilayer and usually have areas of 1.0 μm^2. In the modified process for the fabrication of aluminum striplines we apply the lift-off process to the trilayer with an extra aluminum underlayer of 100 nm thickness. A second modification is that the junctions are defined by etching through the whole trilayer by using a extra RF sputter etching step in addition to the usual RIE etching. A third modification is the use of an extra 100 nm thick aluminum layer underneath the niobium wiring layer. In this way we obtain a configuration where all conducting structures in the RF filters as well as in the integrated tuning elements consist of a combination of aluminum and niobium layers. The details of the process were developed by one of us (S.Kovtonyuk). A similar process with some modifications seems to be possible for copper instead of aluminum in order to achieve an even better conductivity.

In figure 3.3 we present the pumped and unpmumped I-V curves of a Nb junction with an aluminum stripline of 40 μm length mounted in the 0.7 GHz mixer block and used at a temperature of 2 K. The pump frequency is 1056 GHz and we can deduce the following parameters:

Gap Voltage:	Vgap=2.80 mV	Gap smearing:	ΔV=0.31 mV.
Normal R:	RN=38.6 Ω	Subgap R:	RS=3.3 kΩ.
Photon step:	Vph=4.31 mV	Resistance ratio:	RS/RN=85.
Junction Area:	A= 1.1 μm^2		

The gap voltage of 2.80 mV corresponds to a gap frequency is 678 GHz and the operating frequency of 1056 GHz, as reported in the next section, means that we are at 1.56 times the gap frequency.

We also want to draw your attention to the fact that the widths of the photon steps below and above the gapvoltage are almost equal, indicating that almost no heating occurs, in contrast to what we see with niobium striplines. We attribute the good heat conductivity to the use of aluminum, which is in contact with all niobium structures.

Fig 3.3: Pumped and unpumped I-V curves of a Nb junction with aluminum stripline of 40 μm length.

3.5. Measurements with the 0.7 THz mixer.

We have investigated several junctions with different kinds of tuning structures. We report here the results of so-called endloaded striplines of 10 μm width and three different lengths: 60, 50 and 40 micrometer, mounted in the 0.7 THz mixer.

First we present in figure 3.4 the values of IF power and Y-factor as a function of bias voltage for the junction with the shortest stripline and used at 1056 GHz. For reference we include also the I-V curves of figure 3.3. The Y-factor is measured with a chopped hot-cold blackbody source as an incoherent signal and is given in arbitrary units. Note that we detect only a heterodyne response over the bias region with non-overlapping photon steps, i.e. from about 1.5 to 2.6 mV. Similar curves were obtained for other frequencies and for other junctions.

Fig 3.4: IF power and Y-factor curves at 1056 GHz.

In figures 3.5, 3.6 and 3.7 we present system noise temperatures versus frequency for end-loaded junctions with three different lengths of striplines, as measured in the 0.7 THz mixer block. Since we use a mylar beamsplitter under 45° with known loss, DSB noise temperatures are given as actually measured values as well as after correction for the beamsplitter loss. We have not applied a correction for the Rayleigh-Jeans approximation. It is obvious that the longest stripline of 60 micron has its best response at lower frequencies ranging from about 640 to 740 GHz.

In figure 3.5 we show results from the 0.7 THz mixer block with junctions with a 60 μm long Al stripline. Note that we use different local oscillators for the frequencies below and above 680 GHz and that data below 680 GHz refer to a detector temperature of 4.2 K, while above that frequency we have also 2.0 K.

Figure 3.6 gives measured noise temperatures for a junction with a 50 μm long stripline. We have no data between 740 and 840 GHz due to the lack of a local oscillator for these frequencies. However, the wideband FTS (Fourier Transformer Spectrometer) data presented in figure 3.8, indicate that we can expect a continuous behaviour of Tsyst.

In figure 3.7 we show measured values of Tsyst for a junction with a 40 μm long stripline. Measured values increase from a lowest value of 1,966 K at 660 GHz to a value of 6,140 K at 1000 GHz and 10,650 K at 1056 GHz. These last frequencies are at 1.5 times the gapfrequency.

The spectral response in the case of Al striplines of 40, 50 and 60 microns length was measured with a Fourier Transform Spectrometer (FTS). In figure 3.8 we present the spectra in each of the three cases with the same relative magnitude and for different settings of the backshort. For each backshort setting we see peak sensitivities at several different frequencies. We could draw a line through the maxima and obtain a good impression of the maximum sensitivity curve for each junction. The 60 micron long stripline provides the best sensitivity at a frequency of 690 GHz, the 40 micron stripline shows a rather wideband response, but it has a dip at frequencies around 900 GHz. In all cases the FTS response agrees well with the heterodyne response, as can be seen by comparing figure 3.8 with 3.5, 3.6, and 3.7.

3.5. Measurements with the 1.0 THz mixer.

In figure 3.9 we show results measured with the 1.0 THz mixer block, using a series of two 2.0 μm^2 area Nb junctions with 43 μm long Al striplines. The parameters of this junction were used in the calculations shown in Fig 2.2. The heterodyne data of the 1.0 THz mixer block have been measured only over a limited frequency range from 832 GHz to 1000 GHz. As shown, we measure a lowest value for the DSB noise temperature of 1,340 K at 846 GHz and a value of 3,349 K at 1000 GHz. Note that these values have been corrected for the loss in the 60 μm beamsplitter.

4. Discussion.

In this section we mention some aspects that influence the sensitivity of SIS junctions with aluminum striplines in our 0.7 and the 1.0 THz mixers.

The resistance ratio for the unpumped I-V curve is pretty high (see Fig 3.3), indicating that we have a good quality barrier with low leakage current. The gap smearing of 0.31 mV seems rather high and may be caused by impurities in the niobium of the trilayer. The resistivity of the aluminum of the stripline is higher than that of bulk aluminum due to impurities. The last two factors may be improved in the future.

In figure 3.3 we also see an important feature: the photon steps below and above the gap voltage are equal. As mentioned earlier, this indicates that almost no heating occurs.

Pumping on the Helium in our dewar in order to reduce the temperature from 4.2K to 2.0 K is less effective than observed for Nb striplines. This is because the conductivity of aluminum does not increase when lowering the temperature. In general the lower physical temperature reduces Tsyst by about 25%.

For the 0.7 THz mixer there is a frequency range around 900 GHz with reduced sensitivity. This is not only seen in the heterodyne measurements, but also in the wideband FTS measurements. The precise reason for this is not well understood. The fact that the backshort adjustment at these frequencies is not very effective, indicates the we have an absorptive or a reflective effect at the junction substrate around these frequencies.

5. Conclusions.

We calculated the behavior of superconducting Nb SIS detectors with aluminum striplines for frequencies above the bandgap. When compared to Nb tuning structures we expect a better sensitivity for frequencies in the THz regime. So we developed and implemented a new process for the fabrication of Nb SIS junctions with Al tuning structures.

The resulting devices have been tested in waveguide mixers designed for center frequencies of 0.7 and 1.0 THz. For frequencies above 900 GHz our measured noise temperatures compare favourably with results from similar devices with niobium striplines, for which we measured a best DSB noise temperature of 18,100 K at 945 GHz.

In the 0.7 THz mixer block the measured DSB noise temperature of a single junction with a stripline of 40 micron length gradually increases from a lowest value of 1,966 K at 660 GHz to values of 6,140 K at 1000 GHz and 10,650 K at 1056 GHz. The last frequencies are at about 1.5 times the gapfrequency.

Data of the 1.0 THz mixer block are available at this moment only over a limited frequency range of 832 GHz to 1000 GHz. Using a double junction with 43 μm long Al stripline we measure a lowest value of 1,340 K at 846 GHz and a value of 3,349 K at 1000 GHz. These values have been corrected for the loss in the beam splitter, as shown in figure 3.9.

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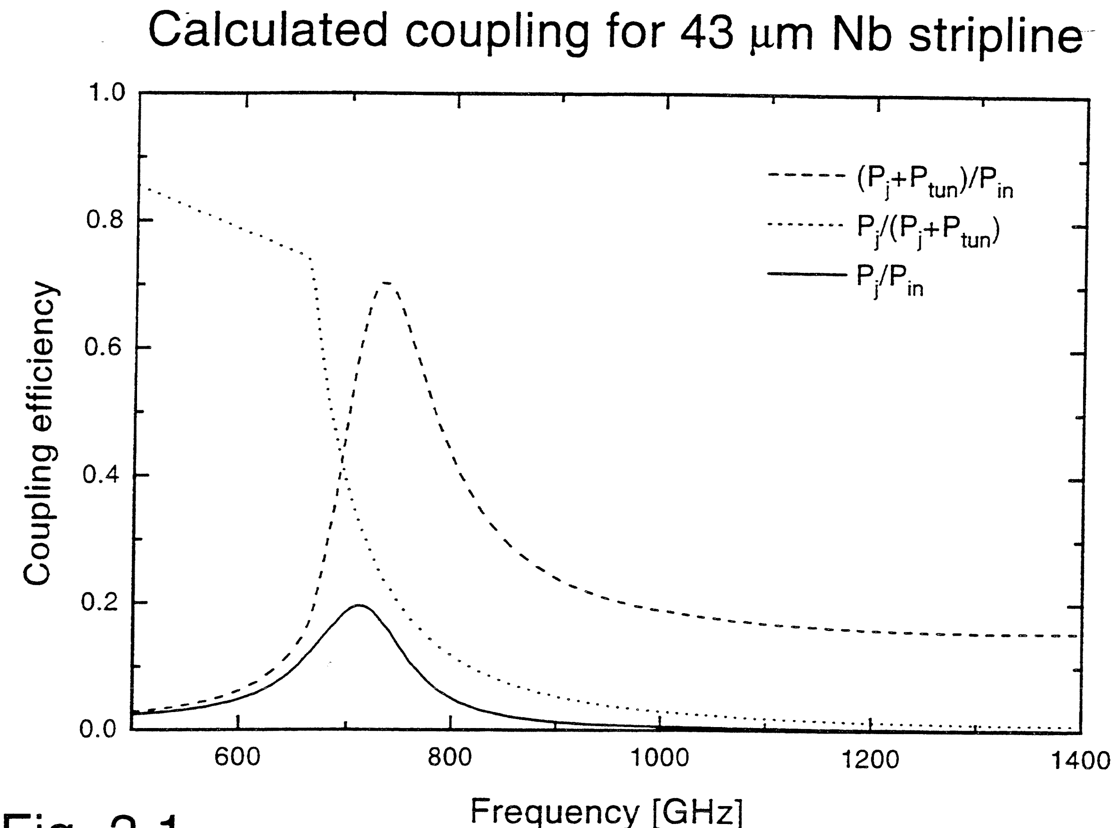
Calculated coupling for 43 μm Nb stripline
1.0
0.8
0.6
0.4
0.2
0.0
Coupling efficiency
(Pj+Ptun)/Pin
Pj/(Pj+Ptun)
Pj/Pin
600
800
1000
1200
1400
Frequency [GHz]

Fig. 2.1

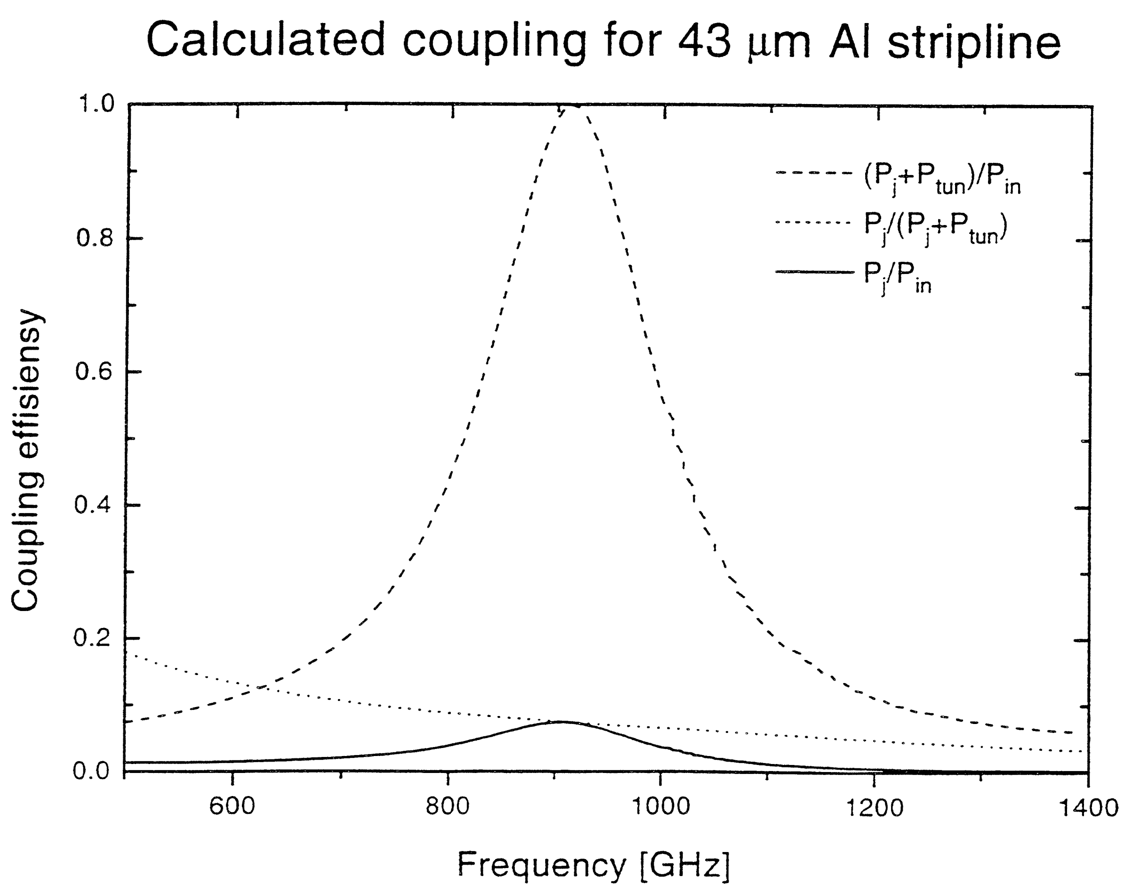
Calculated coupling for 43 μm Al stripline
1.0
0.8
0.6
0.4
0.2
0.0
Coupling effisiensy
(Pj+Ptun)/Pin
Pj/(Pj+Ptun)
Pj/Pin
600
800
1000
1200
1400
Frequency [GHz]

Fig. 2.2

Coupling as a function of backshort position for 1THz mixer.

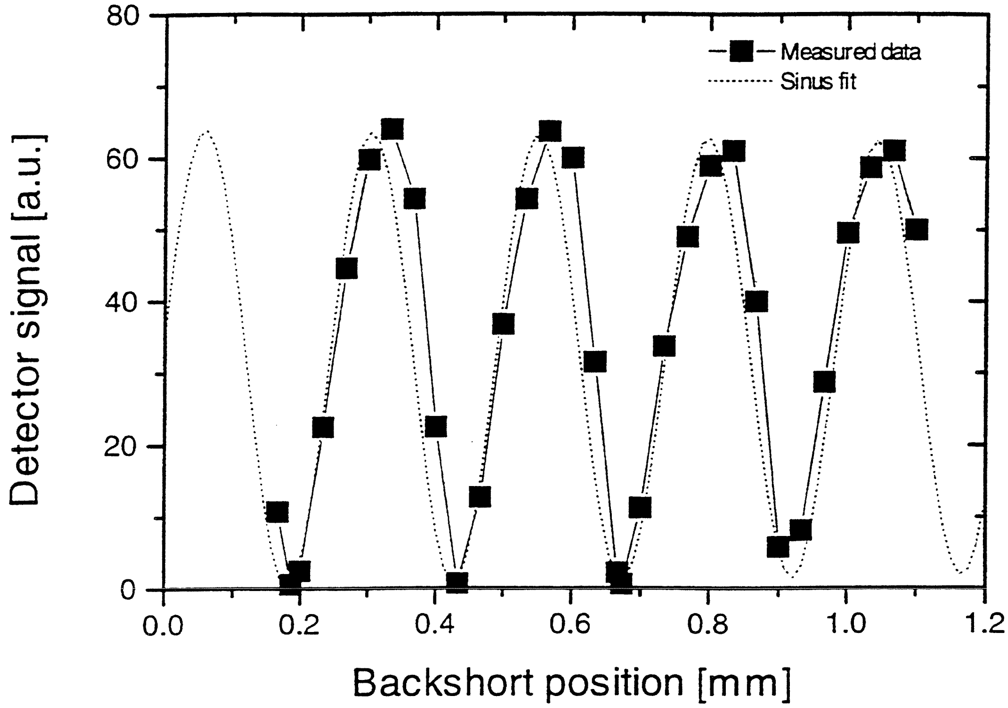

Fig. 3.1

Beam pattern of 1 THz mixer.

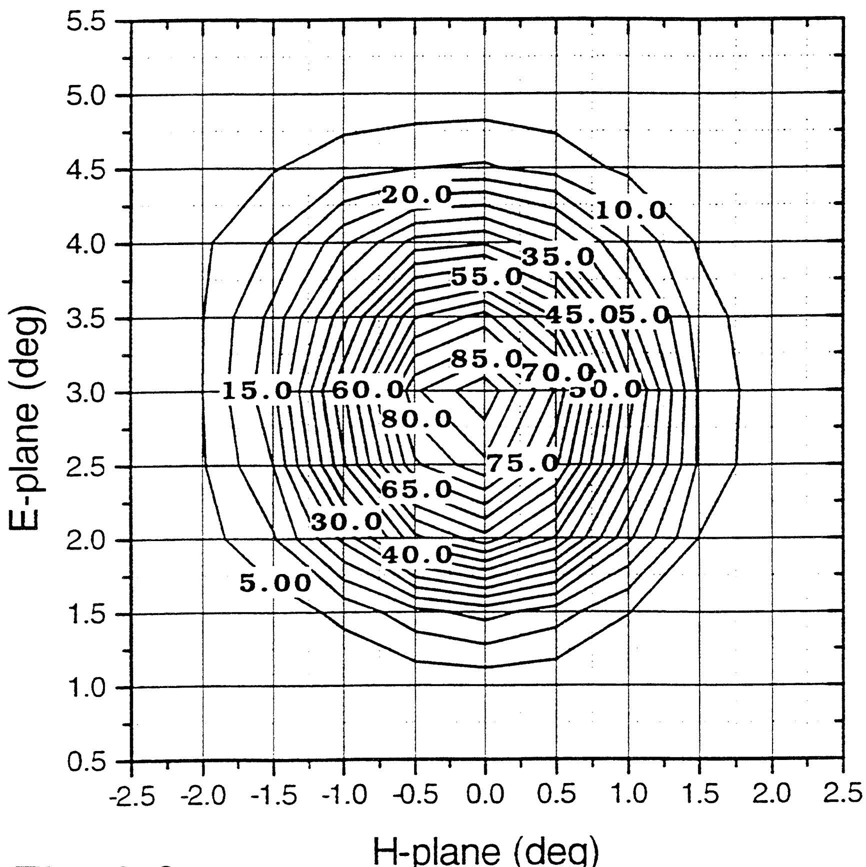

Fig. 3.2

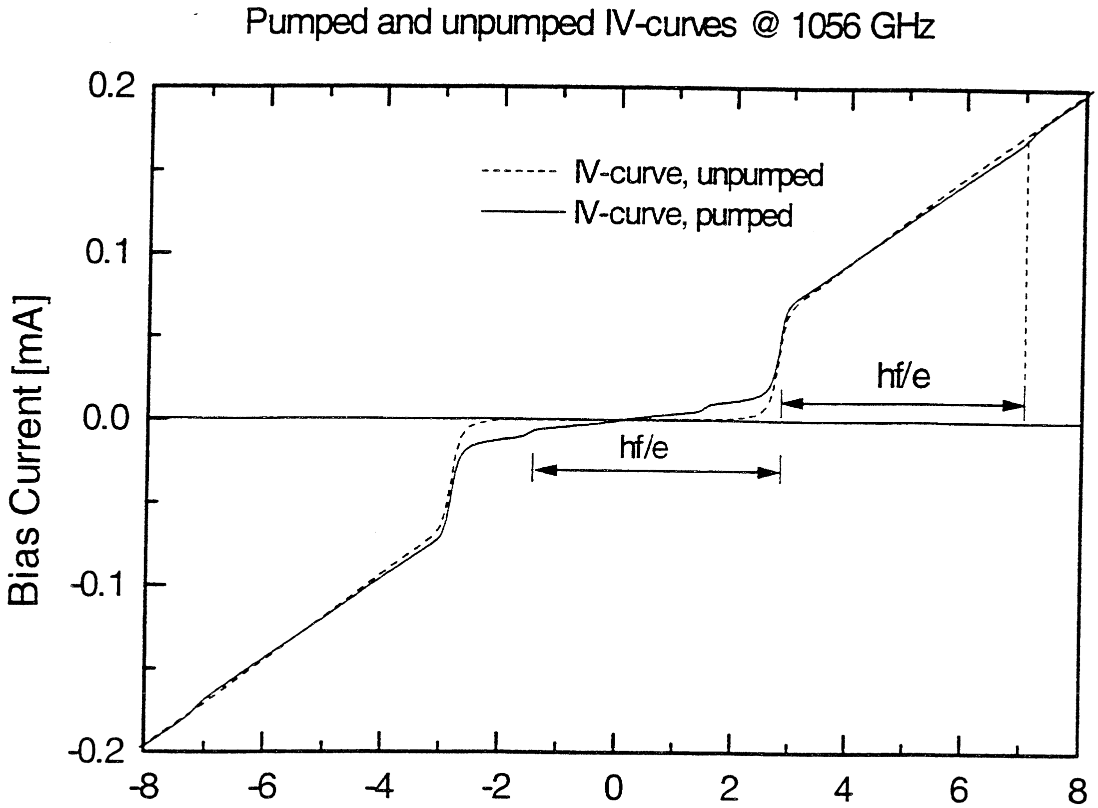
Pumped and unpumped IV-curves @ 1056 GHz
IV-curve, unpumped
IV-curve, pumped
hf/e
hf/e
Bias Current [mA]
Bias Voltage [mV]
0.2
0.1
0.0
-0.1
-0.2
-8
-6
-4
-2
0
2
4
6
8

Fig.3.3

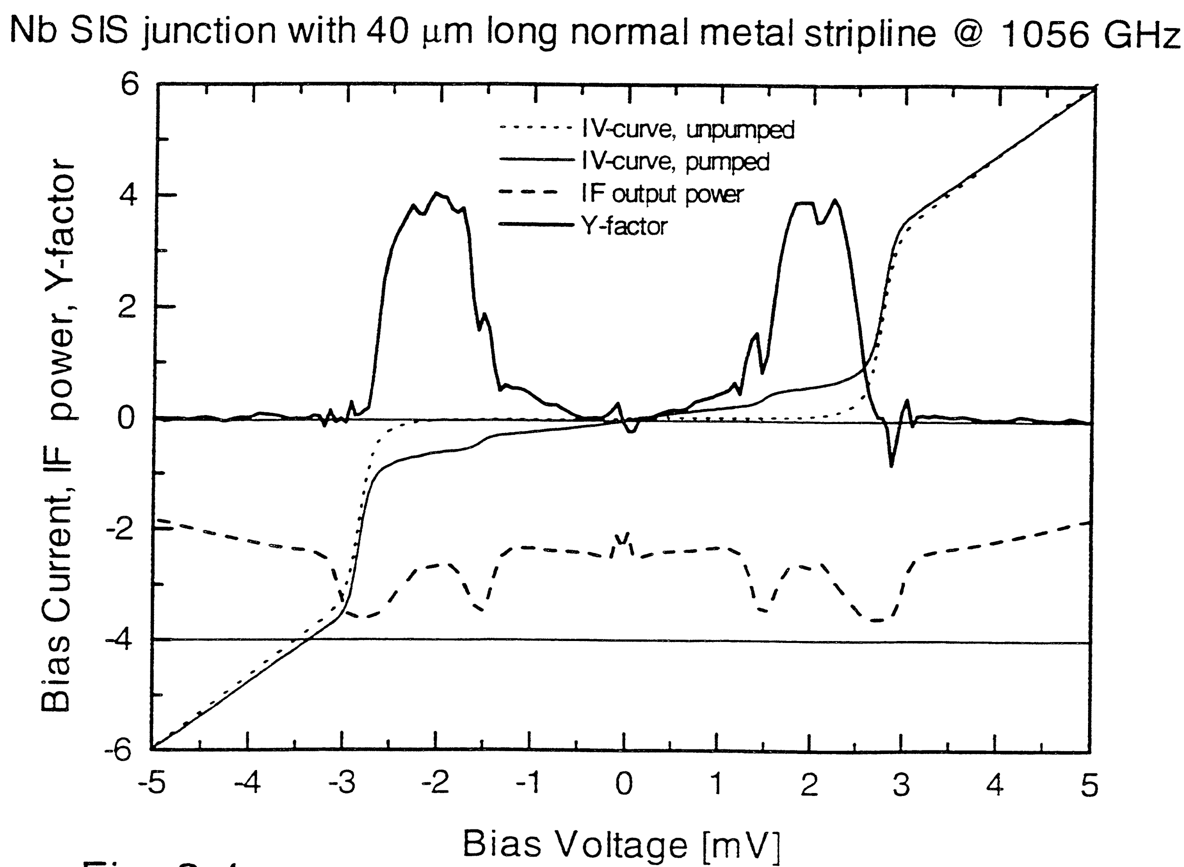
Nb SIS junction with 40 μm long normal metal stripline @ 1056 GHz
IV-curve, unpumped
IV-curve, pumped
IF output power
Y-factor
Bias Current, IF power, Y-factor
Bias Voltage [mV]
6
4
2
0
-2
-4
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5

Fig. 3.4

Nb SIS junction with 60 μm long Al stripline.

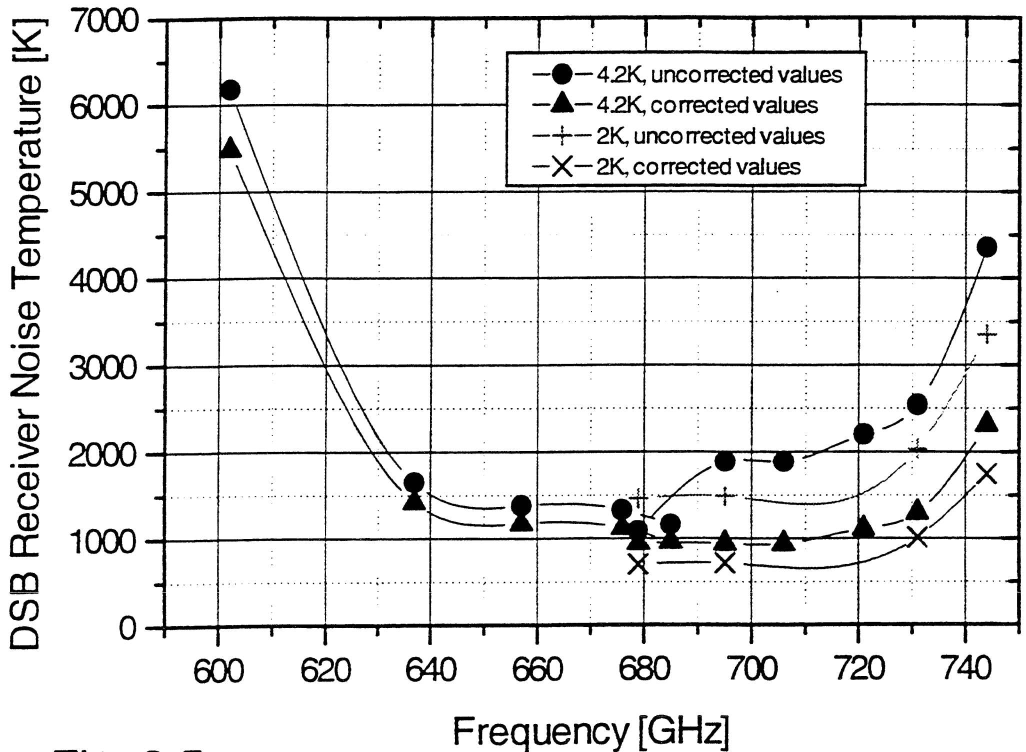

Fig. 3.5

Nb SIS junction with 50 μm long Al stripline.

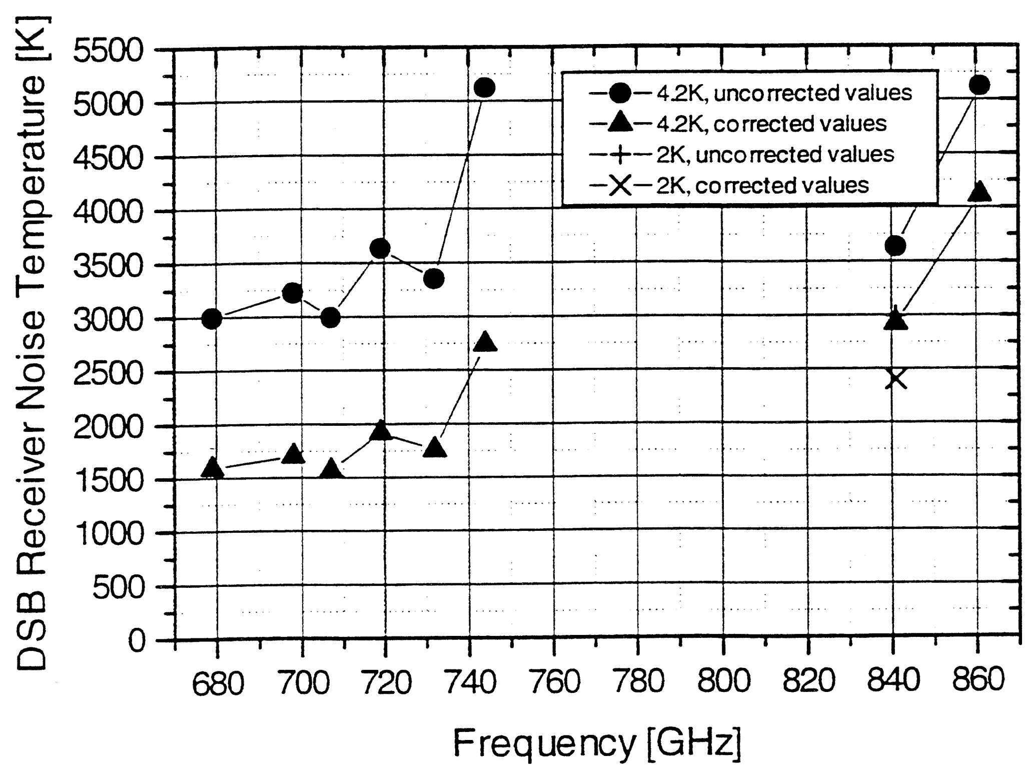

Fig. 3.6

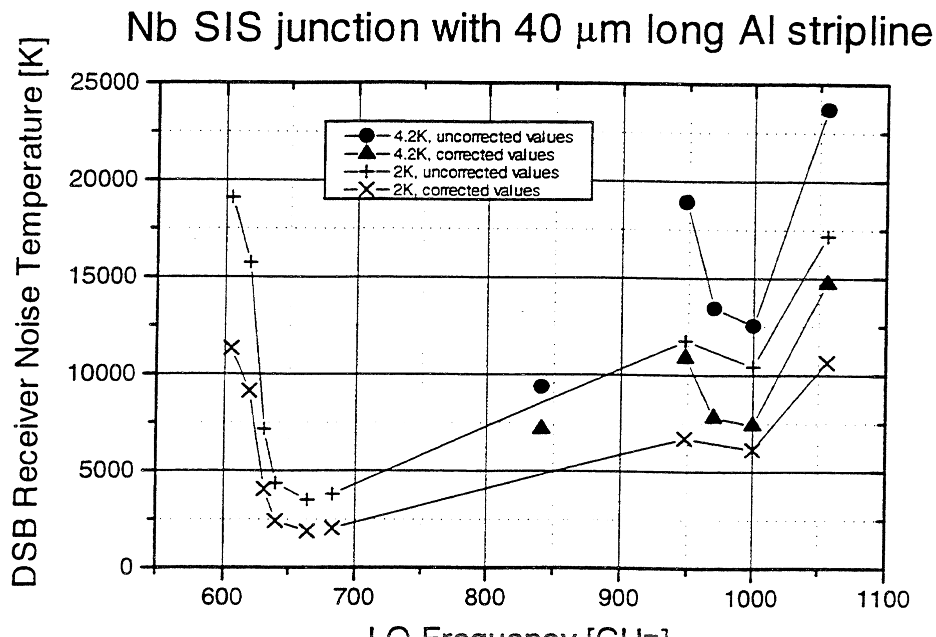
Nb SIS junction with 40 µm long Al stripline
DSB Receiver Noise Temperature [K]
25000
20000
15000
10000
5000
0
4.2K, uncorrected values
4.2K, corrected values
2K, uncorrected values
2K, corrected values
600
700
800
900
1000
1100
LO Frequency [GHz]

Fig. 3.7

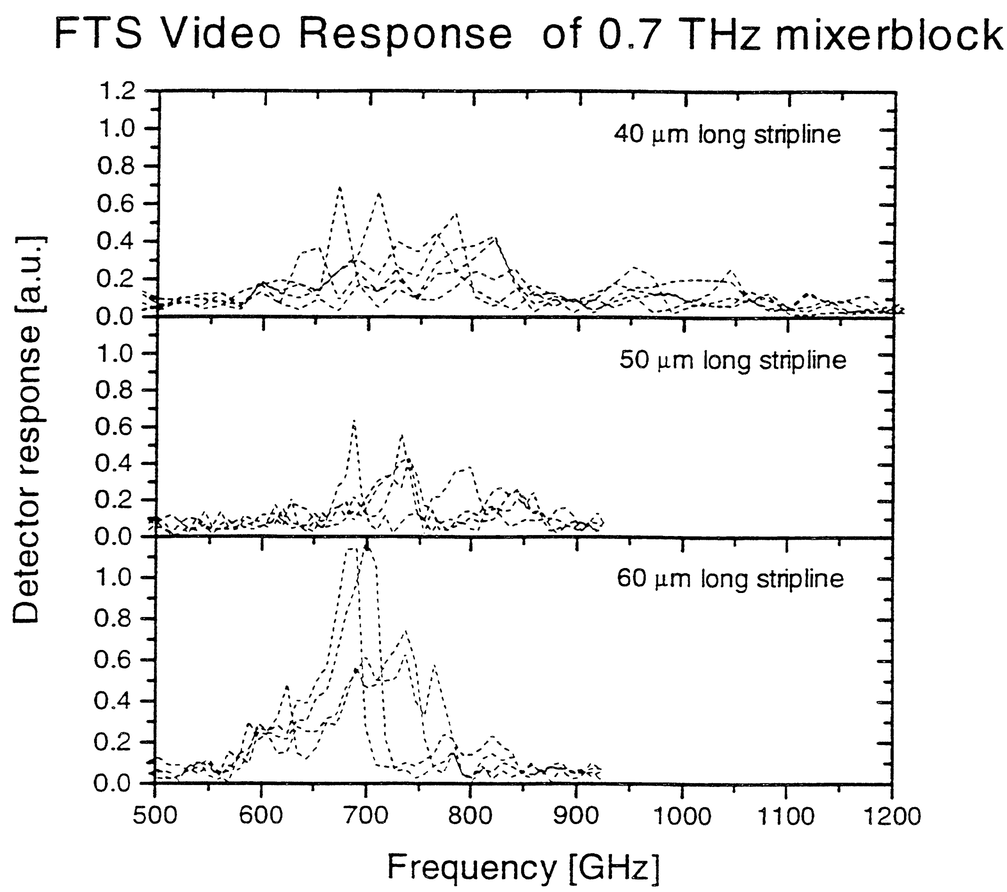
FTS Video Response of 0.7 THz mixerblock
Detector response [a.u.]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
40 µm long stripline
50 µm long stripline
60 µm long stripline
500
600
700
800
900
1000
1100
1200
Frequency [GHz]

Fig. 3.8

T_{syst} for Nb SIS junction with 43 μm Al stripline.

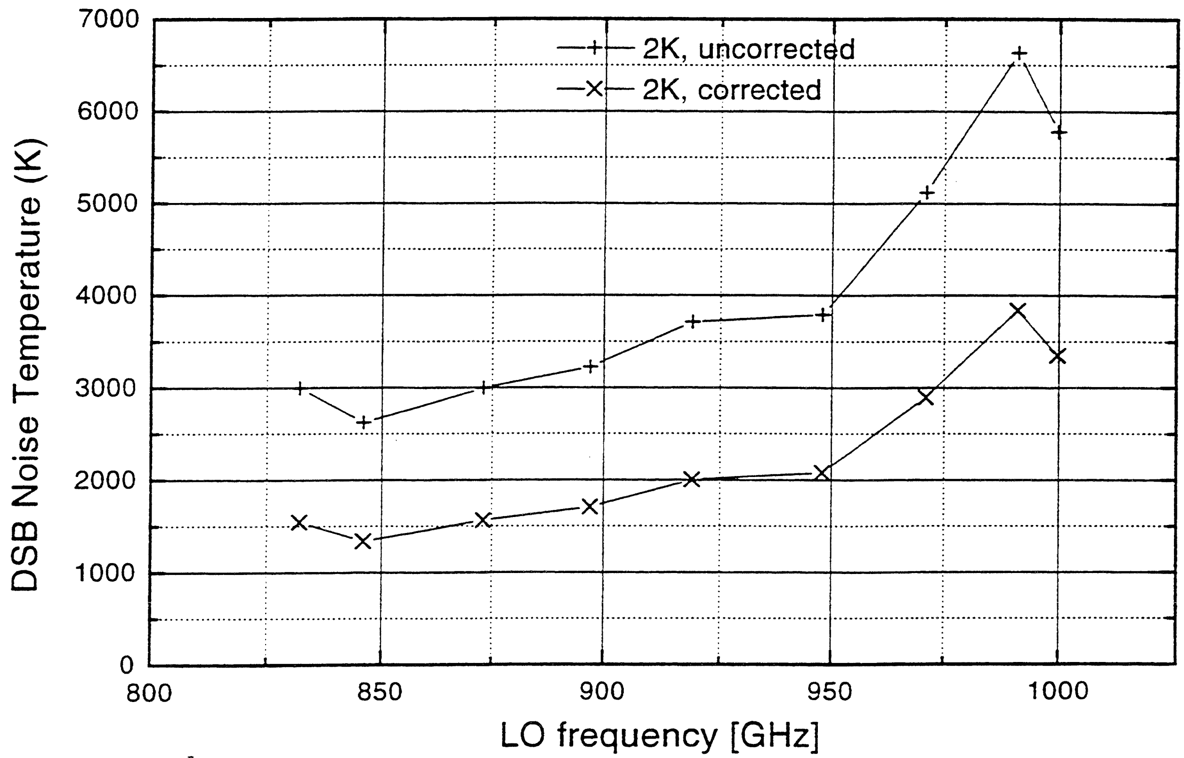

Fig. 3.9