

Cryogenic Low Noise Balanced I.F. Amplifiers

A design review

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Abstract

Low Noise cryogenic balanced amplifiers are of interest to the SIS community in that these amplifiers offer an octave of bandwidth with very good input return loss properties (low VSWR). The purpose of this memo is to give a comparative performance review of GaAs HEMT based balanced I.F. amplifiers. In the computer simulations the loss in the Lange Coupler and circuit components has been taken into account. All simulations are at a 12K ambient temperature, unless otherwise stated. The Merian Pospieszalski (NRAO) noise model has been used and I assume a device gate temperature(T_g) equal to $T_{ambient}$, and drain temperature of 500K.

I. Introduction

The input of a balanced amplifier utilizes a 90 degree hybrid coupler such as the one shown in Figure 1.

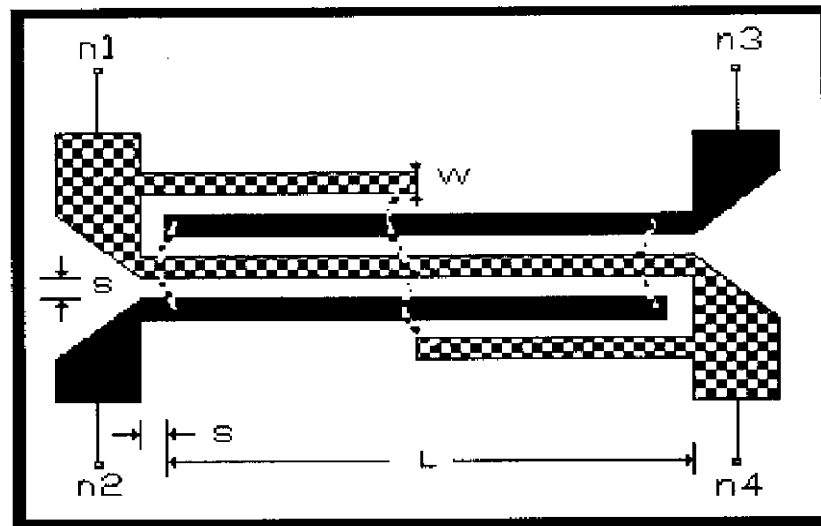
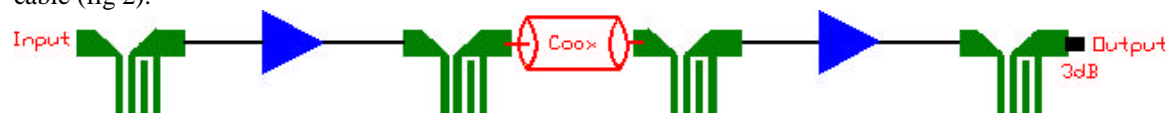


Fig.1 Lange Coupler. Power at input 1 is divided equally in ports 2 and 4 with a 90 degree phase shift.

In 1991 we developed a 1-2 GHz low noise balanced cryogenic amplifier. This design used a packaged Fujitsu HEMT. The amplifier utilizes two stages that are interconnected via a small piece of 50 Ohm Coax cable (fig 2).



About 15 of these amplifiers have been constructed over the years, and consequently the amplifier's noise and gain properties are well known. I have used this amplifier as a **benchmark** for our design.

As a very quick review.

The noise in HEMT devices can be modeled in a way described by Merian Pospieszalski (NRAO)¹. In this model the drain and gates have been assigned temperatures. The gate temperature (T_g) is typically equal to the device physical temperature. The drain (T_d) temperature is on the order of 500K at an ambient device temperature of 12 Kelvin. To be conservative, I have assumed a drain temperature of 500K throughout this paper.

The procedure for extracting the cold S-parameters and noise parameters is as follows: Obtain the room temperature S-parameter and noise parameter values. Fit a 15-element noise model shown in figure 3 to the room temperature parameters to extract the values of the individual components.

Schematic

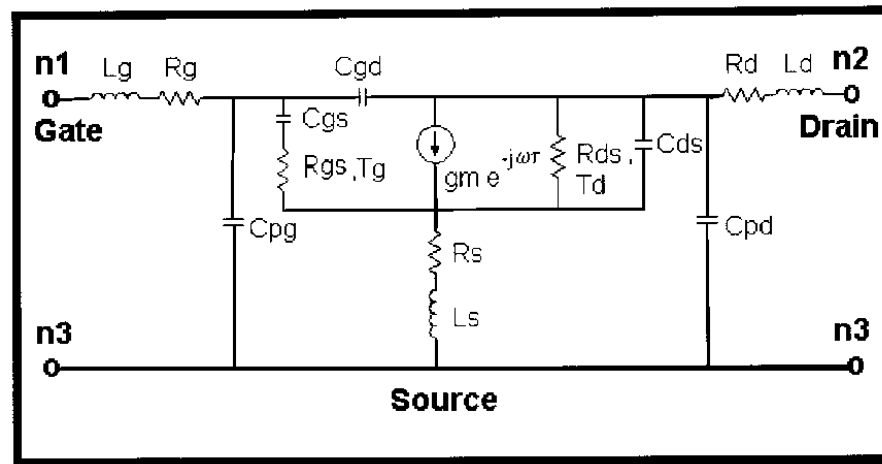
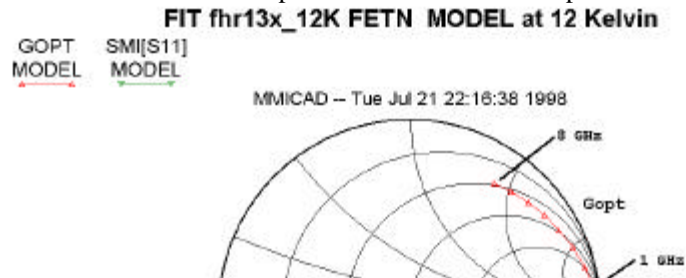


Fig. 3 Merian Pospieszalski Noise model. Note Tdrain (T_d) and Tgate (T_g).

To calculate the cold S- and noise parameters, we make several assumptions.

- 1) As the device is cooled the transconductance (G_m) increases, however this can be compensated by lowering the drain current. G_m is therefore assumed to be the same cold as it is at room temperature.
- 2) Since the physical chip does not change upon cooling, there is no reason for the element values to change.
- 3) T_d is assumed 500K and $T_g = T_{ambient}$

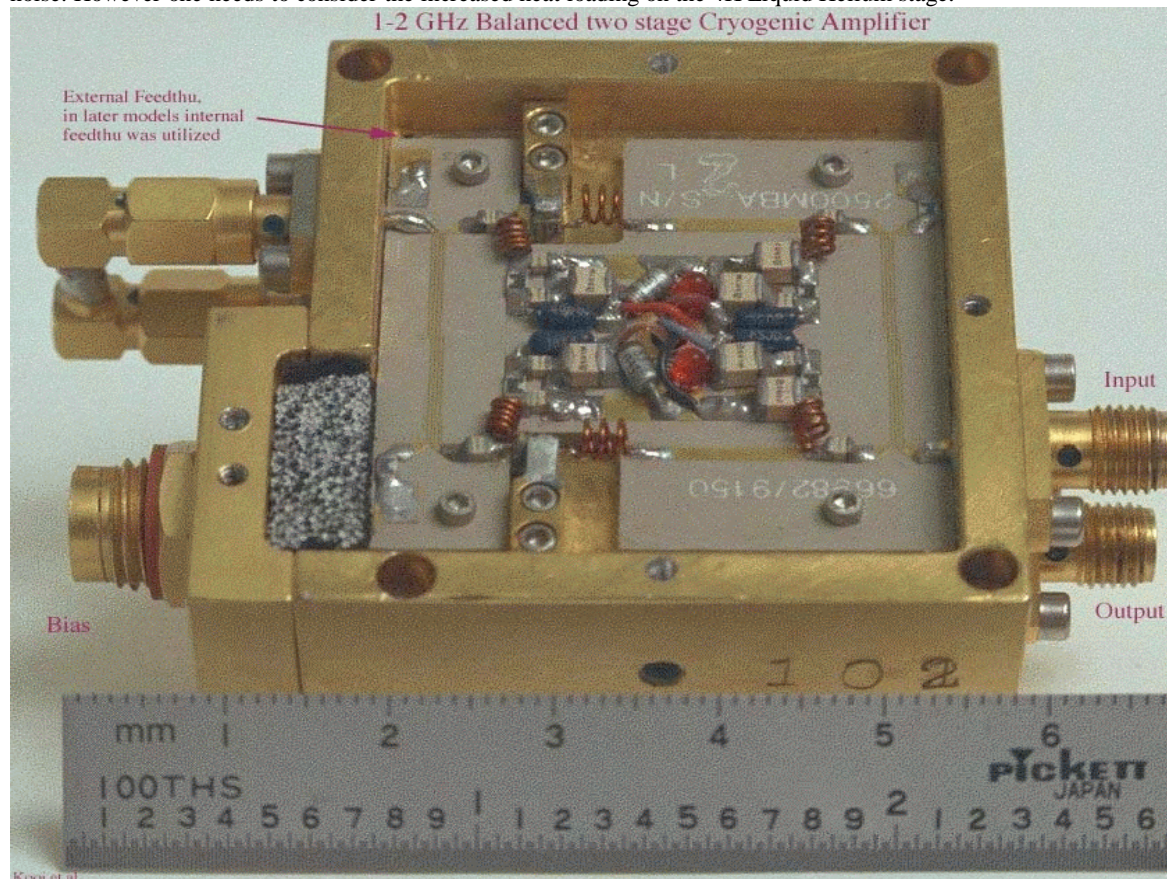
With this information we are able to compute the cold S- and noise parameters.



From Γ_{opt} we can calculate the optimum noise input impedance. Unfortunately, as a function of frequency, the input matching network impedance rotates in opposite direction (clockwise in Fig. 4) while Γ_{opt} rotates counter clock wise. In practice this means that a very good match (T_{min}) can be achieved at only one frequency. For broader bandwidth applications a compromise between noise and amplifier bandwidth will have to be found. This is precisely the reason that the noise performance for broad band amplifiers is always a few degrees above the minimum achievable noise temperature (T_{min}). Please note that even though the noise in both HEMT devices is completely uncorrelated, half the noise from each port will add so that the minimum achievable noise temperature for a balanced amplifier is T_{min} .

II. 1-2 GHz LNA Performance, 1991 design with packaged HEMT's

A GaAs HEMT typically requires a bias of 2V, 5mA, so that the total dissipated power requirement per stage is on the order of 20mW, or 40mW for the complete amplifier. The 1-2 GHz 1991 design has both stages integrated into one housing. This makes for a compact design, however it may not be the most desirable configuration for the higher IF frequency amplifiers. One alternative is to place the first stage on the 4 Kelvin stage, close to the mixer, while the second stage is placed on the 12 Kelvin stage. This may be interesting in terms of minimizing pass-band ripples and noise. However one needs to consider the increased heat loading on the 4K Liquid Helium stage.



LNA 1-2 GHz, file: benson.ckt

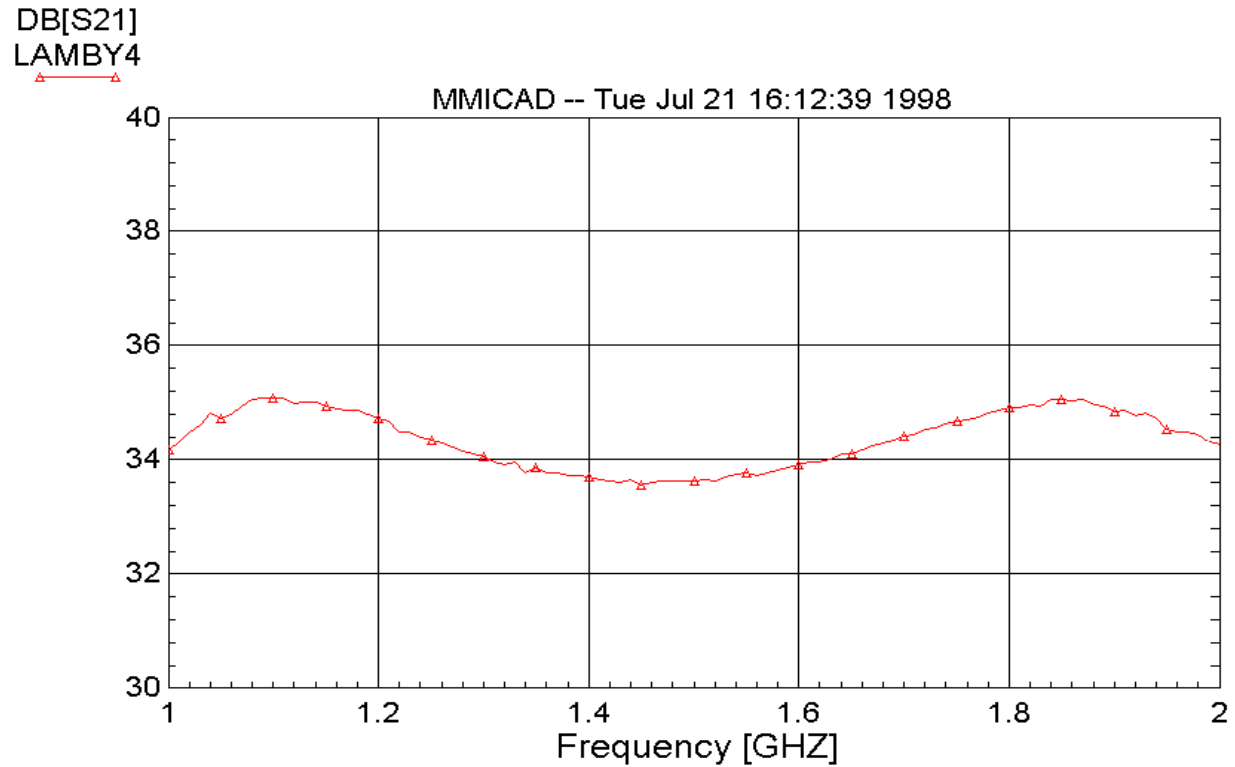
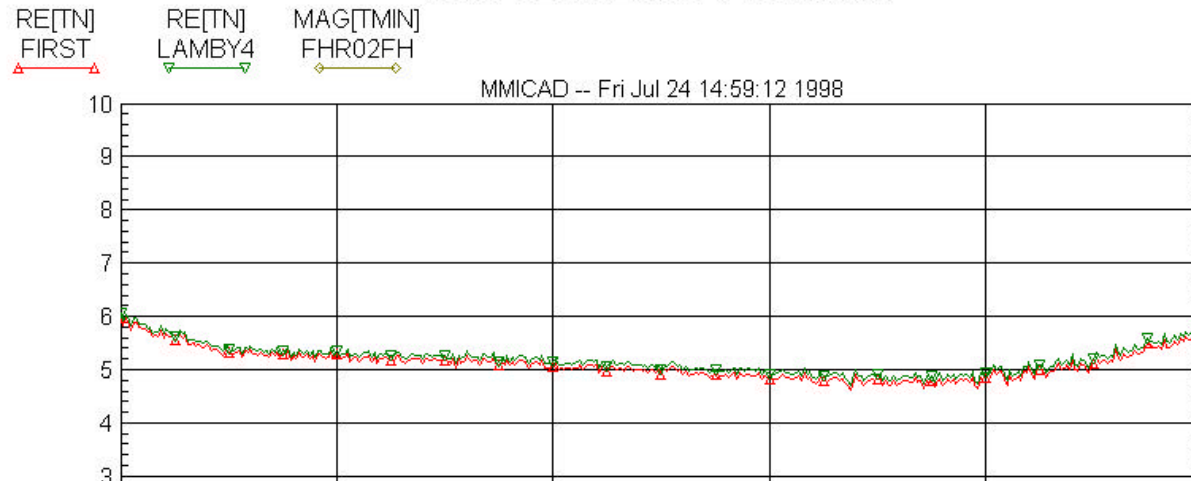


Fig. 6 Predicted Gain Response(dB) of the 1-2 GHz packaged FHR02FH balanced amplifier. Measured gain is 35 +/- 1.5 dB.

LNA 1-2 GHz, file: benson.ckt



The measured input reflection coefficient of the 1991 low noise balanced amplifier is on the order of -14 to -20dB. However the computer simulations predict an input return loss which is at least 10dB better. In terms of actual reflected power this difference between measurement is only a few percent and is caused in large part by an phase-imbalance between the HEMT and the matching network stages.

LNA 1-2 GHz, file: benson.ckt

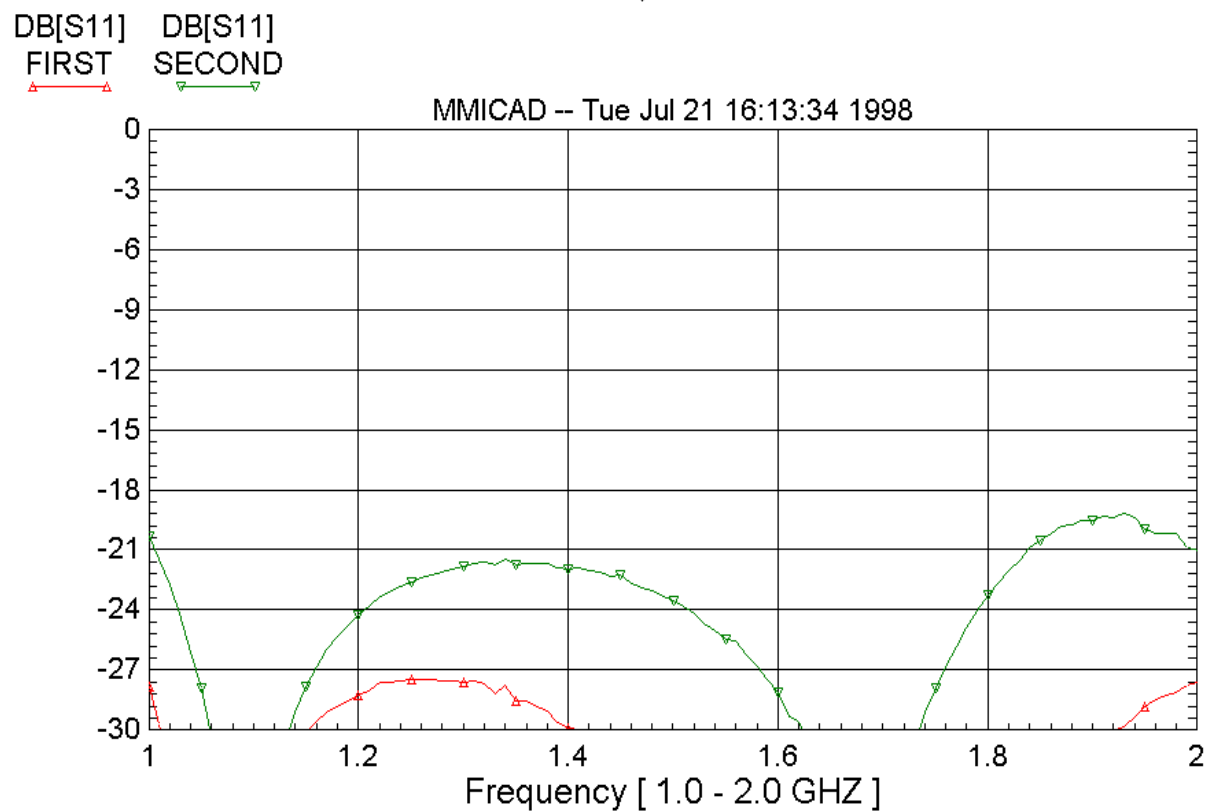


Fig. 8 Input reflection loss (dB) for the First and Second amplifier stage.

III. 1-2 GHz LNA Performance with the FHR02X chip (Unpackaged)

Having convinced myself of the circuit model's accuracy, I re-ran the model with a FHR02X chip from Fujitsu (12K noise and S-parameters). The RF matching networks have been re-optimized for the FHR02X chip. Figures 9 and 10 depict the gain and noise performance.

LNA 1-2 GHz, file: first_fhr02x_d4.ckt

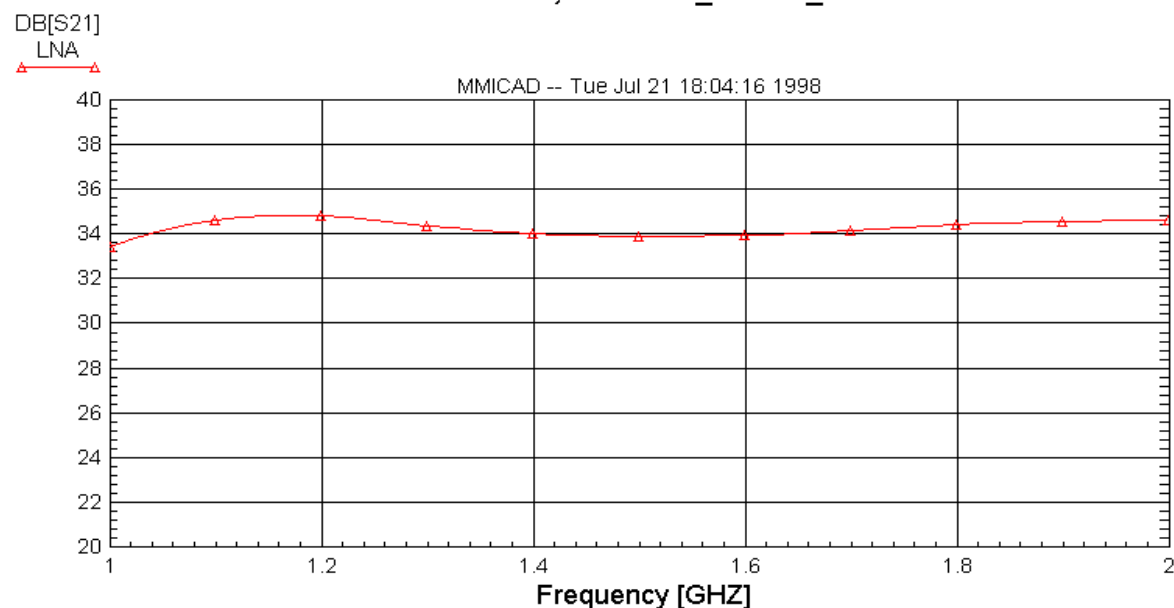


Fig. 9 Predicted Gain Response (dB) of a 1-2 GHz un-packaged FHR02x balanced amplifier

The noise is plotted below. Note that the noise performance has improved by about 1 Kelvin. The gain curve is also considerably more flattened as well. These improvements are due to the smaller θ_{opt} and S-parameter variations (Fig. 3.4) as compared to the packaged device. The trade off is that the amplifier is more difficult to assemble.

LNA 1-2 GHz, file: first_fhr02x_e1.ckt

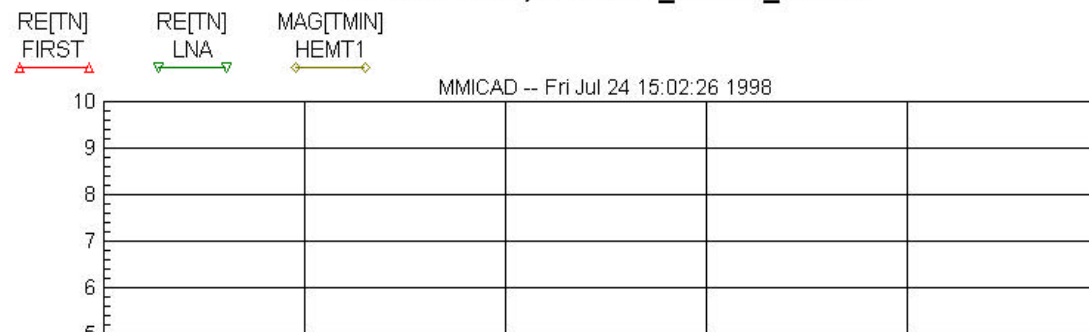


Fig. 10 Predicted Noise response. The bottom trace is the first stage noise contribution. T_{min} is plotted for reference.

IV. 2-4 GHz Balanced LNA Performance with FHR02X Chip HEMT Design

The next step is to design an amplifier for the 2-4 GHz frequency band. The optimum generator impedance (Z_{opt}) and S-parameters are such that a good power and noise match is readily achievable. A 0.35dB loss in the Lange coupler is assumed at this frequency (will have to be measured to be more precise). The Input reflection coefficient is very similar to the 1-2 GHz low noise amplifier, about 3% or better. The FHX13X chip seems to be superior in performance over the FHR02X, though both have the same gate width (240 μ m). This is primarily because the FHX13X has a larger transconductance, 50mS as opposed to 30mS.

LNA 2-4 GHz, file: lna24_all_e1.ckt

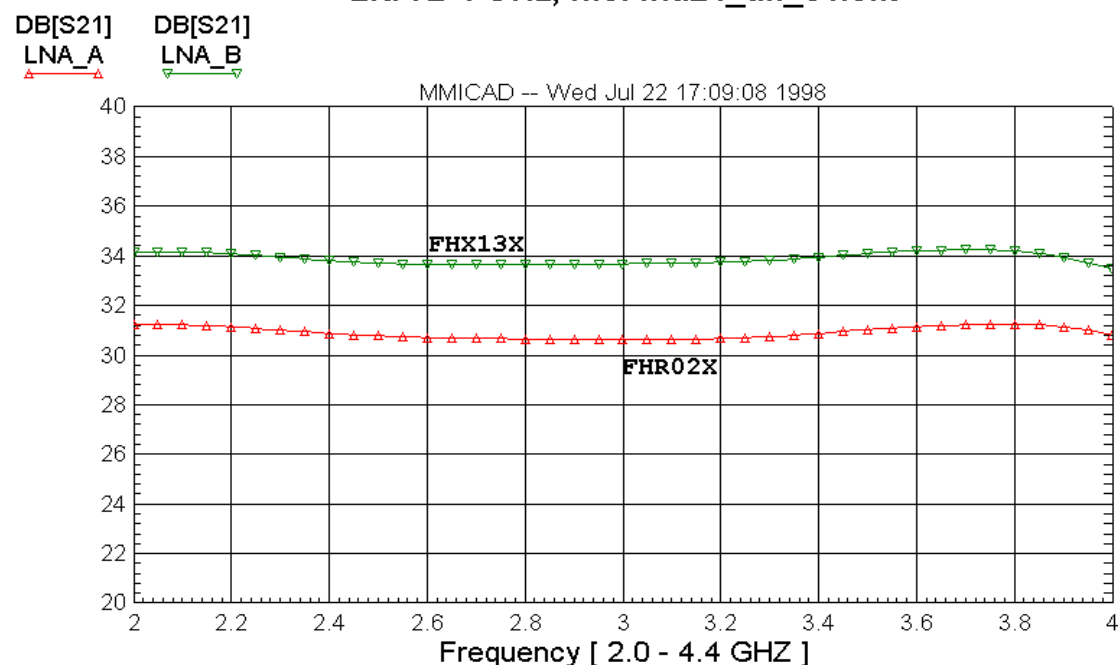


Fig. 11 Predicted Gain Response(dB) for two different Fujitsu HEMT's. T_{ambient}=12K

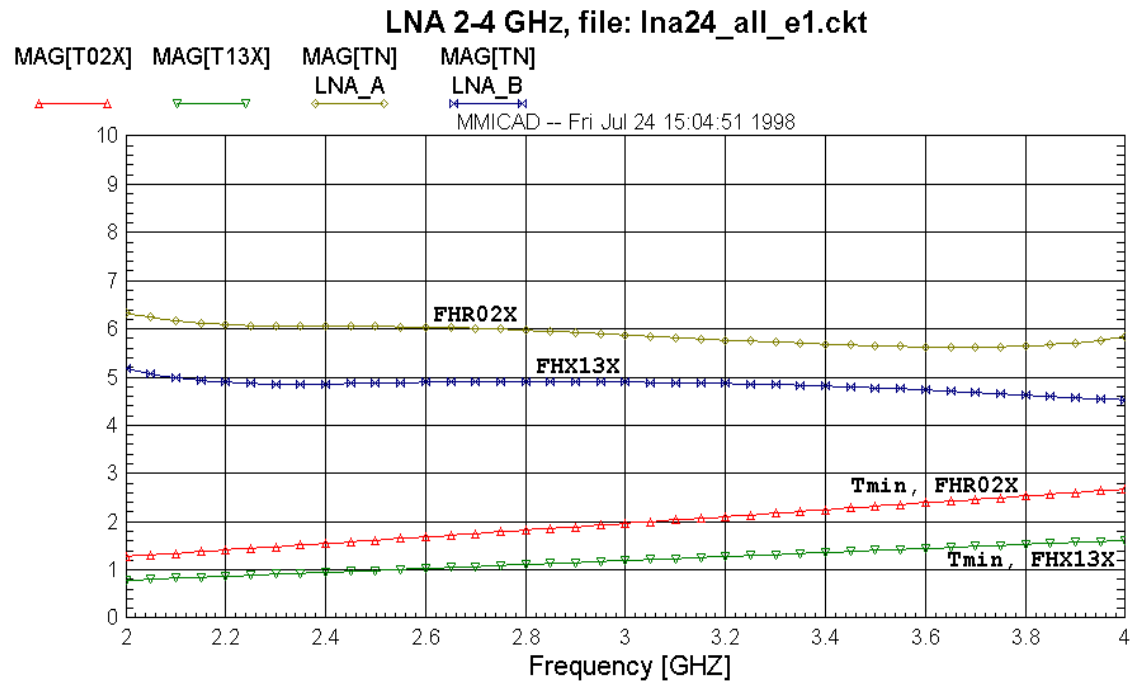


Fig. 12 Predicted 2-4 GHz Noise response for two different HEMT devices. T_{min} is plotted as a reference.

V. 3-6 GHz Balanced Low Noise Amplifier Performance

Four Hemt devices have been under consideration for this frequency Range

- a) Fujitsu FHR02X (gate width=240 μm)
- b) Fujitsu FHX13X (gate width=240 μm)
- c) Kukje KH1032-C00 (Korean, 180μm gate width)
- d) MGF4319G, Mitsubishi packaged

The 300 Kelvin model for the Kukje Hemt was provided by Sandy Weinreb's group at the University of Massachusetts². The FHR02X data came from a NRAO 1991 internal report³ while the FHX13X and MGF4319G noise and S-parameters were obtained from the manufacturer's data sheets. For a final circuit design, the device parameters will have to be measured, preferably in situ.

The Fujitsu FHX13X noise performance is very similar to the modeled Kukje HEMT performance, however the transconductance of the Kukje Hemt is considerably higher (Figure 13). Both devices are considerably better than the FHR02X and MGF4319G HEMT's. Because the MGF4319G is a packaged device it is much more difficult to obtain a good match over an octave of bandwidth. The amplifier gain curves are show in figure 13. The FHX13X is essentially an improved version of the FHR02X chip (larger G_m). Note that a 3dB attenuator has been included at the output of the amplifier.

LNA 3-6 GHz, file: Ina36_all_e1.ckt

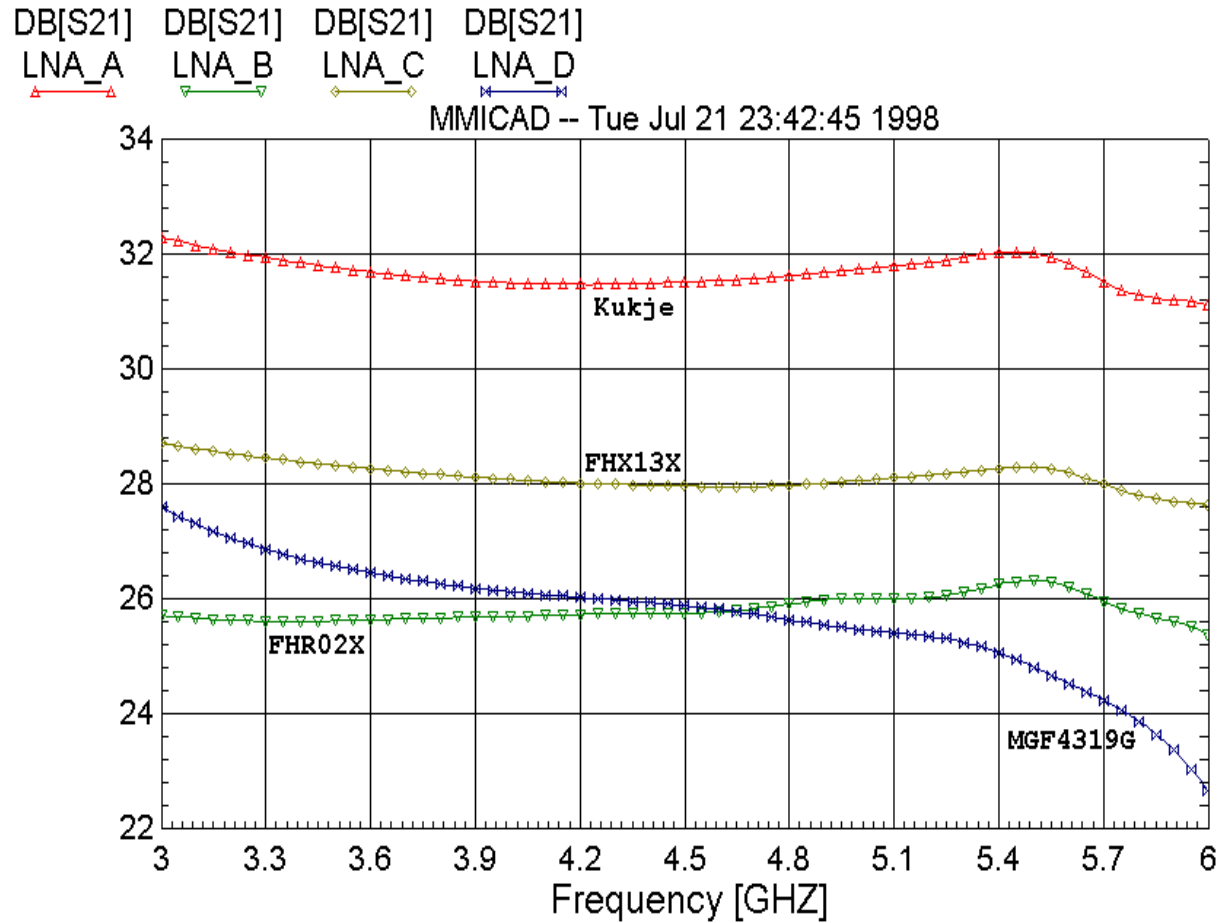


Fig. 13. Gain curves for four different HEMT devices. Circuits were optimized. $T_{ambient}=12K$. Figure 14 shows the optimized noise performance of a 3-6 GHz low noise amplifier with four different HEMT devices. To take radiation, Ohmic and substrate loss into account, a 0.4dB attenuator (at a physical temperature = $T_{ambient}$) has been added at each Lange coupler. The 0.4 dB is an educated guess, and the actual loss should be measured to improve the accuracy of the model.

LNA 3-6 GHz, file: lna36_all_e1.ckt

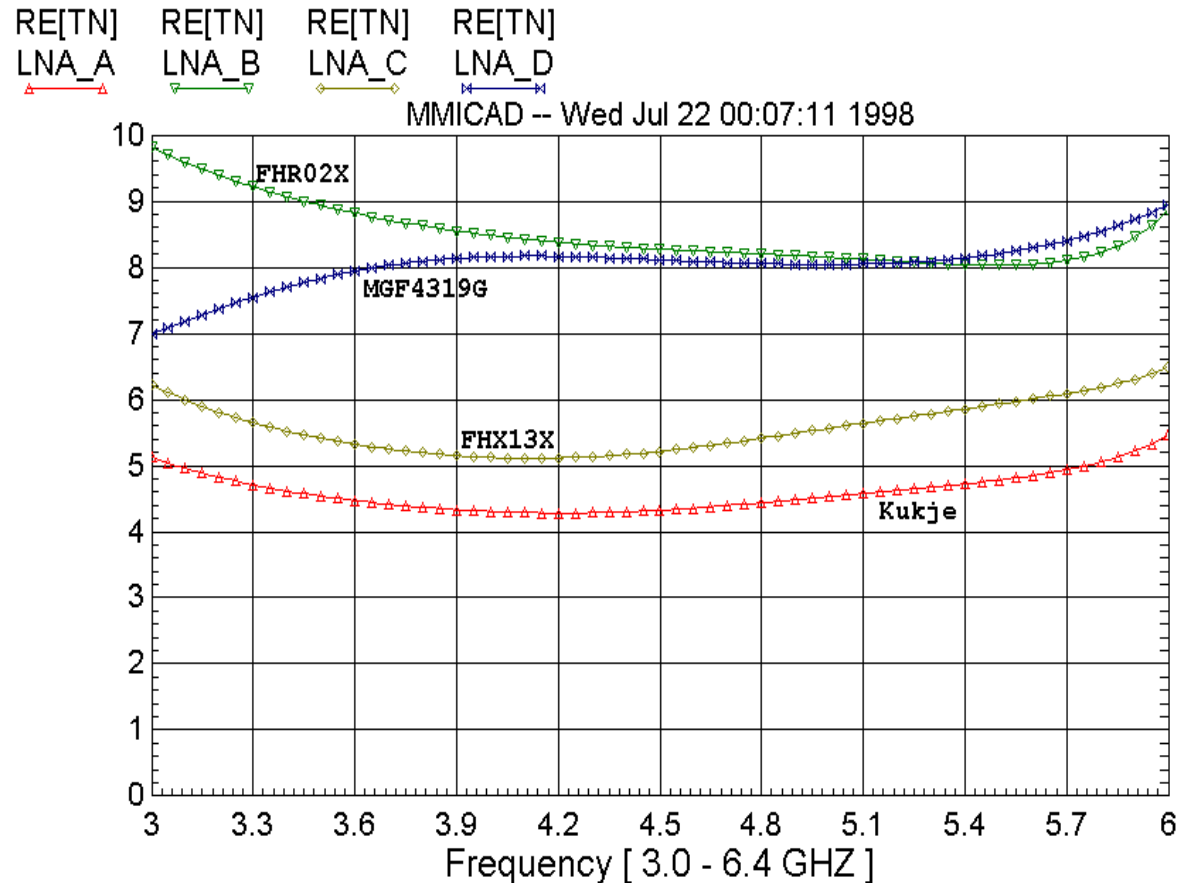


Fig. 14 Noise performance of a 3-6 GHz balanced LNA with four different HEMT's. $T_{\text{ambient}}=12\text{K}$, $T_{\text{drain}}=500\text{K}$, $T_{\text{gate}}=T_{\text{ambient}}$

To better understand the optimum performance of each device I have plotted T_{min} in Figure 15. The reason that the amplifier's noise performance with the FHR02X chip is considerably worse than with the FHX13X chip is that the transconductance is lower (same gate width). The Kukje Hemt has a smaller gate width than the FHR13X and therefore an higher transconductance. A smaller gate width also reduces the device parasitics, and thus allows for a better noise match over a large frequency range. Of course the increased transconductance also means an increased potential for out of band oscillations.

LNA 3-6 GHz, file: lna36_all_e1.ckt

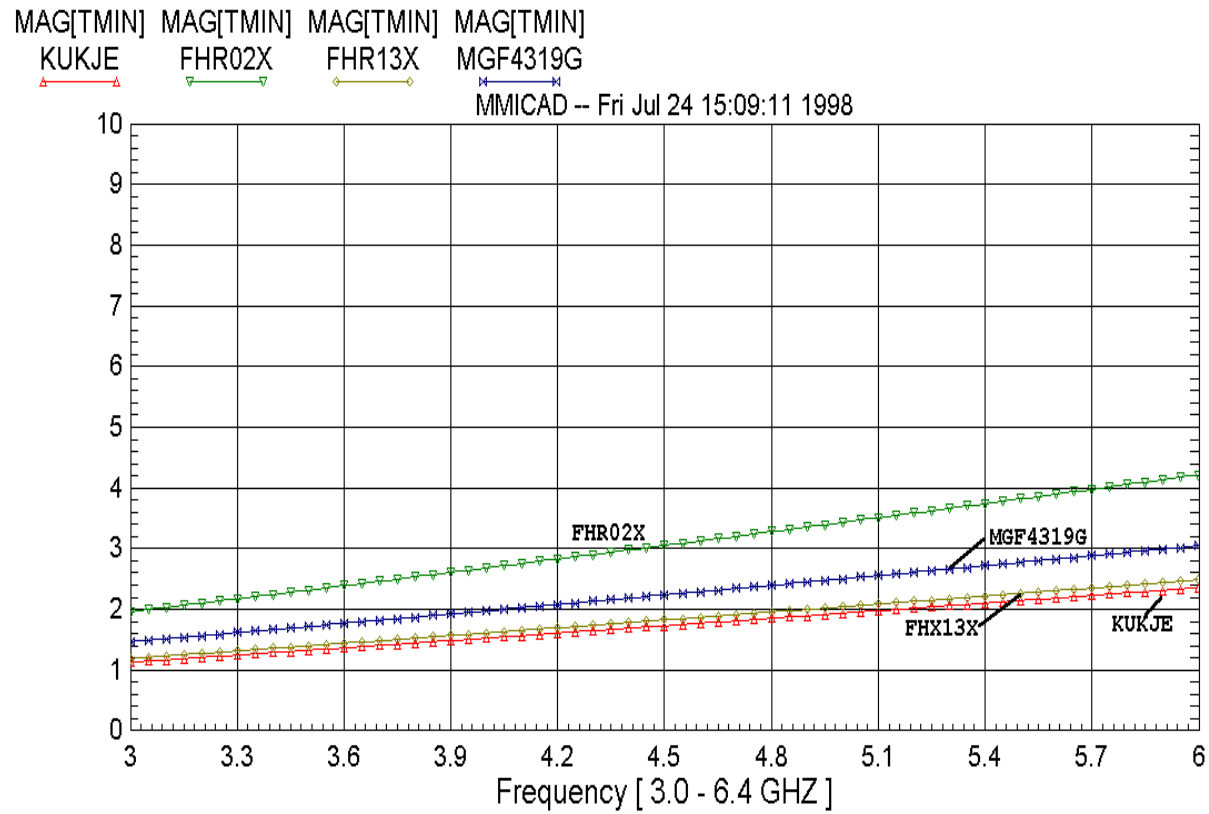


Fig. 15 Minimum noise temperature (T_{min}) of the four different HEMT's. $T_d=500K$, $T_g=12K$, $T_{ambient}=12K$

VI. 4-8 GHz Balanced Low Noise Amplifier Performance

Two Hemt devices have been under consideration for this frequency range

- Fujitsu FHX13X, 240 μm gate width
- Kukje (Korean KH1032-C00), 180 μm gate width

As mentioned, the 300 Kelvin model for the Kukje Hemt was provided by Sandy Weinreb's group at the University of Massachusetts². The FHX13X noise and S-parameters were obtained from the manufacturer's data sheets. For a final circuit design, they will have to be measured, preferably in situ. The Fujitsu FHX13X noise performance is very similar to the modeled Kukje HEMT, however the transconductance is considerably higher (Figure 16).

LNA 4-8 GHz, file: Ina48_all_e1.ckt

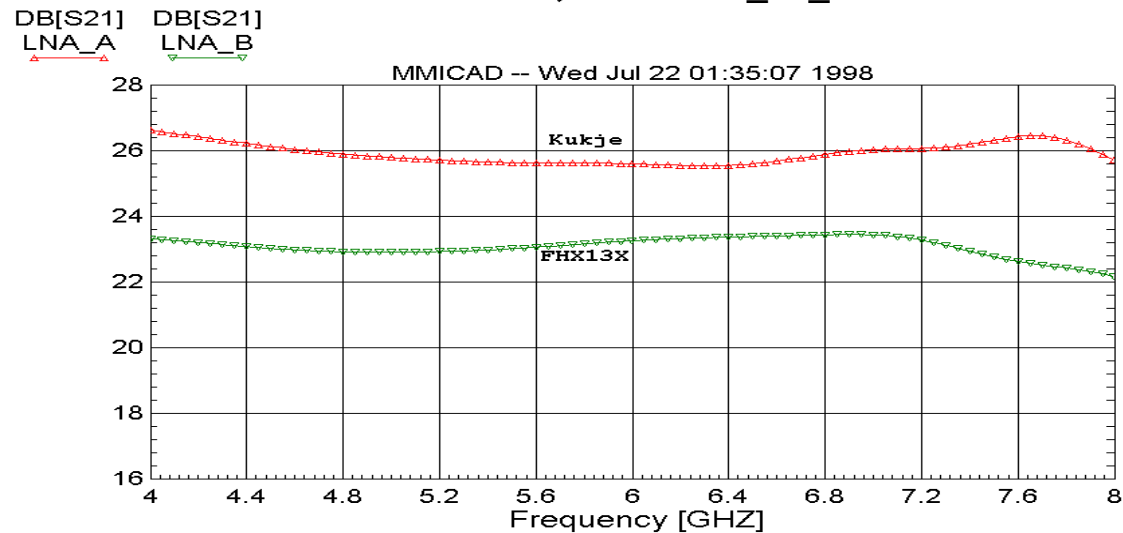


Fig. 16 LNA gain (dB) for two different HEMT devices. A 3dB attenuator on the output is included.

The Lange coupler loss is estimated to be about 0.45 dB (will have to be verified). The amplifiers simulated noise performance is plotted in figure 17 below.

LNA 4-8 GHz, file: Ina48_all_e1.ckt

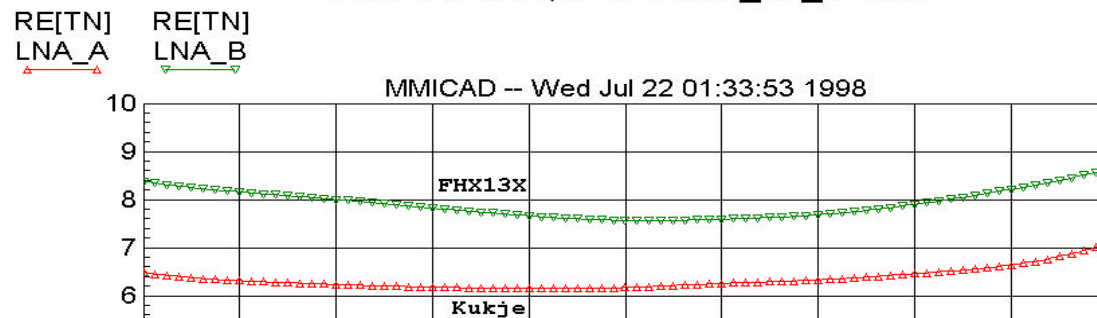


Fig. 17 Noise performance of a 4-8 GHz balanced LNA with two different HEMT devices. Tambient=12K. Finally, the minimum noise performance of the Kukje and Fujitsu FHX13X, FHR02X HEMT devices are shown in figure 18.

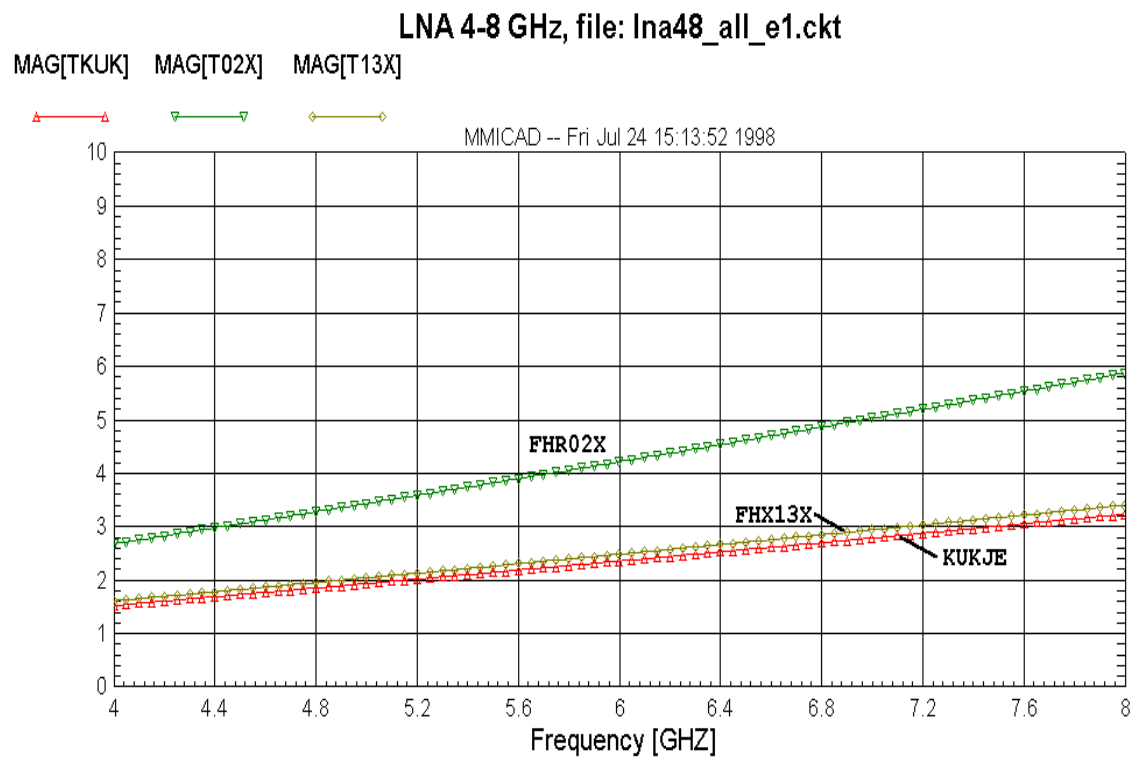


Fig. 18 Minimum noise temperature (Tmin) of the Kukje and FHX13X HEMT's. Td=500K, Tg=12K, Tambient=12K

VII. Discussion

From the above discussion it is evident that the noise and gain performance is critically dependent on the HEMT performance. To refine the amplifier circuit models it is recommended that:

- 1) Carefully measure the Kukje and FHR13X chips at 300K (LN₂??) in a very similar environment as the final amplifier layout.
- 2) Measure the board dielectric constant at Cryogenic temperatures.
- 3) Study the Lange coupler in some detail, measure the loss and input reflection coefficient, understand the effect of using an the SMA/K connector.
- 4) Look into the possibility of a MIC Lange Coupler design.
- 5) Carefully characterize some of the needed components, such as wire-bonds, and spiral inductors.
- 6) Possibly measure some InP HEMT devices. Since this is quite difficult proposition, it would only be viable if enough identical devices with proper gate width are available.
- 7) Consider the tradeoffs of a modular design (Figure 2) verses a more integrated design as shown below in Figure 19. Note that the amplifier will be slightly longer in length as compared to a modular design.

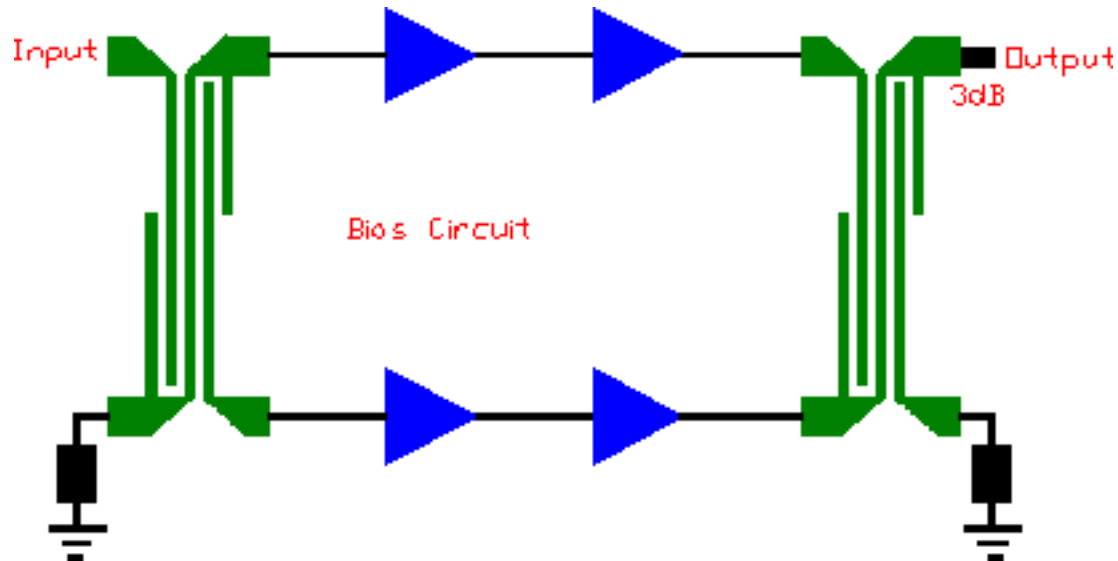


Fig. 19 Balanced LNA configuration (Integrated Design). The first stage is used for noise optimization while the second stage is used to equalize the gain across the IF band. The termination impedance is 50 ? ??
?

The advantages of the integrated design is that there are only two Lange Couplers and that there is no interconnect to give problems. The disadvantage is that is more difficult to test that the hybrid (Figure 2) design, and that the stages cannot be physically separated.

619 Lederie GRC, University of Massachusetts, Amherst, MA 01035

- 3) J.D. Gallego and M.W. Pospieszalski, "Design and performance of a cryogenically-coolable ultra low noise, L-band amplifier", *NRAO internal report # 286, March 23, 1990.*

VIII. Addendum

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As was mentioned on page 5, the measured input reflection coefficient of the 1991 low noise balanced amplifier is about 10 dB worse than the computer simulations would predict. This is caused in large part by a phase-imbalance between the individual HEMT's and the matching networks. The net-effect of the phase-imbalance is significant and is demonstrated on the next few pages. Note that all these designs are preliminary. In figure 20 the input reflection loss of a perfectly balanced 3-6 GHz amplifier is plotted against a $\pm 20\%$ gate inductor variation at one of the chips. This may be considered a worst case scenario.

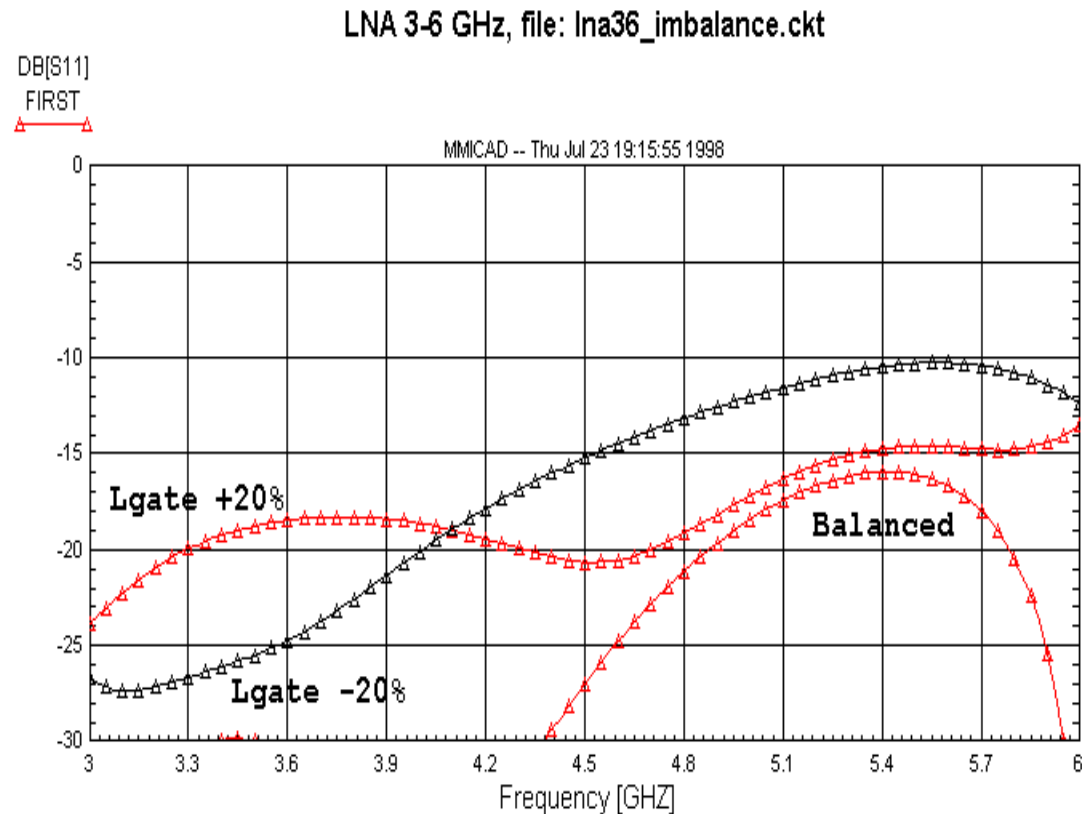


Fig. 20 Degradation of the input return loss caused by a phase-imbalance in one of the input matching networks.

LNA 3-6 GHz, file: lna36_imbalance.ckt

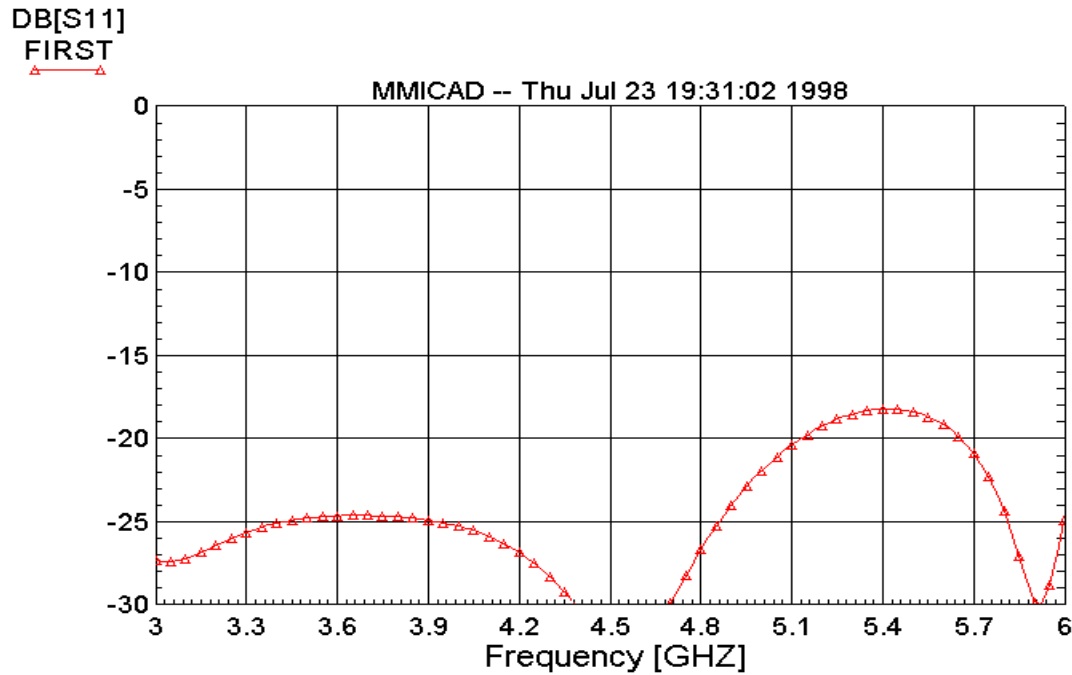
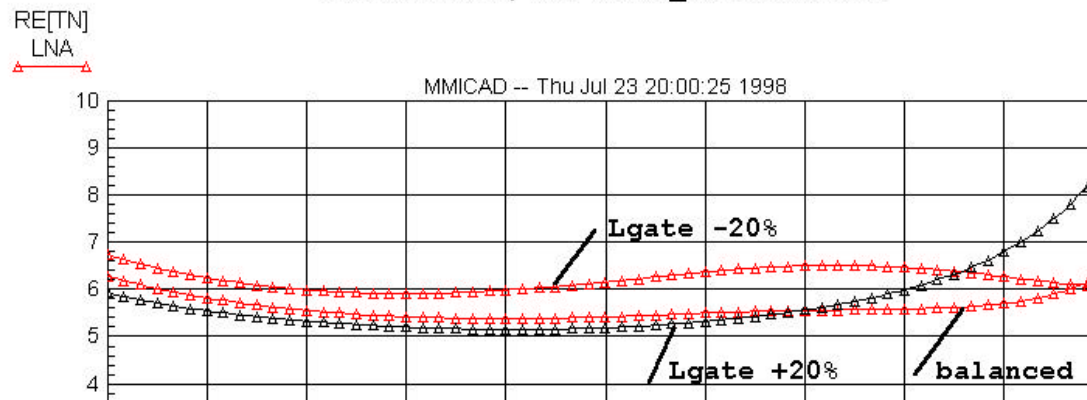


Fig. 21 First stage input reflection (dB) of a 3-6 GHz low noise balanced amplifier with one of the FHX13X HEMT's interchanged with a FHR02X device.

In practice these amplifiers are often separated by a piece of 50 Ω coaxial cable from the actual mixer. The coaxial length is typically 12 cm, or about 1000 degrees at 4.5 GHz. In Figure 22 the effect of driving a phase imbalanced amplifier from a perfectly matched 50 Ohm source (ideal mixer) via a 12.5 cm length of coaxial transmission line is computed. Note that the amplifier's noise and gain are now referenced to the output port of the mixer. The coaxial line is presumed lossless.

LNA 3-6 GHz, file: lna36_imbalance.ckt



The gain variation is rather minimal, as is seen in figure 23 below.

LNA 3-6 GHz, file: lna36_imbalance.ckt

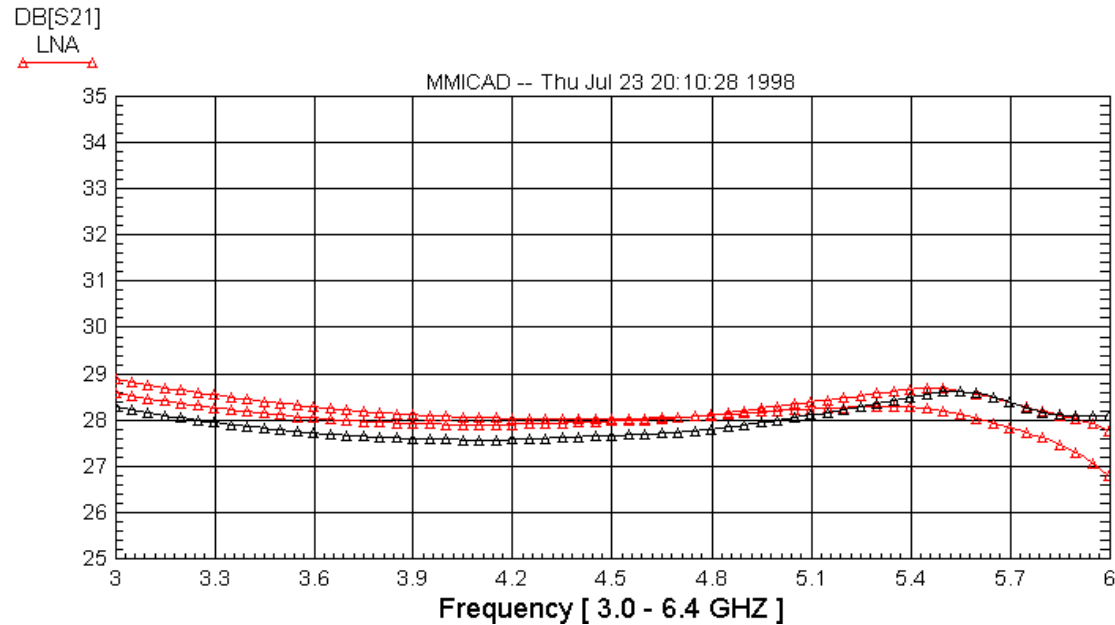
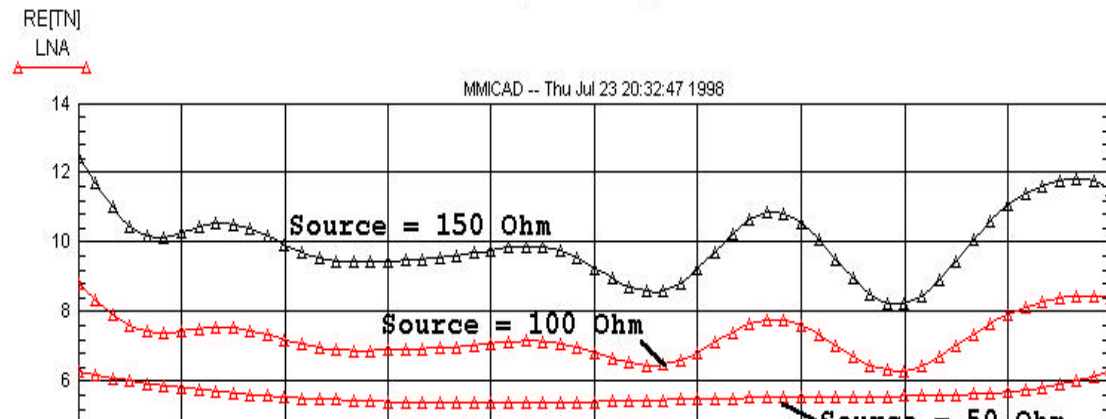


Fig. 23 Amplifier's gain (dB) as seen from the mixer. The LNA is driven via a 12cm long 50 Ohm coax cable. The source impedance of the mixer is 50 ohm, FHX13X HEMT's. Gate inductance on one of the HEMT's is changed.

The real problems start when the mixer is not perfectly matched to 50 Ω . In this case the power coupling to the amplifier is reduced, passband ripples introduced, and the amplifier's effective noise temperature increased. The number of pass-band ripples is simply the coaxial electrical length divided by $\lambda/4$ radians. Reducing the electrical length to $\lambda/4$ radian will result in one ripple similar in magnitude (Fig 26, 27).

LNA 3-6 GHz, file: lna36_imbalance.ckt



The gain variation is shown in Figure 25. Note how power is lost in the mismatch (Gmix increases).

LNA 3-6 GHz, file: lna36_imbalance.ckt

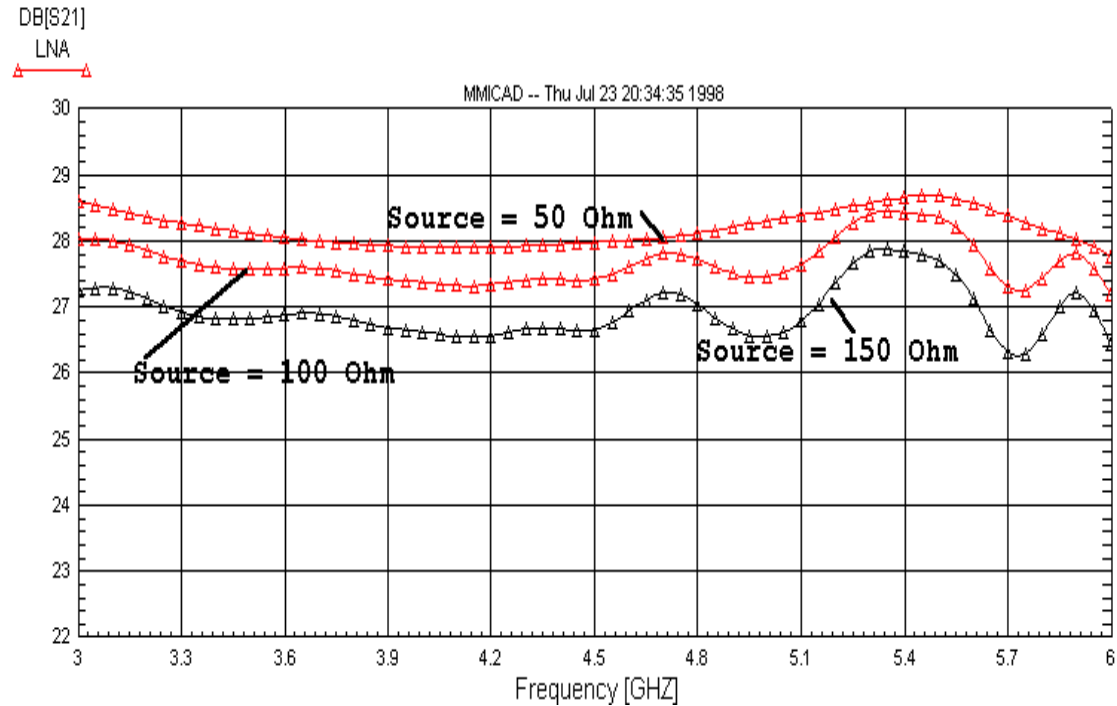
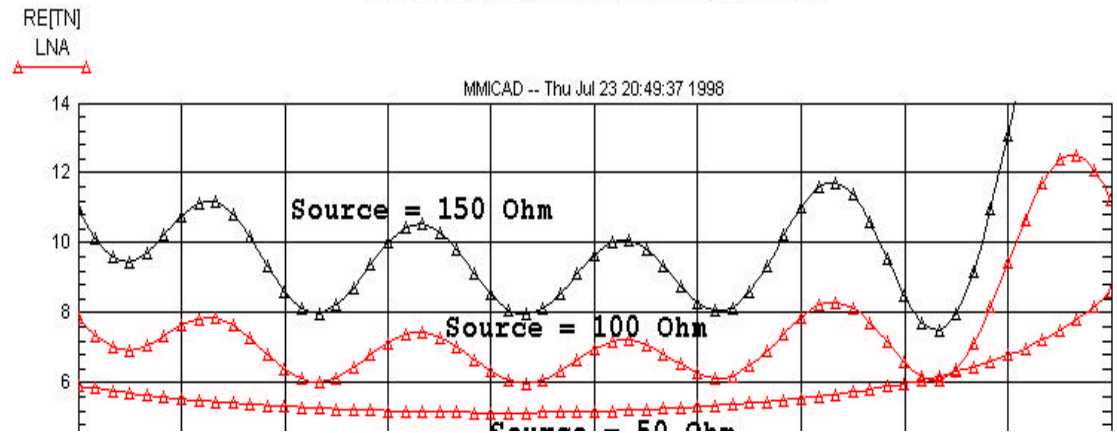


Fig. 25 Amplifier's gain (dB), as seen from the mixer. The LNA is driven via a 12cm long 50 Ohm coax cable. The source impedance of the mixer is varied. FHX13X HEMT's. Amplifier is balanced. (Compare with Figure 27).

In a real device there will be some amplifier phase-imbalance and so the situation will be worse yet. In Figure 26 and 27 the gate inductance of one of the HEMT matching networks is increased by 20%, identical FHR13X HEMT's.

LNA 3-6 GHz, file: lna36_imbalance.ckt



LNA 3-6 GHz, file: lna36_imbalance.ckt

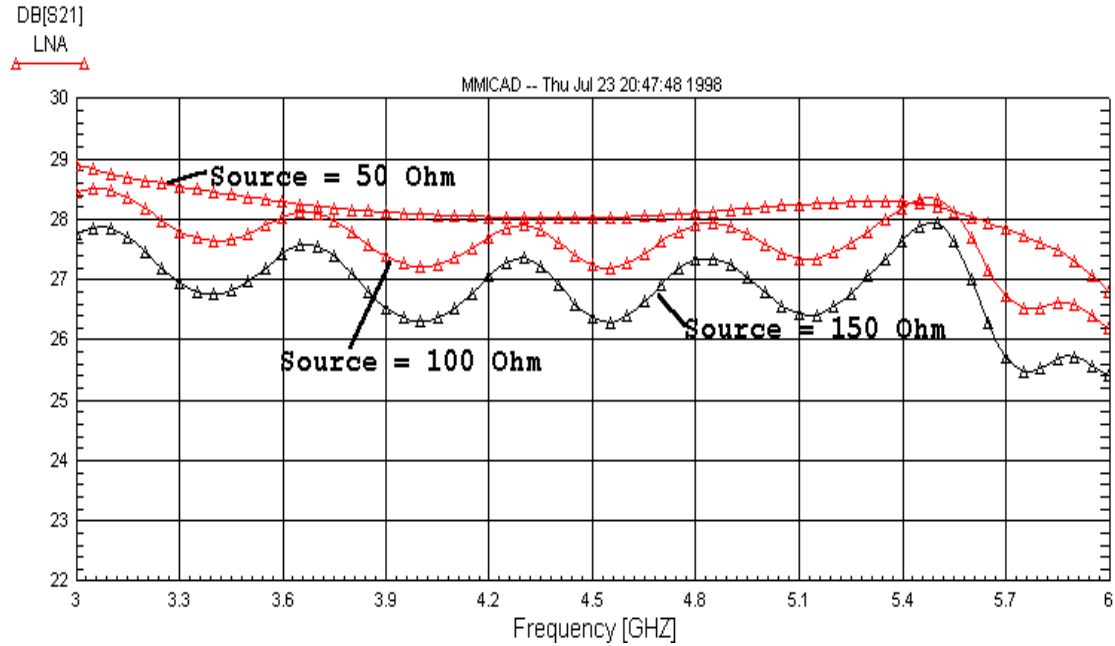
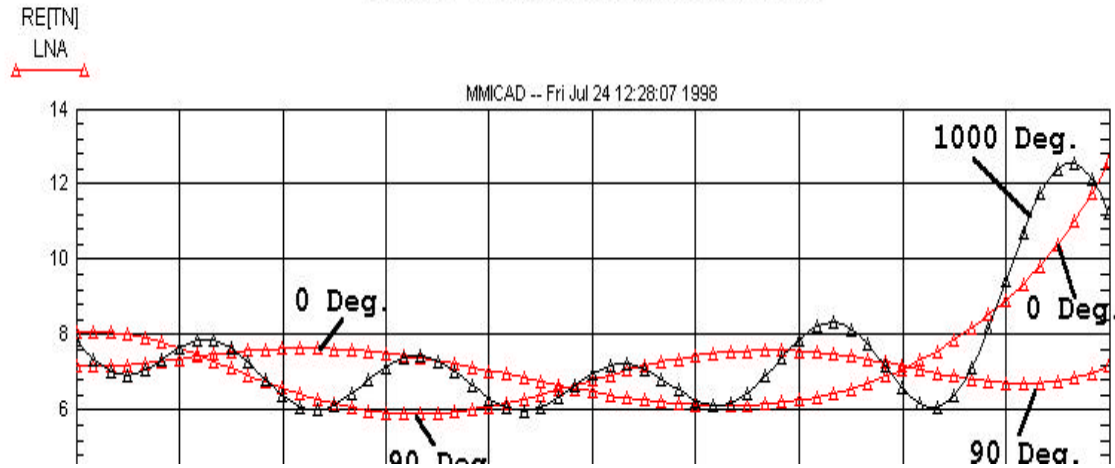


Fig. 27 Amplifier's gain (dB), as seen from the mixer. The LNA is driven via a 12cm long 50 Ohm coax cable. The source impedance of the mixer is varied. FHX13X HEMT's. Amplifier is imbalanced, by changing one of the gate inductance's. (See also Figure 28).

Lastly we show the effect of decreasing the length of coaxial line from 1000 degrees to 0 degrees given a 100 Ohm mixer source impedance. The amplifier is phase-imbalanced. The optimal coax length is 90 degrees, because the noise wave coming out of the LNA input port is canceled upon return.

LNA 3-6 GHz, file: lna36_imbalance.ckt



LNA 3-6 GHz, file: lna36_imbalance.ckt

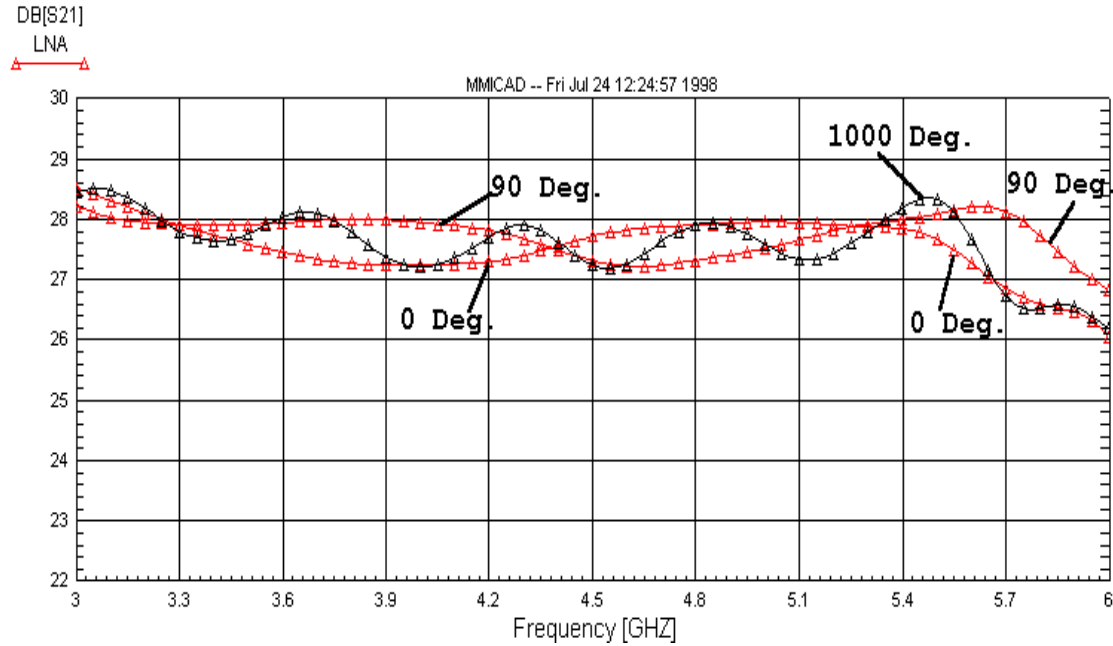
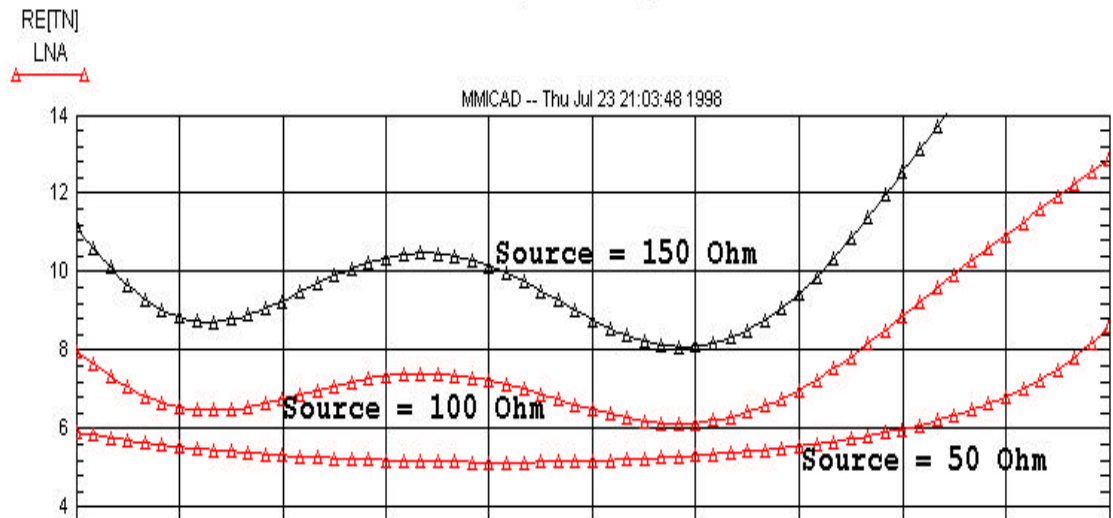


Fig. 29 Amplifier's gain (dB) as seen from the mixer. The mixer output impedance is 100 Ohm. The optimum Coaxial length is 90 degrees. FHX13X HEMT's. Amplifier is imbalanced by changing one of the gate inductance's.

If the coax length is increased to say 180 degrees (22mm at 4.5 GHz), then the passband performance will suffer severely from any mismatch between the mixer and low noise amplifier. This is demonstrated in figures 30 and 31.

LNA 3-6 GHz, file: lna36_imbalance.ckt



LNA 3-6 GHz, file: lna36_imbalance.ckt

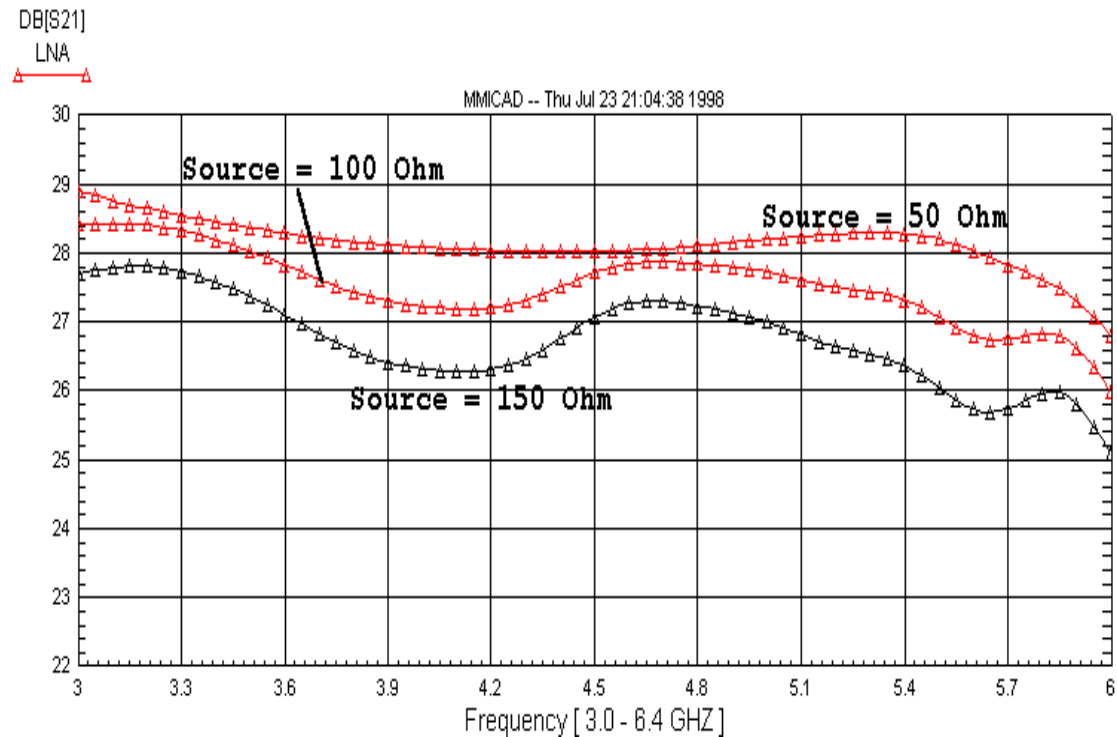


Fig. 31 Amplifier's gain (dB), as seen from the mixer. The LNA is driven via a 22 mm long 50 Ohm coax cable (180 degrees @ 4.5 GHz). The source impedance of the mixer is varied. FHX13X HEMT's. Amplifier is imbalanced, by changing one of the gate inductance's. (Compare to Figure 27).

So what are the conclusions?

- 1 Clearly the input match of the balanced amplifier is a critical item in the amplifier design. It may worth while to study the effects of circuit/HEMT phase-imbalance when putting an amplifier together. At a minimum, great care should be taken to keep both stages identical.
- 2 Secondly, the mixer pumped IF impedance should be as close as possible to 50 Ohms, which places a lot of importance on the mixer IF matching network.
- 3 Thirdly, the actual SIS junction should match well to the IF matching network.
- 4 And finally, it may help to keep the distance between IF matching network and the balanced amplifier to 90 degrees.

It is important to keep in mind that the with a 2:1 mismatch the p-p passband ripple should only be as much as 2dB. Of course this is very dependent on the input reflection coefficient of the LNA. Ideally one