Comparison of Measured and Predicted Performance of a SIS Waveguide Mixer at 345 GHz

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Abstract

The measured gain and noise of a SIS waveguide mixer at 345 GHz have been compared with theoretical values, calculated from the quantum mixer theory using a three port model. As mixing element we use a series array of two Nb-Al_2O_3-Nb SIS junctions. The area of each junction is 0.8 μm^2 and the normal state resistance is 52 Ω. The embedding impedance of the mixer has been determined from the pumped DC-IV curves of the junction and is compared to results from scale model measurements (105 x). Good agreement was obtained. The measured mixer gain however is a factor of 0.45 ± 0.5 lower than the theoretical predicted gain. The measured mixer noise temperature is a factor of 4 - 5 higher than the calculated one. These discrepan-

cies are independent on pump power and are valid for a broad range of tuning conditions.

Introduction and measurement set up.

This study is done as part of an ESA research contract to investigate the feasibility of SIS-mixers as space qualified THz-mixers. Predictions of the mixer performance are mainly based on the quantum mixer theory, by Tucker, reviewed in [1]. At lower frequencies the validity of the theory has been investigated thoroughly [2], and quantum limited noise behaviour has been measured in very few cases [3].

Our main purpose for this study is to identify sources of noise in the receiver and to asses the quality of the tuning of the mixer. Receiver noise temperatures measured with the Y-factor method are shown in Fig.1. An overview of the route that we follow to obtain all information using only noise measurements is outlined in Fig.2.

Measurements were done with two different mixerblocks. One mixer block (TT) a backshort and an E-plane tuner[4] , and another similar mixerblock (ST), without the E-plane tuner. We use non-contacting backshorts with two quarter lambda high/low impedance sections covered with an insulating SiO_2 layer of 200 nm.

As mixing element we use an array of two Nb-Al_2O_3-Nb junctions in series, each with an area of .8 μm^2 and a normal state resistance of 52 Ω. The ωRC product of the array is approximately 5 at 350 GHz. All measurements have been done with a magnetic field of two fluxquanta in the junctions and over an IF bandwidth (B) of 80

MHz around 1.4 GHz.

Measured mixer data

The mixer gain (GMM) is calculated from the subtraction of the IF-output power in response to a 300 K and a 77 K input load. GMM={Pout(300)-Pout(77)}/{Gif.Gf.-ΔPin}, where Gif is the gain of the IF-chain, Gf is the gain of the IR-filter at 77 K, and ΔPin is the difference in input power between a 300K and a 77K load on the 77 K radiation screen in the dewar.

To achieve the highest accuracy Gif is determined in situ by using the unpumped mixer junctions as a calibrated noise source as a function of bias voltage[5]. The total IF output power as a function of bias voltage is given by

$$Pif_{up}(V) = G_{IF}\,[2eBG_l I_{dc}(V)\coth(\frac{eV}{2kT})\,(\frac{dI_{dc}}{dV}(V)+G_l)^{-2} + kB\,(T_{isol}|\Gamma_{IF}(V)|^2 + T_{IF})\,]$$

and is fitted to the measured power. V is the biasvoltage, and $I_{DC}(V)$ is the unpumped IV-curve. e is the electron charge, k is Boltzmanns' constant and T is the physical temperature of the junction, taken to be 4.5 K. G_l is the input impedance of the IF-chain.

Gif is obtained with an accuracy of 5% from the slope of measured IF-power as a function of bias voltage above aprroximately two times the gap voltage. The noise temperature of the IF-stage is $T_{IF} + |\Gamma(V)|^2 T_{isol}$, where T_{IF} is the noise temperature of the HEMT-amplifier (Berkshire Technologies) and T_{isol} assembles the noise contributions from the bath temperature, and possible contributions of imperfect isolation between amplifier and mixer. Γ(V) is the reflection due to the impedance mismatch between the IF-chain and the junction. Since Tif= 3±0.5 K and Tisol=5.5±0.5 K are obtained from the fitting, the second term, which is essentially depedend of the dynamical conductance of the junction array, can have a significant contribution.

ΔPin is calculated from Plancks' law. The gain of the dewar window (Gw), the beamsplitter (Gbs) and the IR-filter (Gf) have been measured separately with a Michelson interferometer. Gbs=0.89±1%, Gw=95±2% and Gf=95±1% for the frequency of interest. In the calculation of the input power on the mixer it is assumed that the window is at 300 K.

GMM is given in Fig. 3 as a function of bias voltage for both mixers.

Determination of the embedding impedance

Knowledge of the embedding impedance is crucial to the theoretical calculation of the mixer performance of an SIS junction. For design purposes we used a 105 x scale model of the mixer mount. The impedance measured on the final structure as a function of backshort position and at optimum E-plane tuner position, is given by the larger circle in Fig. 4. The estimated geometrical capacitance of the junction array (22 fF) has been added in parallel to the impedance measured in the scale model.

The embedding impedance in the real mixer has been determined from the pumped IV-curves. We regard the series array of two junctions as one equivalent junction. The measured and calculated pumped curves are compared using the voltage match method[6], where both the embedding impedance and the pump power are adapted to give a best fit. A typical example of a measured and a fitted curve is given in Fig. 5. The correspondence between the two curves was always very good execpt for a small region at the quasi particle step above the gap voltage.

The embedding impedance has been determined for various backshort positions at one (optimum) E-plane tuner position. The expected circle in the Smith chart is fitted through the points in Fig. 4. The given points are lying in a very small part of one half lambda cycle of the backhort. The pattern is repeated for the next half lamba cycle, without a measureable increase in loss. To make that more clear the data of two cycles are given as a function of backshort position in Fig 4. The data as predicted by the scale model and a direct measurement of the coupled power (the pump step height) are also given as a function of backshort position. The DC-current at a biaspoint on the quasiparticle step has been normalized to one.

Comparison between measured and calculated mixer performance

The embedding impedances determined from the pumped IV-curves (and checked by the scale model measurement) have been used to calculate the gain and the noise behaviour of the mixer. We used the three port model in the low IF approximation, justified by the ωRC-product of the junctions and the IF frequency of 1.4 GHz. The terminations on the LO-port and at both side band ports were each determined separately. They differed considerably as can be seen in Fig.6, giving the pumped IV-curves at a single tuner setting for three different frequencies.

1 GAIN

The calculated mixer gain (GMC)

$$GMC(V) = 4G_L(G_{usb}|Z_{01}(V)|^2 + G_{lsb}|Z_{0-1}(V)|^2)$$

is given as a function of bias voltage in Fig.3. Z_{01} and Z_{0_1} are the relevant elements of the 3x3 conversion matrix[1] and Gusb and Glsb are the real parts of the terminating impedances at both side band frequencies, as determined from the pumped IV-curve. This gain is directly compared to the gain (GMM) determined from the measurements in Fig.3.

The discrepancy between GMM and GMC is independent of LO-power and also within a 15% error independent of the tuning conditions. It must be noted this has only been checked for the points given in the Smith Chart of Fig. 4. Around those points the fitting of the embedding impedances is the most accurate. For the most inductive tuning points the discrepancy in the gain is larger. At those points the bias supply seems to skip over the regions with negative differential resistance, deteriating the DC-curve and IF-output. For points more to the edge of the Smith Chart the amount of pump power necessary to get a well developed pump step is larger and the gap of the superconductor decreases, making accurate fits more elaborate.

2 NOISE

To obtain a measure for the noise contribution of the mixer we compared the measured and the calculated total noise output of the receiver in an IF-bandwidth of 80 MHz.

The noise contribution of the mixer is calculated from the DC-IV curve and the embedding impedances using the current correlation matrix[1]. As in the unpumped case the junctions array is regarded as one equivalent junction obtained by dividing both the measured current as the measured voltage by the number of junctions. The mixer gain used in the calculation is the gain determined from the measurements. This means that we attribute the discrepancy between GMC and GMM fully to the loss/coupling efficieny of the lens/horn/waveguide at 4K in front of the mixe. The calculated and the measured IF-output power as a function of bias voltage are given in Fig. 7a. However to get the correspondence at the first pump step as shown in Fig. 7a , an extra input noise power kBT_{ex}, with $T_{ex} = 80 \pm 20$ K, had to be added in the calculation at both side bands in addition to the shotnoise and temperature noise contribution. This value for T_{ex} is again independent of pump power and tuning conditions within the same restrictions to the tuning range as mentioned in the calculation of the gain. The calculated and measured noise contributions of the various parts of the receiver are given in terms of noise temperature in Fig. 7b.

The results in Fig. 7 are for the ST-mixerblock but a similar performance is found in the TT-block. Though still within the error margin the deviation in the gain has a tendency to be less in the ST-mixer compared to the TT-mixer, probably as a result of the improved fabrication and the use of an integrated horn.

We verified that the extra noise contribution was not a real extra input signal due to LO-signal at the side band frequencies by filtering the LO with a high Q Fabry-Pérot filter.

Discussion and Conclusions

We compared the performance of two types of waveguide SIS-mixers with the three port quantum mixer theory. We have obtained good agreement between the scale model measurements and impedances determined from pumped IV-curves. The quality of the fittings is very high in the sensitive tuning region of the mixer.
However we observed a reproducible difference between the measured and the calculated gain of both mixers. The difference can be explained partly by losses in the lens and horn.
The performance of the backshort seems to be quite lossless regarding the good agreement between the scale model measurements and the impedances fitted to the pumped IV-curves.
The noise values are more than a factor of four higher than expected from theory. This seems to be a general feature of mixers using a series array of junctions. Up to now we did not yet have single junction mixerrs available.

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C-4

Captions

Fig. 1 Receiver noise temperature for the two types of waveguide mixers measured with the Y-factor method, corrected for the beamsplitter loss.

Fig. 2 Overview of the different input an output parameters in the process of comparing the measured and calculated performance of the mixers.

The measurements yield Trec as result of a Y-factor (H/C) measurement. The gain and noise of the IF(Gif,Tif) and of the mixer(Gm,Tm) are obtained from the absolute IF-output power at different input loads, knowing the loss and the physical temperture of the input window(Gw,Tw).

The embedding impedance of the junctions is determined either with use of a scale model or by fitting the pumped IV-curves to the theory. When a scale model is used the geometrical (and parasitic) capacitance of the junction has to be estimated separately.

When the embedding impedance is known, the mixer performance is calculated as a function of bias supply at different LO-power levels.

Fig. 3 Measured (+) and calculated (•) coupled gain for both waveguide mixers. The TT-mixer has a 500-50 Ω transformer at the IF-port to enhance the gain.

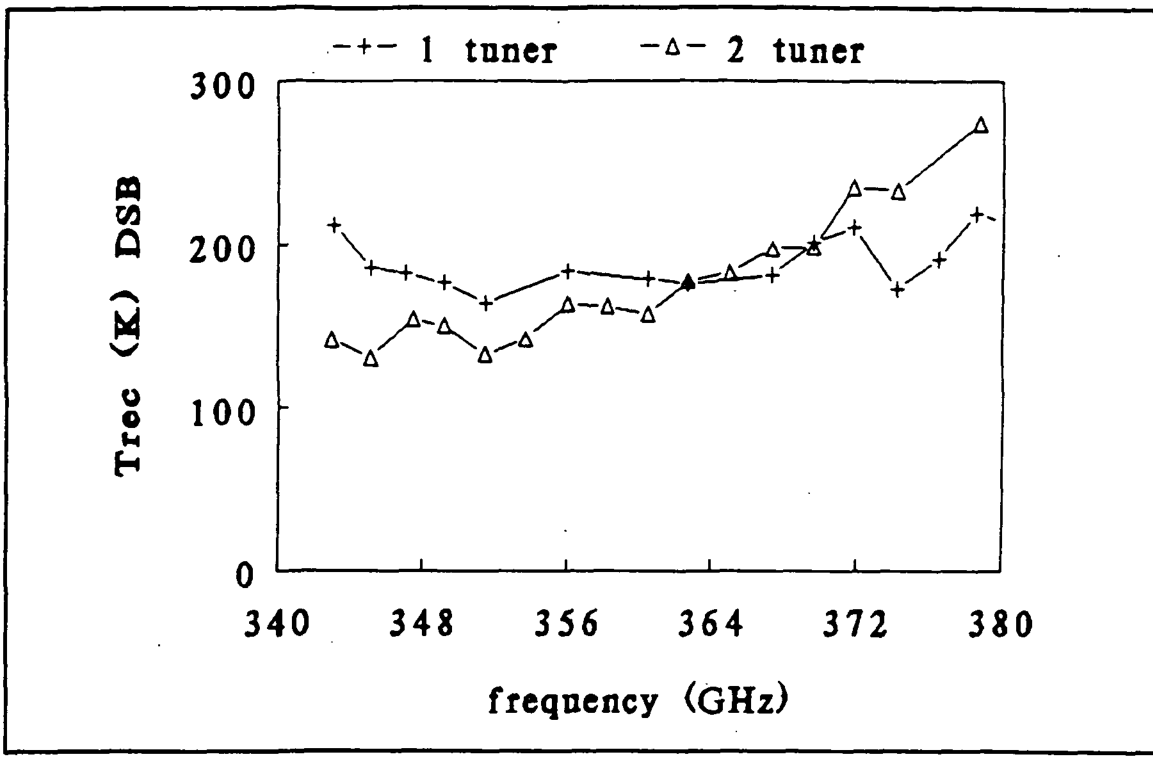
Fig. 4 Embedding impedance as a function of backshort position, as calculated from the scale model (-+-) and as determined from the pumped IV-curves (■,◆). As a direct measure of the coupled power the pumped step height at the optimum biaspoint (-o-) is also given as a function of backshort position

Fig. 5 Measured (-▪-) pumped IV-curve at 351 GHz and calculated(-) curve using the given fitting parameters for the embedding circuit. The admittances are normalized to the 104 Ω.

Fig. 6 Detailed view of DC-IV curve of the series array of junctions, pumped at three different frequencies. The tuning conditions and the pump power are identical at all frequencies.

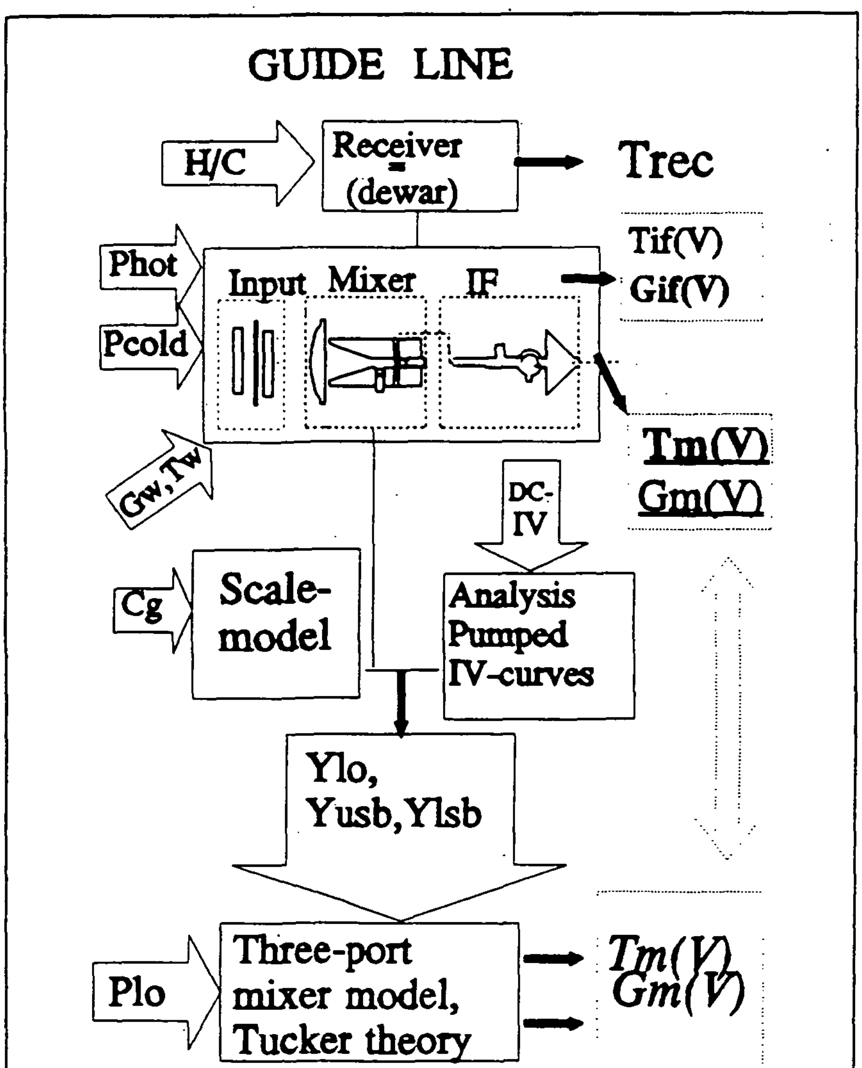
Fig. 7A Total measured (+,o) and calculated (-) IF-output power in a bandwidth(B) of 80 MHz at two different input signals, as a function of bias voltage. For the calculated IF-power an extra noise power of 80kB has been added to the input of the mixer. The contributions of the shot noise and temperature noise of the junctions (dPjunctie) and of the IF-stage (dPif) are given also.

Fig. 7B The total measured (+) and calculated (•) reciever noise temperature as a function of bias voltage. For reference the contribution to the calculated reciever noise temperature of the IF-stage (dTif), the junctions (dTm) and of the input losses (dTw) are also given.



-+- 1 tuner
-Δ- 2 tuner
Trec (K) DSB
300
200
100
0
340
348
356
364
372
380
frequency (GHz)

Fig. 1



GUIDE LINE
H/C
Receiver = (dewar)
Trec
Phot
Pcold
Input
Mixer
IF
Tif(V)
Gif(V)
Tm(V)
Gm(V)
Gw,Tw
DC-IV
Cg
Scale-model
Analysis Pumped IV-curves
Ylo, Yusb,Ylsb
Plo
Three-port mixer model, Tucker theory
Tm(V)
Gm(V)

Fig. 2

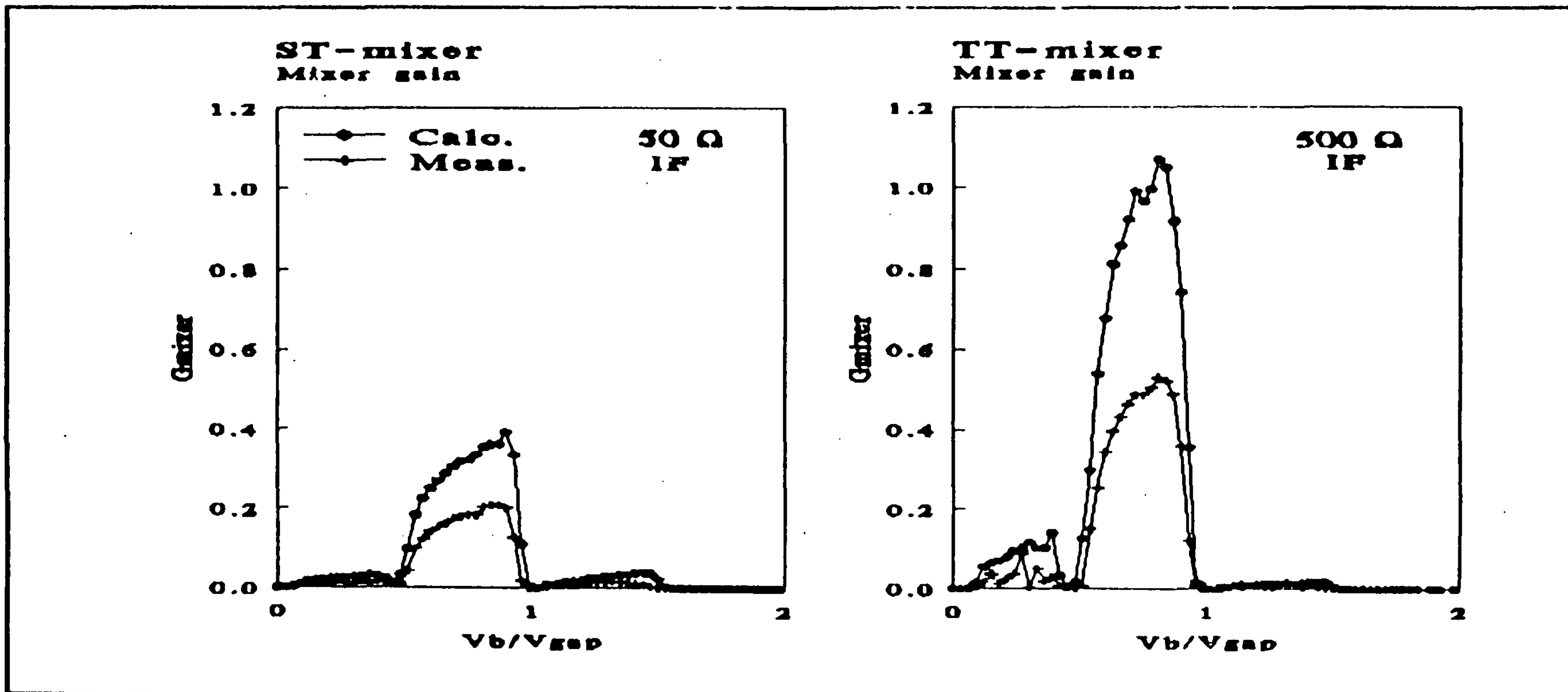

ST-mixer
Mixer gain
Calc.
Meas.
50 Ω
IF
Gmixer
Vb/Vgap
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
TT-mixer
Mixer gain
500 Ω
IF
Gmixer
Vb/Vgap

Fig. 3

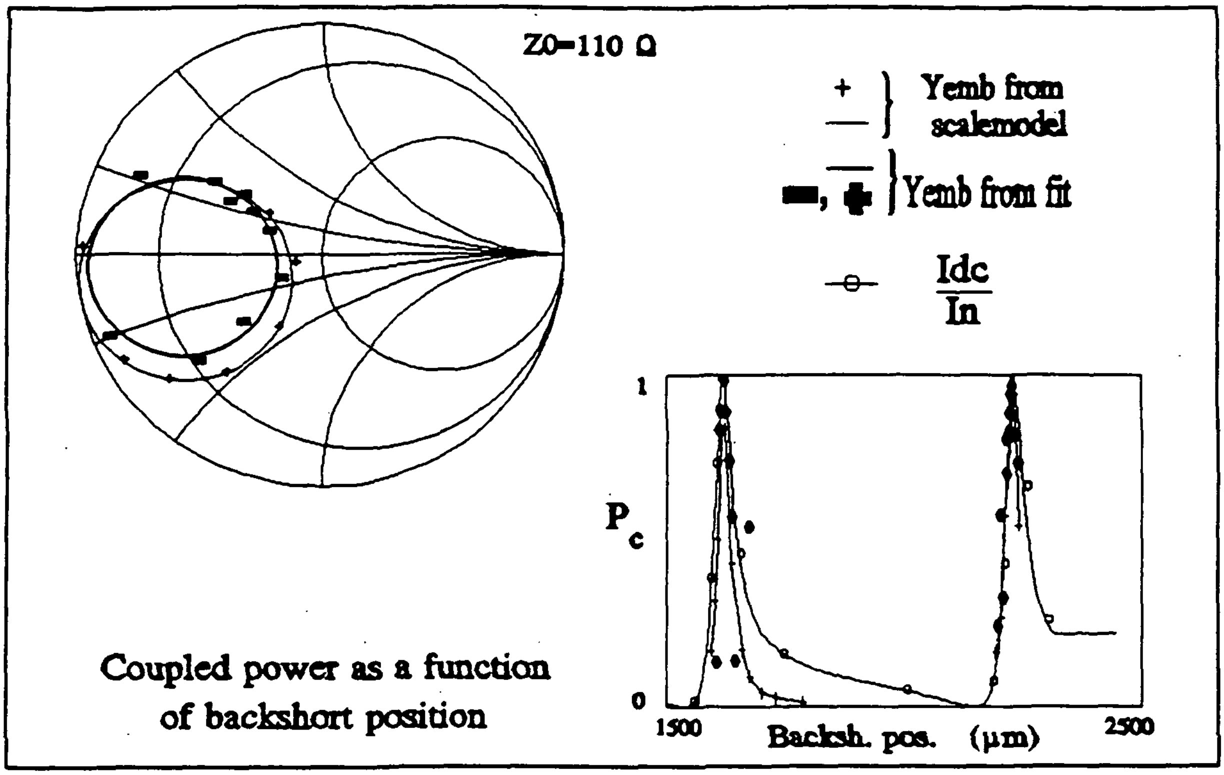

Z0=110 Ω
+ } Yemb from scalemodel
Yemb from fit
Idc / In
Coupled power as a function of backshort position
P_c
1
0
1500
Backsh. pos. (μm)
2500

Fig. 4

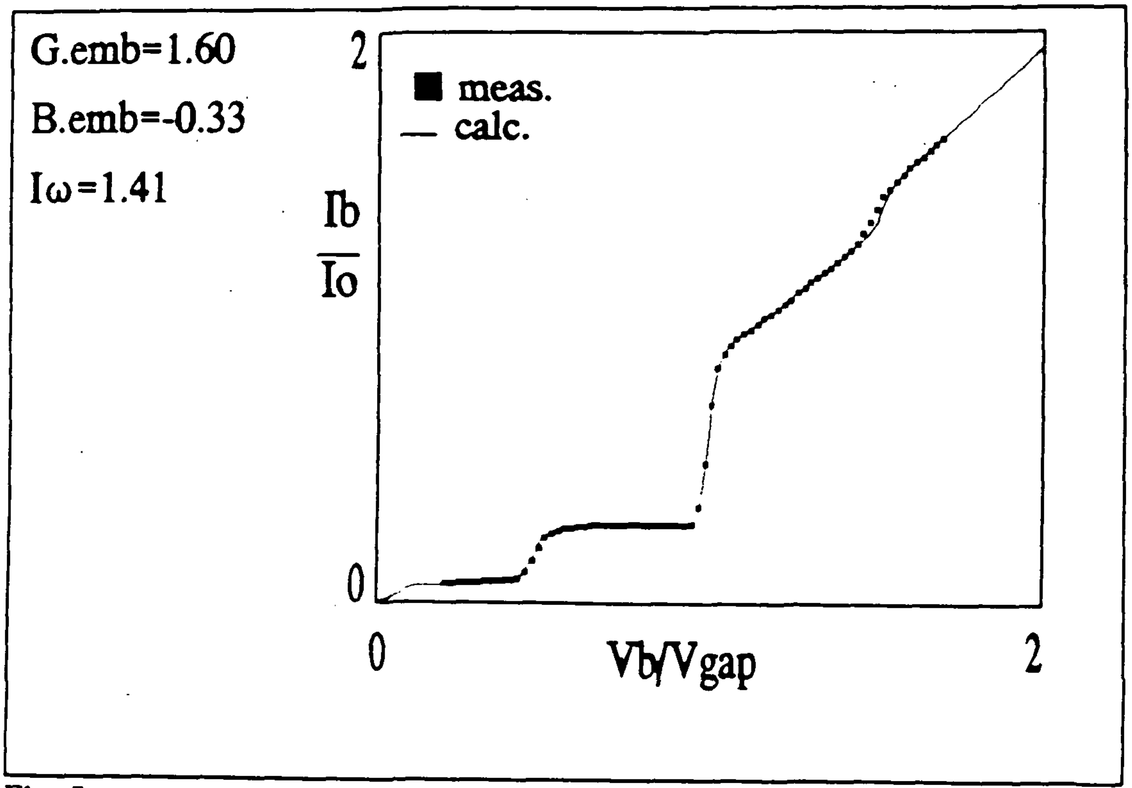
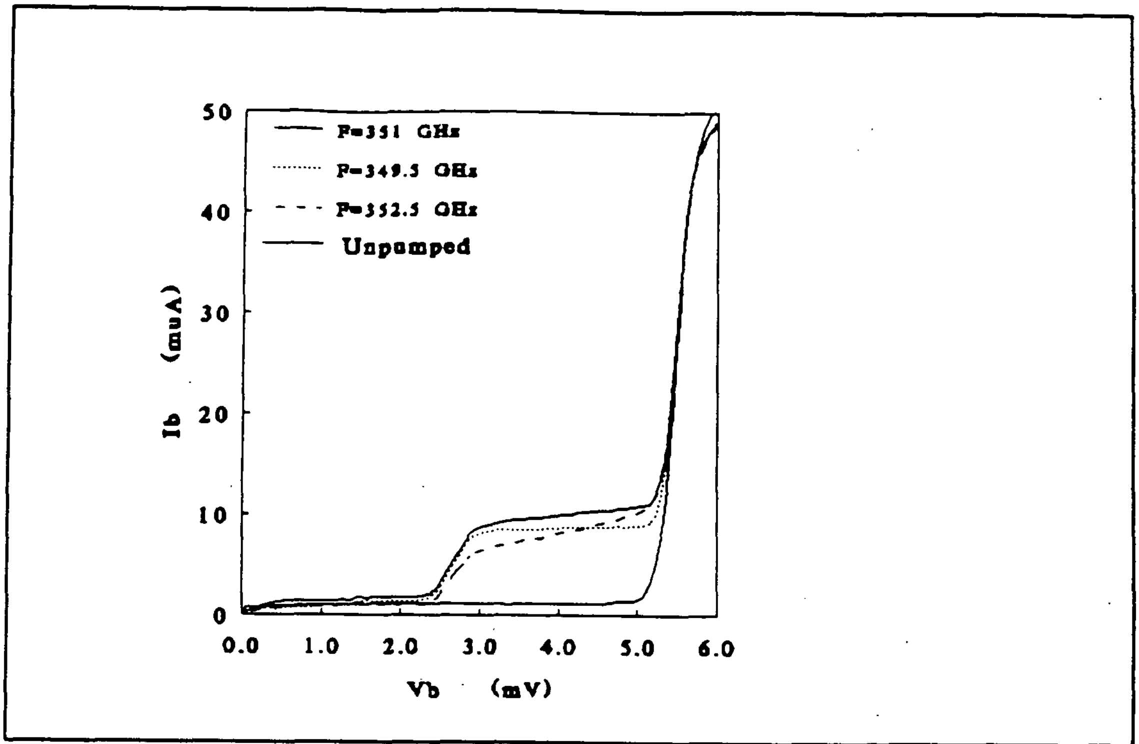
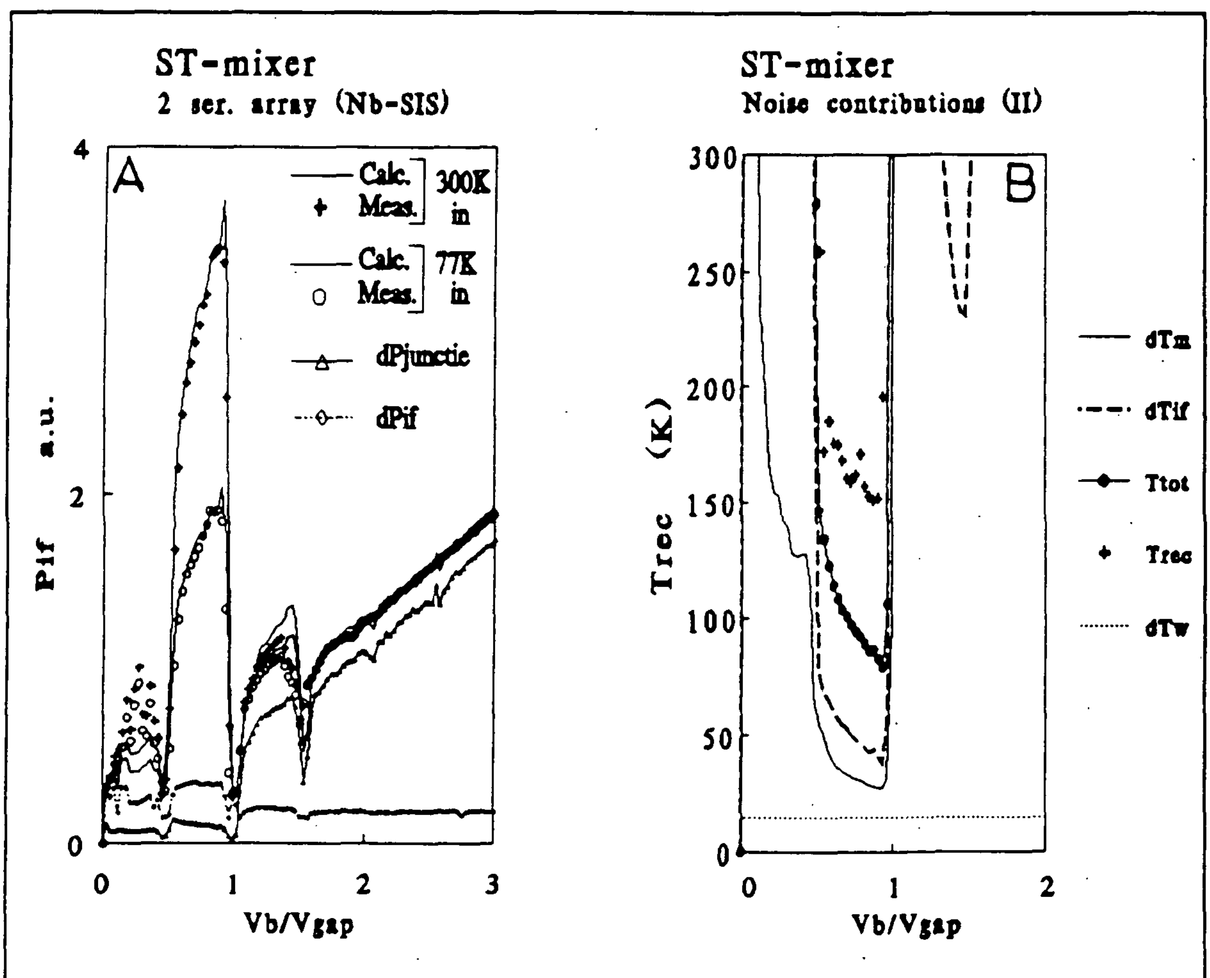

G.emb=1.60
B.emb=-0.33
Iω=1.41
2
meas.
calc.
Ib / Io
0
0
Vb/Vgap
2

Fig. 5



F=351 GHz
F=349.5 GHz
F=352.5 GHz
Unpumped
Ib (muA)
Vb (mV)

Fig. 6



ST-mixer
2 ser. array (Nb-SIS)
A
Calc.
Meas.
300K in
Calc.
Meas.
77K in
dPjunctie
dPif
Pif a.u.
Vb/Vgap
ST-mixer
Noise contributions (II)
B
Trec (K)
dTm
dTif
Ttot
Trec
dTw
Vb/Vgap

Fig 7.