REGARDING THE IF OUTPUT CONDUCTANCE OF SIS TUNNEL JUNCTIONS AND THE INTEGRATION WITH CYROGENIC InP MMIC AMPLIFIERS

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Abstract

There is a strong interest in the Submillimeter community to increase the IF bandwidth of SIS receivers in order to facilitate extra-galactic astronomy. However, increasing the IF bandwidth generally also means increasing the IF operating frequency of the mixer, because it is very difficult to achieve a good IF impedance match to a low noise amplifier (LNA) for more than an octave bandwidth.
Complicating the matter is that most cryogenic amplifiers do not have a very good input match, which nearly always results in severe standing waves between the mixer and amplifier, especially since the amplifier is connected to the mixer via a finite (10 cm) length of coaxial line. The use of a cryogenic isolator would eliminate the standing wave issue, however all of the currently available cryogenic isolators have less than an octave of bandwidth. The second approach would be to integrated an low noise amplifier into the mixer block, minimizing the distance between the junction and LNA.

In this paper we investigate the SIS junction's IF output conductance and the possible integration of SIS mixers with InP MMIC low noise amplifiers, as an alternative to the traditional matching network/isolator approach. In particular we look into the use of a grounded Gate and grounded Source configured low noise InP amplifier, and the performance one is likely to achieve.

I. Introduction

From literature the IF output impedance of a Superconducting-Insulator-superconducting (SIS) junction is typically 10 times the normal state resistance of the junction [1-3]. The junction's IF output is shunted by the parasitic capacitance of the junction (A SIS junction is made of two closely spaced superconductors) and RF matching network. The resulting capacitance of a AlO_x tunnel junction with 10kA/cm^2 current density is on the order of 80fF/ μm^2. The matching network required to match the SIS junction's RF impedance to the waveguide embedding impedance is commonly implemented in micro-strip mode, and fabricated with either SiO or SiO_2 as the dielectric between the wire layer and ground-plane. For example, the JPL process uses

450- and 200 nm thick SiO (εr=5.6) dielectric layers. The relatively high dielectric constant of the dielectric guaranties that any type of RF matching network implemented in micro-strip mode introduces a significant parasitic capacitance, hence significantly limiting the obtainable IF bandwidth of the mixer.

Consider the ωR_nC product of a SIS junction. For a niobium SIS junction using an AlO_x barrier with current density equal to 7-10kA/cm ^{2}, the ωR_nC product is unity at about 100 GHz. It can be seen that the combined junction and RF matching network geometric capacitance is nearly the same for all micro-strip tuned SIS devices. This is especially the case if one considers that the fabrication process for SIS devices is universal, i.e. similar world-wide. We are justified therefore to do a case study of the popular and widely used "End-Loaded stub" RF matching network, without loosing too much generality [4-10].

For the wave-guide devices currently in use at the CSO, the RF matching network has a parallel plate capacitance of approximately 220 fF, and a junction capacitance of 40 fF giving a combined parasitic capacitance of 260 fF at the IF Port of the mixer (Fig. 1). Superconducting mixer computer simulations using Supermix, a recently developed software tool [11], have been performed in order to better understand the IF output conductance, optimum IF load impedance and IF frequency limitations of the SIS mixer. Using the results of these simulations, we investigate what happens when one of these devices is interfaced directly with an ultra-wide bandwidth InP MMIC device.

II. IF Output Conductance

The outline of the computer simulations is shown in Figure 2. We use a program called "Supermix" [11] which is developed at Caltech. The antenna impedance is taken to be 40-i20 Ohm. For clarity we show the RF choke with the SIS junction situated at the center of the bowtie antenna. To the left of the junction the RF matching network is visible. Also shown are two bond-wires, ordinarily one of the bond-wires is connected to ground, the other to a IF matching/bias network [12]. The IF output in the computer model is taken through the RF matching network and terminated into a 50 Ohm load via a transformer. This technique enables us to calculate both the mixer gain and IF output impedance.

In Figure 3 we plot the junction's IF output admittance as a function of bias voltage. For reference sake we show the pumped and unpumped IV curves as well. The IF frequency is 6 GHz, and 3 harmonics were used in the harmonic balance part of the program. The Junction's IF output impedance consists of a real part (10Rn) shunted by a capacitive component of 307 fF. This includes the quantum susceptance and is a more accurate value than the estimated 260 fF mentioned earlier. To see how the junction's IF admittance varies as a function of IF frequency we ran the mixer simulation from 0.5 to 12 GHz. The results is shown in figure 4. Clearly the IF admittance is made up out of a parallel RC, whose values are 10Rn, and 307 fF.

III. RF Port Reflection Coefficient

Intuitively one may think that it is best to conjugate match the above mentioned IF output conductance. This does indeed provide maximum mixer gain (Fig. 5), but also gives a reflection gain at the RF input of the mixer! This likely results in significant standing waves (VSWR) between the mixer and the telescope and consequently an unstable baseline for the back-end spectrometer. A more suitable value for S11(RF) is perhaps -3 to -5 dB, which results in a slightly lower mixer gain but more stable receiver.

We used the optimizer in Supermix [11] to calculate the required IF load impedance from 0.5 to 12 GHz that provides a particular RF reflection coefficient. When we do this, the mixer gain (Gmix) happens to be nice and flat as well. The required IF load impedance is complex and is plotted against IF frequency in figure 6.

Traditionally the IF port of a SIS junction has often been terminated by a real impedance, simply because it turns out to be very complicated to precisely calculate the required load impedance needed to achieve both an acceptable RF reflection Coefficient and mixer gain. For comparison's sake, we plot Gmix and S11(RF) for two distinct real load impedance's, 2Rn and 5Rn. In the case of a 1-2 GHz IF frequency, a IF load impedance of 5Rn is quite acceptable. It provides a near optimum mixer gain and a RF reflection coefficient of about -1 to -3 dB. The disadvantage is of course that the mixer gain is very much IF frequency dependent (10dB from 1-12 GHz)! For higher IF frequencies then 2 GHz, an IF load of 2Rn is not a bad choice. However the mixer gain is still a slight function of IF frequency and 2-3 dB in mixer gain is sacrificed as compared to an optimal design.

The real and imaginary components of the calculated IF load admittance are presented in Figure 6. Note that the real part of Yif varies from 10Rn for a conjugate match (maximum Gmix and S11(RF)) to 2.3 Rn for a RF reflection coefficient of -10dB. The imaginary part is essentially constant at -296 fF, the conjugate of the combined junction capacitance, junction quantum susceptance and RF matching network parasitic capacitance. In general, the required IF load impedance will be on the order of (2.8-3.7) * Rn shunted with a negative capacitor whose magnitude is the total combined junction capacitance.

IV. IF Matching Network

Since nature does not provide us with a negative capacitance, we need to come up with some kind of compromise to obtain the required IF load impedance. An inductance will do at a single frequency, with a 3dB bandwidth related to the Q of the circuit. A wider bandwidth (octave) is achieved with a more complicated circuit. As an example we use a 7 pole Chebyshev impedance transformer, implemented in micro-strip mode (Fig 7) and centered from 4-8 GHz. The conditions are S11(RF) = -3dB with a flat/optimal mixer gain. On the Smith chart we show the simulated IF load impedance and actual obtained IF impedance as measured at the junction (Match[S22]). If we replace the junction with the required IF load, and look into the 50 Ohm output of the matching network we see a return loss of -14 dB (4% reflected power).

Now that we have designed a complete IF matching network, we calculate the combined IF matching network/RF choke impedance from 0.5 - 12 GHz and present this to the IF port of the mixer. Re-running the superconducting mixer software (Supermix) with this new load impedance gives us the final mixer performance (Fig. 8). Note that Gmix is nice a flat at -1.4 dB, while the RF reflection coefficient is -5dB. This is slightly different from the design goal of -3dB, because we were not able to perfectly match the required IF load for a RF reflection coefficient of -3db (Figures 6, 7). It should also be noted that at the LO frequency (0 GHz) the RF reflection coefficient goes positive. In practice this problem can be prevented by including a termination resistor in series with a small inductance.

V. Reality check

To compare our superconducting mixer simulations against actual measurements, we plot the IV and Total Power curves of both the simulation and measurement in Fig. 9. The difference in the total power curve shape is primarily due to a difference in Antenna impedance. From the simulations we get a 345 GHz mixer noise temperature of 12 K and a mixer gain of -1.4 dB (IF frequency = 6 GHz). The optics loss at the RF frequency is measured to be about -0.5 dB using a Fourier Transform Spectrometer. Using the intersecting line technique[13, 14] we calculate an actual optics temperature of 25K.

The 352 GHz measured result uses a SIS receiver with a 1-2 GHz GaAs balanced low noise amplifier (noise temperature equals 5-6 K) as opposed to the 6 GHz intermediate frequency in our computer simulations. Finally, if in our simulations we use an InP Hemt amplifier centered at 6 GHz with a noise temperature of 7K, we calculate a receiver temperature of about 53K DSB. This compares very well with the measured receiver temperature of about 52K (different IF frequency). From this discussion it is clear that the noise in the receiver is very much dominated by the optics loss in front of the mixer!

VI. InP MMIC's

A promising technology for wide IF bandwidth applications are InP MMIC's. In figure 10 we show the characteristics of three of such devices. The simulations cover 1-20 GHz and show very good gain and noise performance, especially for the grounded gate devices. The input impedance for a grounded gate device is about 20 Ohm, with the optimum noise impedance close to 50 Ω. The models were obtained from Professor Sander Weinreb [15]. At the present time, none of the MMIC's have been measured. Nevertheless it is very instructional to connect the MMIC models to the SIS junction under discussion ("End-Loaded stub" RF matching network) and re-run the Supermix mixer simulations.

The result is shown in Figure 11. The MMIC is wire-bonded directly to the RF choke without a matching network. Because the MMIC's and SIS device are not matched to one another, the mixer gain and RF reflection coefficient are quite erratic. This experiment clearly demonstrates two important points.
First, if a MMIC is to be used with a existing SIS junction then an IF matching network is inevitable. This of course will restrict the IF bandwidth that can be achieved.
Secondly, to obtain a wide IF bandwidth system the junction has to have very low parasitic capacitance[16] an be designed to properly match the MMIC. In other words, both MMIC and SIS devices need to be very well characterized and understood.

VII. Conclusion

SIS devices employing highly capacitive RF matching networks such as the popular "End-Loaded" stub can be used up to IF frequencies of at least 8 GHz. The parasitic capacitance from the actual SIS device, RF matching network, and junction's quantum susceptance is significant for most mixers in operation at the present time. Increasing the IF bandwidth to 8 GHz, or higher, requires a knowledge of the proper IF load impedance if one is to obtain an optimally flat mixer gain and acceptable RF reflection coefficient. As a rule of thumb, the IF load impedance will be on the order of (2.8-3.7) * Rn shunted with a negative capacitor whose magnitude is the total combined junction capacitance. Presenting a real load impedance to the IF port will limit the mixer performance at the higher IF frequencies. Another important observation is that the RF choke will resonate with the junction parasitic capacitance at about 9-10 GHz for most SIS devices currently in use. This sets a practical upper limit to IF frequency, unless the junction is redesigned of course.

Low noise InP MMIC technology is very promising indeed. If one is to take full advantage of the MMIC's bandwidth however, the Junction/RF matching network combination needs to be carefully re-designed and characterized. Current SIS devices

can of course be used with MMIC's, but will need to use some sort of IF matching network, which will limit the available IF bandwidth.
Last, we have demonstrated Supermix as being a very useful tool for superconducting mixer analyses.

VIII. References

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Motivation

SIS mixers employing an "End-loaded Stub" RF matching network are currently in use at many institutions, such as the CSO, CFA, JCMT, KOSMA, MPIfr and SMT.
We investigate if the this type of RF matching network lends itself to IF bandwidth's as high as 12 GHz.

Questions:

- What is the best possible mixer performance achievable given a 4-8 GHz IF frequency.
- What is the mixer performance when InP MMIC's are integrated with this kind of RF matching network.

Basic Issue:

- What is the IF Load Admitance required to obtain near unity mixer gain and at the same time an acceptable RF reflection Coefficient ($S11_{RF}$).

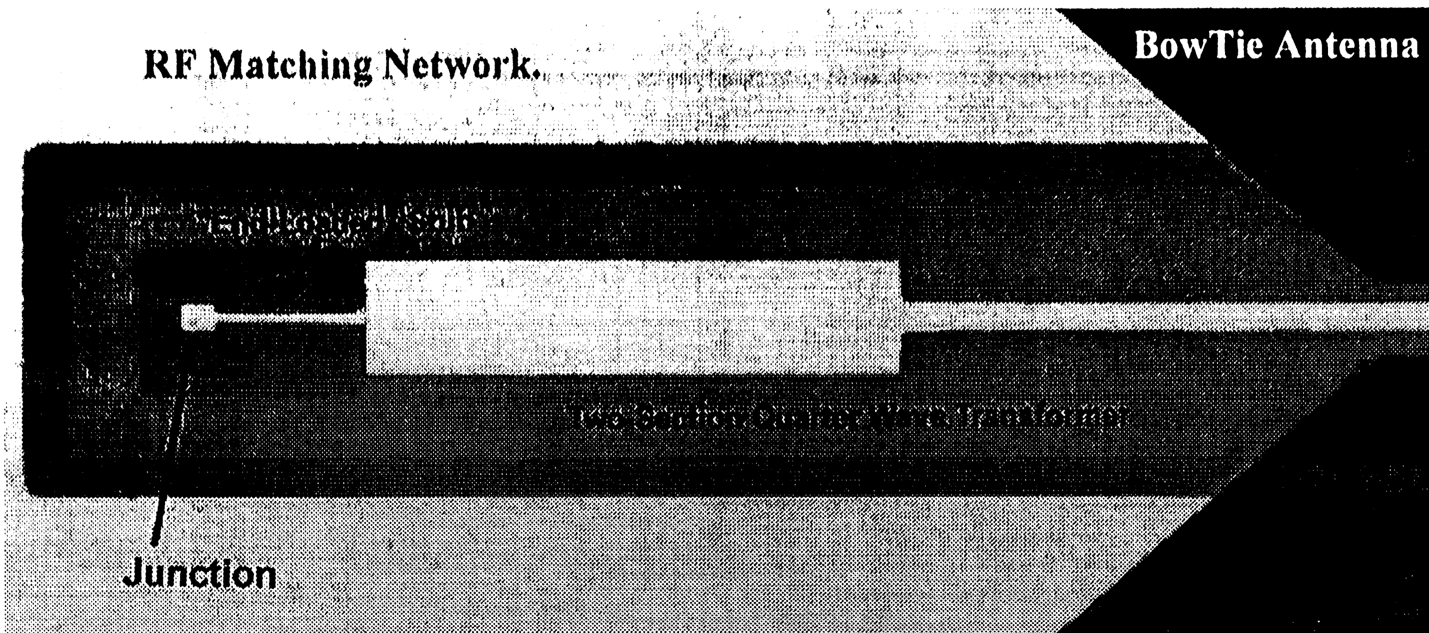


Fig. 1 End Loaded Stub RF matching Network and motivation for the work

Outline of Computer Simulations

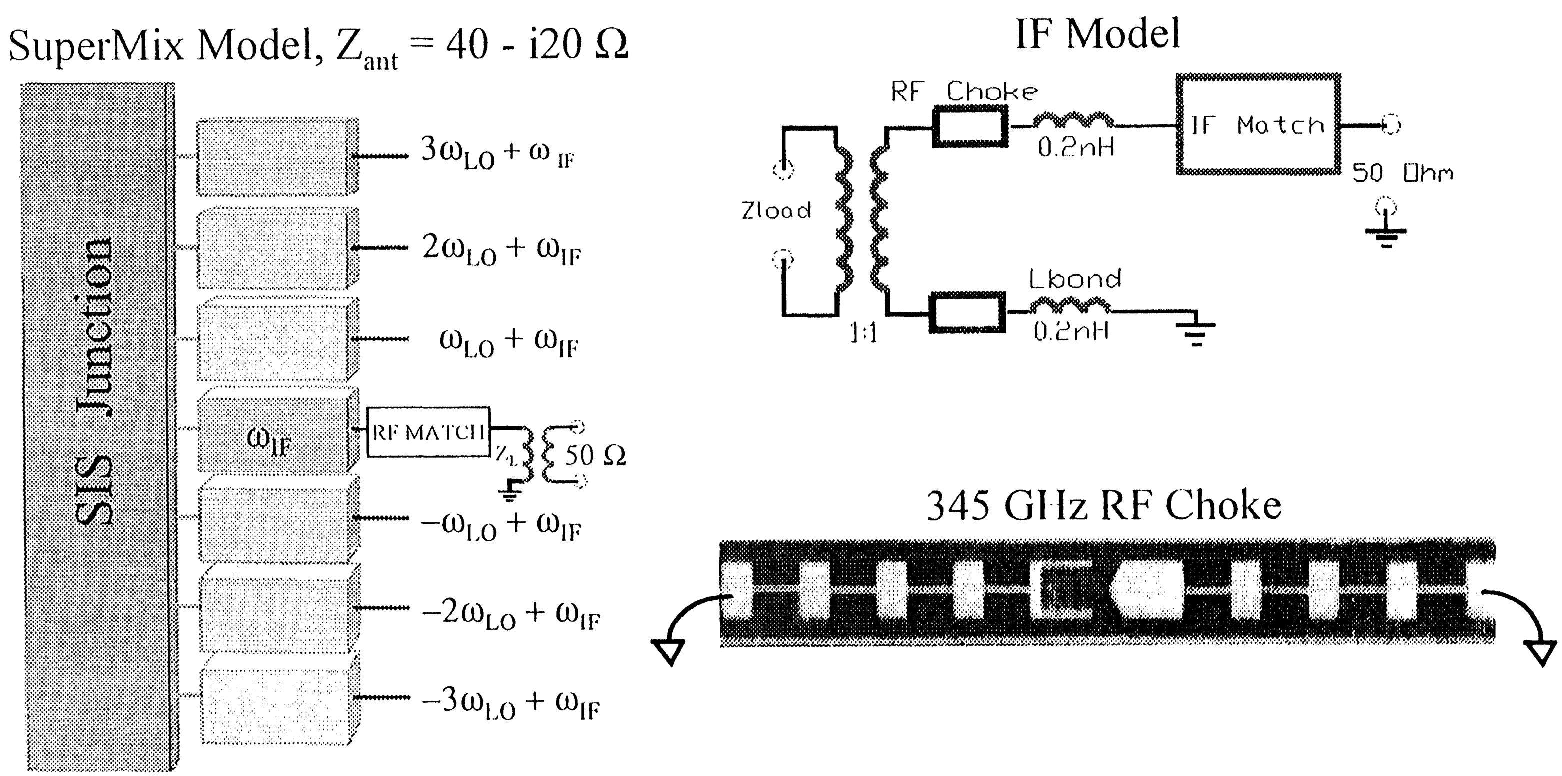


Fig. 2 Outline of the Computer Simulations. The Supermix mixer model assumes 3 harmonics for the harmonic balance. The Antenna impedance is taken to be 40-i20 Ohm. The IF model includes the RF choke and bond wires. A ideal transformer is used to obtain the load impedance at the junction/RF matching network, situated in the center of the Bowtie antenna.

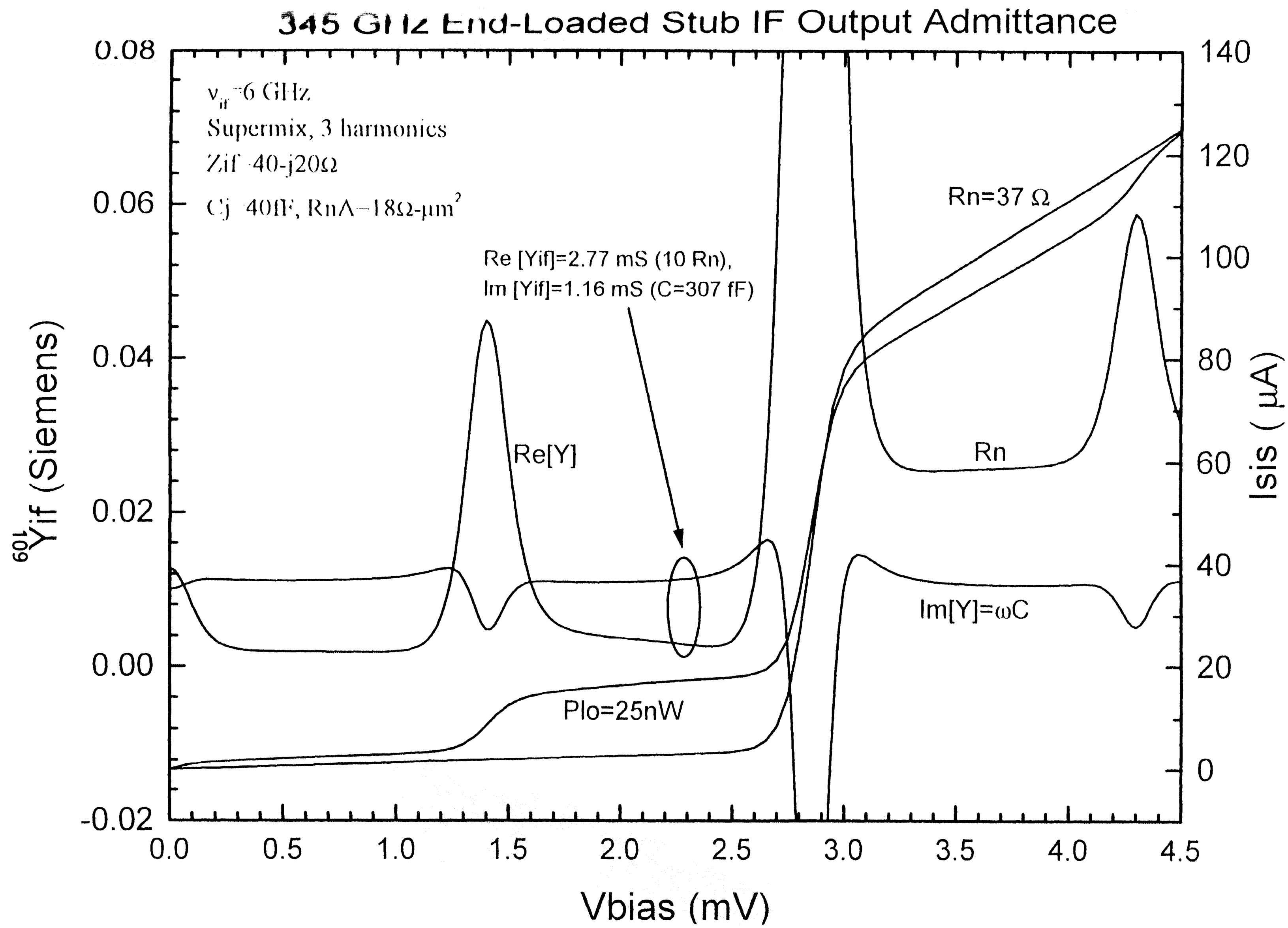


Fig. 3 345 GHz End-loaded stub IF output admittance. The real part of the IF impedance is close to 10Rn, while the imaginary part corresponds to a 307 fF capacitance. This capacitance is a combination of junction, RF choke and quantum susceptance.

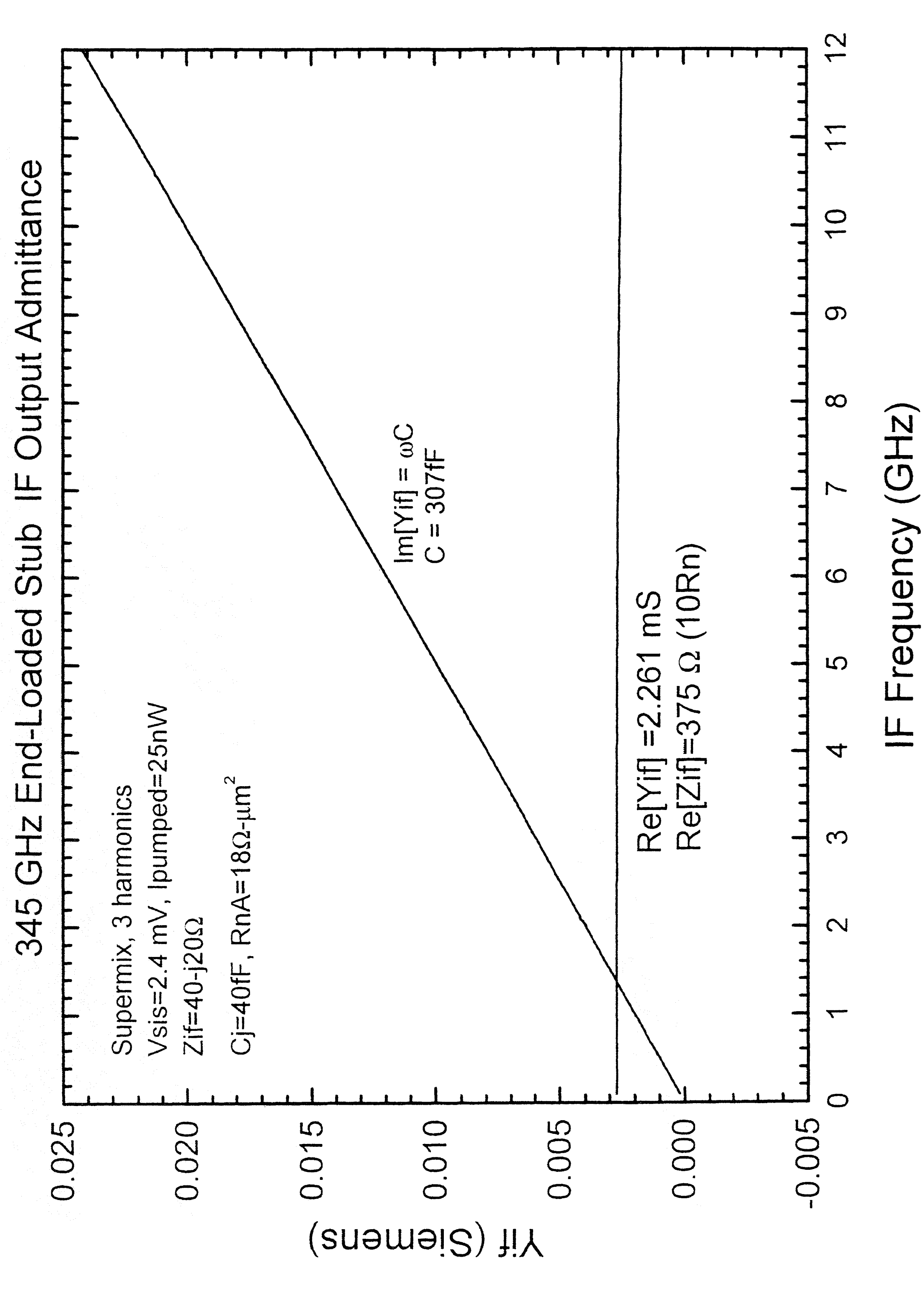


Fig. 4 End loaded Stub IF output admittance as a function of IF frequency.

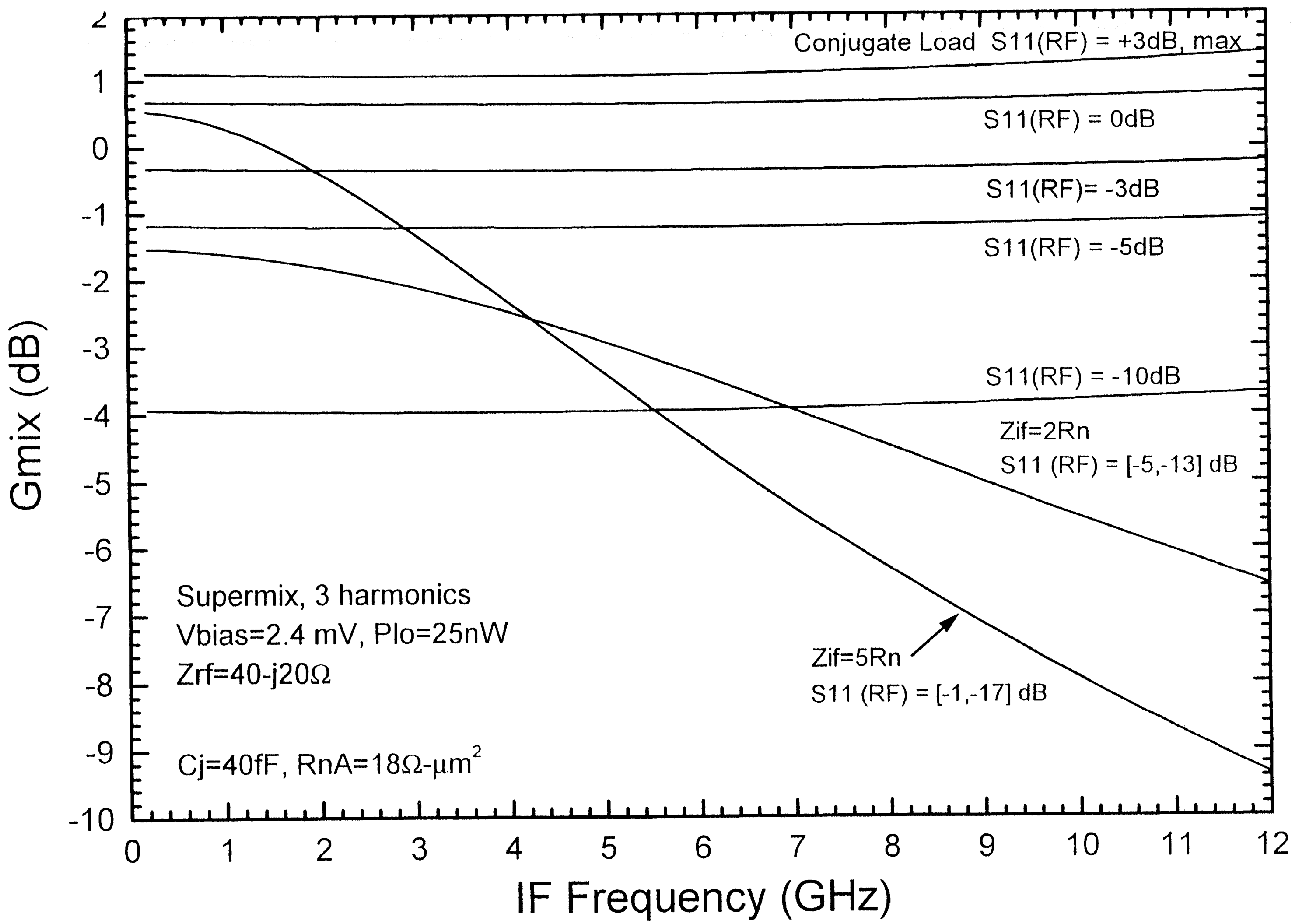


Fig. 5 Mixer gain and RF reflection, S11(RF), as a function of IF frequency for different IF loads. Presenting a conjugate load results in a mixer gain, but also a large RF reflection gain (+3dB)! Presenting a real load such as 2Rn or 5Rn is adequate at the lower IF frequencies, but results in a large loss in mixer performance at the higher IF frequencies.

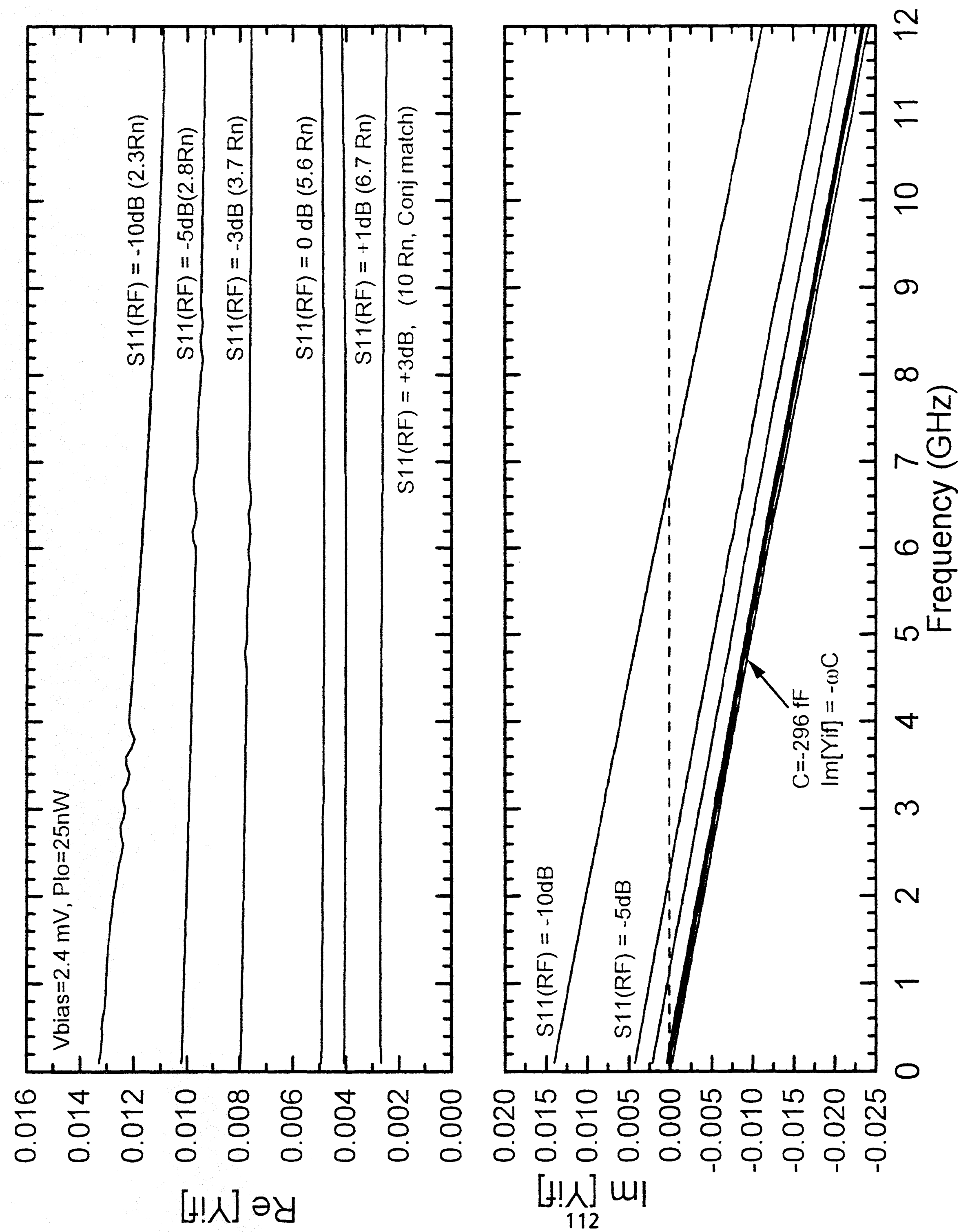
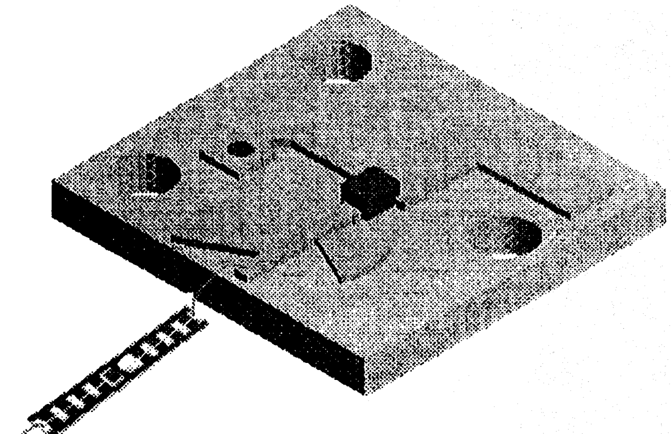
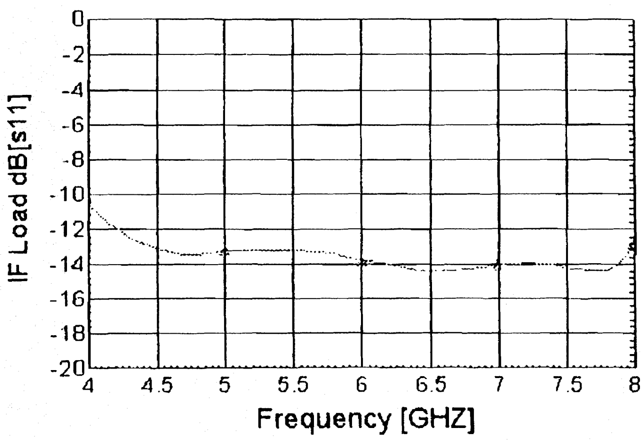


Fig. 6 IF load impedance required to obtain a fixed RF reflection Coefficient, S11(RF), and flat mixer gain. Note that a negative capacitance is required to achieve a good match over the whole IF frequency range.

4-8 GHz IF Matching Network

Conditions:
- S[rf][rf]=-3dB
- Flat/Optimal Gmix.





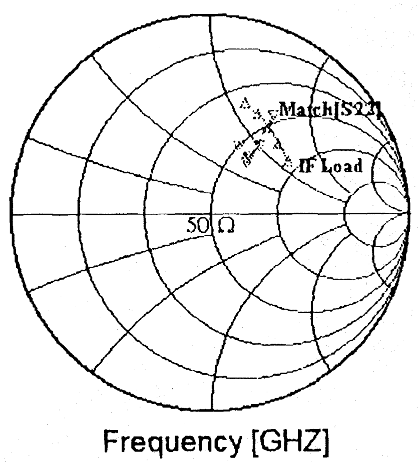


Fig. 7 A 4-8 GHz IF matching network which transforms a 50 Ohm input impedance to the required IF load impedance given the condition, S11(RF) = -3dB.
Since it is physically impossible to provide a negative capacitance, a good impedance match can only be provided over a limited (octave) of bandwidth.

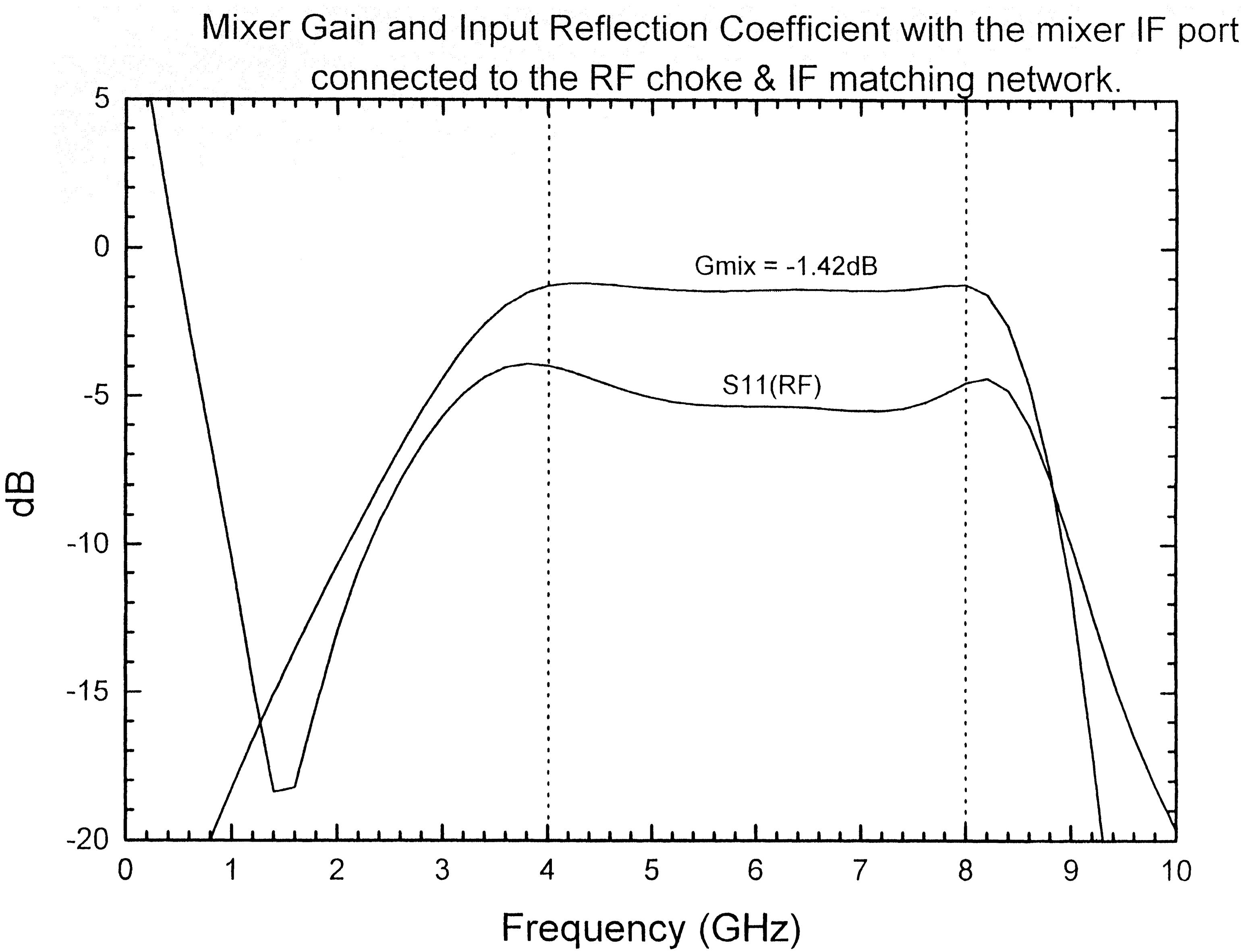


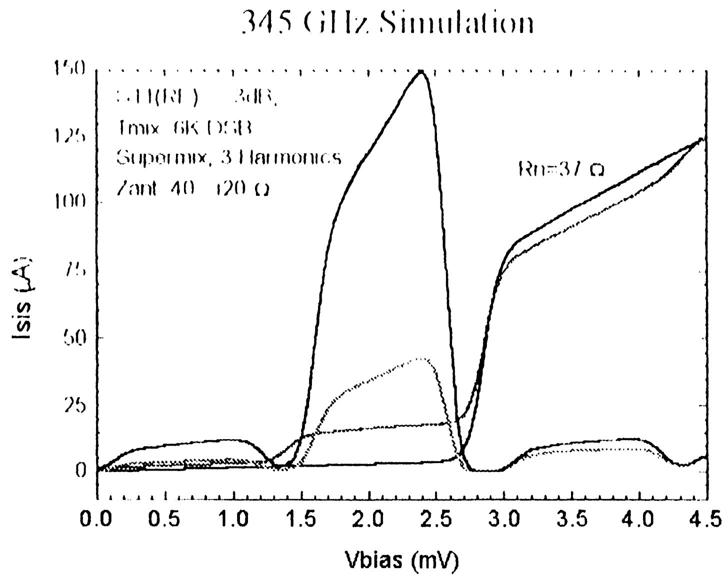
Fig. 8 The calculated IF load presented by the IF matching network and RF choke is now used to terminate the IF port of the mixer model. Supermix computer simulations are re-run, and the result for Gmix and S11(RF) plotted.

T_{mix} = 12 K DSB (Supermix)
G_{mix} = -1.4 dB (Supermix)

Trec* 53K DSB (Calculated)

G_{optics} = 0.9 (-0.5dB) (Measurement)
T_{optics} = 25K (Measurement)
T_{if} ~ 7K (4-8 GHz) (Gallego *et. al)*

Trec 52K DSB (1-2 GHz IF Measured)



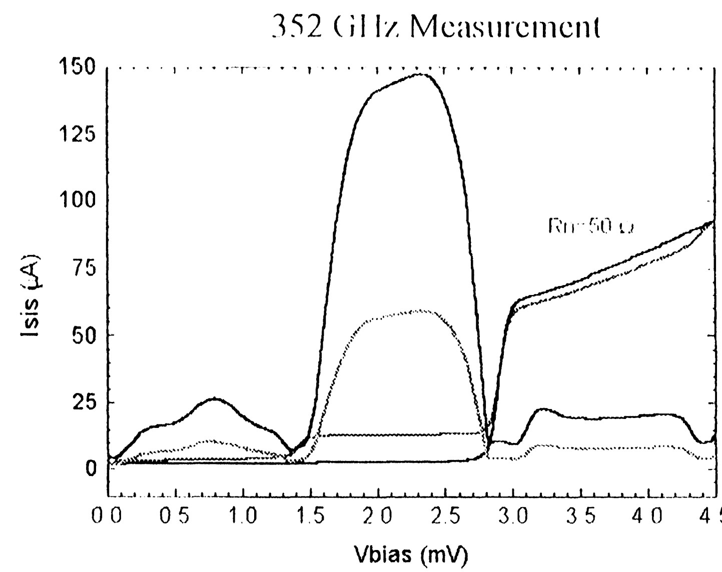


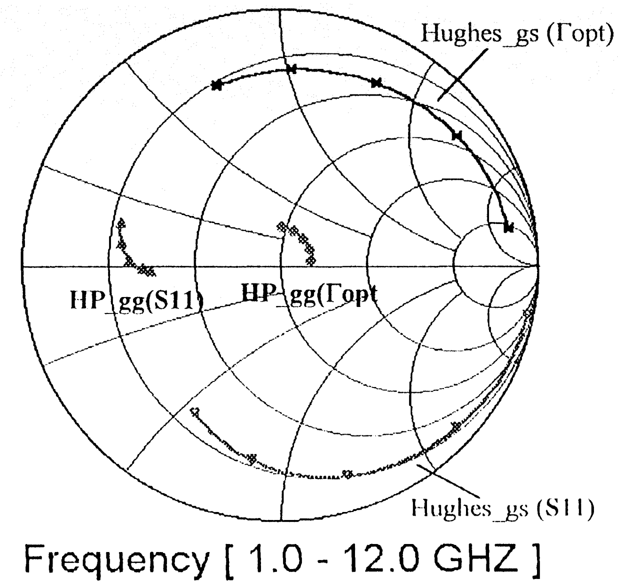
Fig. 9 To show that the simulations fit closely to actual measurements, we show this graph. The 352 GHz data was taken with a 1-2 GHz IF. The noise temperature of the LNA is about 5-6 K. The simulations assume a IF frequency of 6 GHz, but with similar IF noise characteristics. Material loss is measured in the lab and verified by the intersecting line technique (Blundell, Feldman *et al)*.

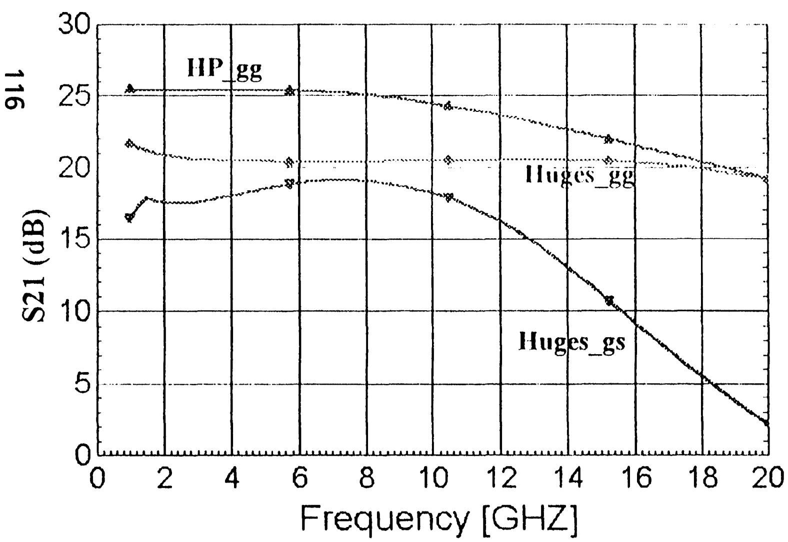
InP MMIC MODELS

DC Power: 10mW, primarily due to resistive drain loading for low frequency operation

Tnoise: 5-8K

Gain: 20-25 dB





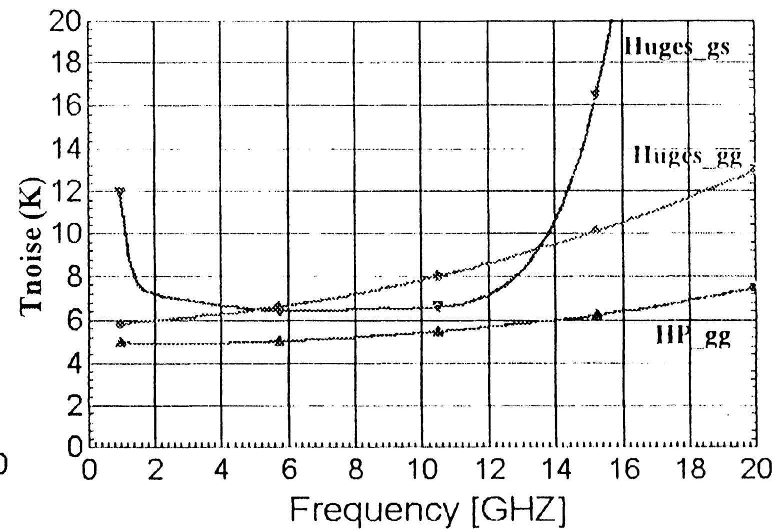


Fig. 10 InP MMIC computer simulations. Models obtained from Sander Weinreb. These simulations assume a fixed 50 Ohm input/output termination.

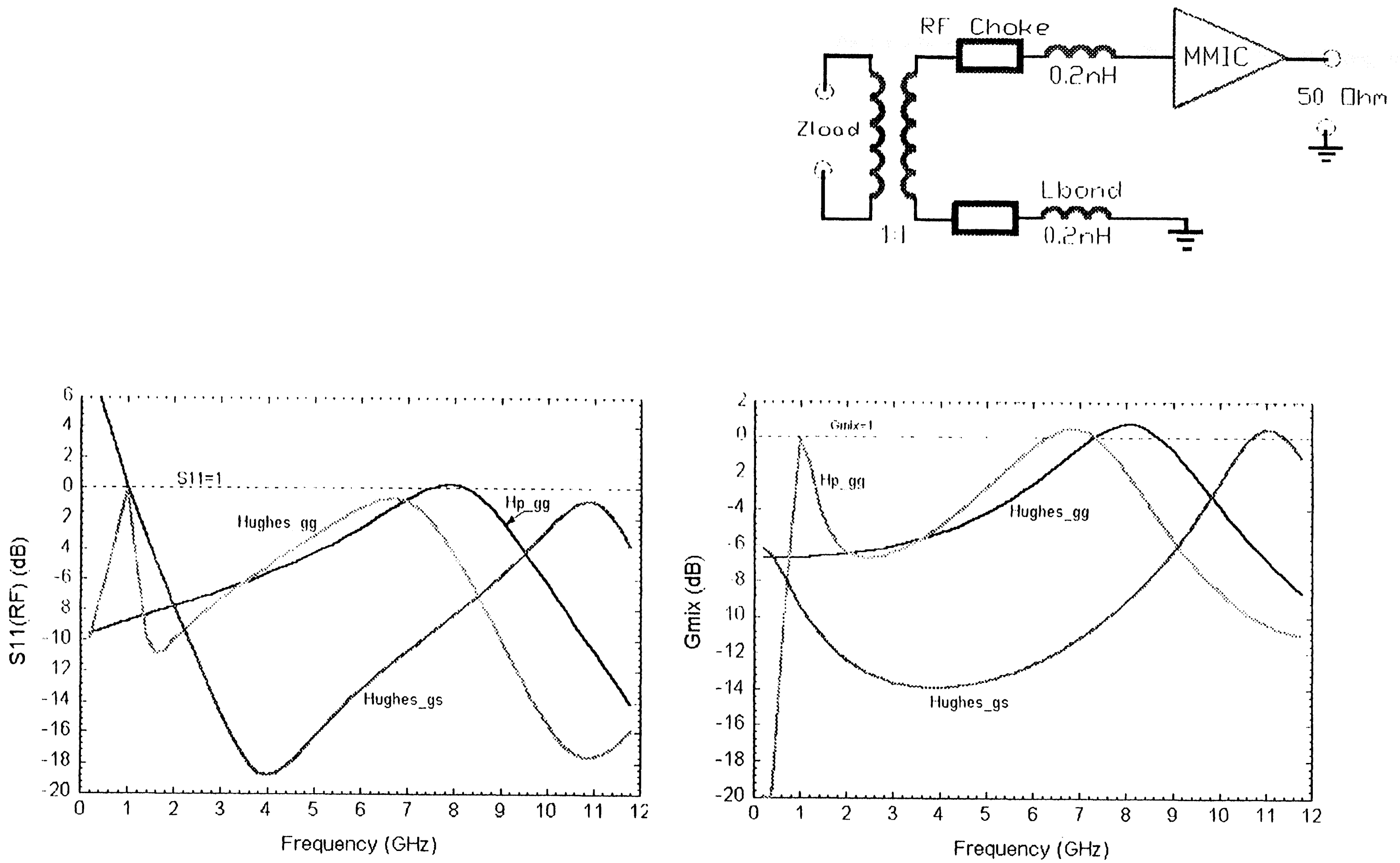


Fig. 11 Supermix computer simulations with the InP MMIC's connected to mixer IF port via a RF choke. That the IF load impedance presented by the MMIC to the mixer is far from ideal, is evident by the mixer gain and RF reflection, S11(RF). To take full advantage of the MMIC's very large IF bandwidth, the mixer will have to be redesigned so that the MMIC amplifier/RF choke combination provides an adequate termination to the mixer IF port (less capacitive RF matching network).