

EE523 Final Project

GaAs MESFET Amplifier Design Using Conjugate Matching Technique

Wee-hua Tang
Department of Electrical Engineering
University of Kentucky

Abstract

A general view of the design of a GaAs MESFET (Gallium Arsenide Metal Semiconductor Field Effect Transistor) microwave amplifier using HPADS in the H-band is presented in this paper. A simultaneously conjugate matching technique is applied to realize maximum gain at a center frequency of 4 GHz. The amplifier is designed using both transmission lines and microstrip lines. A comparison of the two designs analyzed using HPADS is presented and discussed.

Introduction

In 1938 John Schottky suggested that the potential barrier could arise from stable space charges in the semiconductor alone without the presence of a chemical layer. The model derived from his theory is known as the Schottky barrier. If a field-effect transistor is constructed by a metal-semiconductor Schottky-barrier diode, the device is called a metal-semiconductor field-effect transistor (MESFET) [1]. A milestone was reached in 1968 when the AT&T System adopted the balanced transistor amplifier that was developed by Engelbrecht and Kurokawa. Then the next significant step was the fabrication of 1- μm MESFET's on GaAs.

GaAs FETs have a better performance than silicon FETs because the conduction electrons of GaAs have a mobility that is six times larger and a peak drift velocity that is two times larger than silicon. As a result, FET's with f_{\max} of 50 GHz became popular in 1971 [2]. Recently, GaAs FETs have been used at frequencies in excess of 100 GHz. In this report, a GaAs MESFET is used to realize a gain of at least 20 dB at 4 GHz. The amplifier will be simultaneously conjugate matched to a 50 Ω source and load impedance. The matching network will be designed using microstrip on a 100 mil Aluminum substrate.

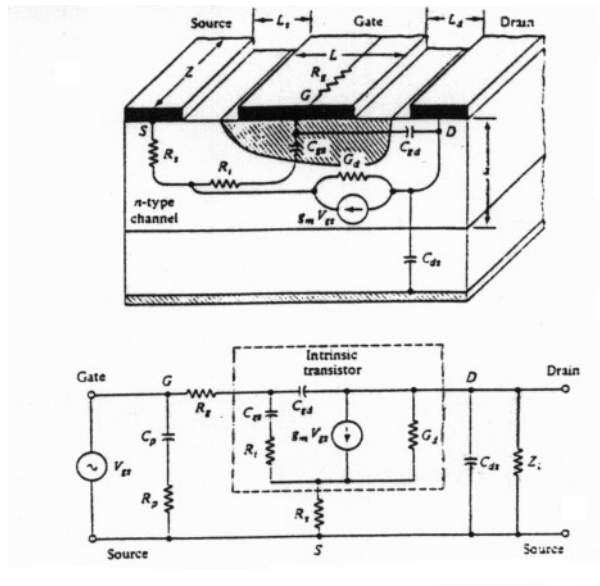
Theory

A typical small-signal equivalent circuit of a GaAs FET is illustrated in Fig. 1. For the purpose of this study, the intrinsic elements of the small signal model were $R_i = 7 \Omega$, $R_{ds} = 400\Omega$, $C_{gs} = 0.3 \text{ pF}$, $C_{gd} = 0.01 \text{ pF}$, $C_{ds} = 0.12 \text{ pF}$, $g_m = 250 \text{ mS}$. From the small signal model of the MESFET, the S-parameters were determined using HPADS over the frequencies range of 0 to 15GHz. These results are illustrated in Table 1.

Before designing an MESFET amplifier, the stability of the amplifier must be analyzed. This is done using the stability test described in [3]. There were two types of stability that are stated in [3]:

Unconditional stability: The network is unconditional stable if $|\Gamma_{in}| < 1$ and $|\Gamma_{out}| < 1$ for all passive source and load impedance ($|\Gamma_s| < 1$ and $|\Gamma_{out}| < 1$).

Conditional stability: The network is unconditional stable if $|\Gamma_{in}| < 1$ and $|\Gamma_{out}| < 1$ only for a certain range of passive source and load impedance.



Intrinsic Elements
 g_m =transconductance
 G_d =drain conductance
 R_i =input resistance
 C_{gs} =gate-source capacitance
 C_{gd} =gate-drain capacitance

Extrinsic Elements
 R_g =gate metallization resistance
 R_s =gate-source resistance
 C_{ds} =drain-source capacitance
 Z_i (R_{ds})=Drain to source resistance

Fig. 1 Cross section and equivalent circuit of a GaAs MESFET (source from [1]).

	S[1,1]	S[1,1]	S[1,2]	S[1,2]	S[2,1]	S[2,1]	S[2,2]	S[2,2]
Frequency	Mag	Ang	Mag	Ang	Mag	Ang	Mag	Ang
GHz		deg		deg		deg		deg
0.00	1	0.00	2.22e-12	0.00	22.2216	180	0.7778	0.00
1	0.9626	-13.0509	0.0055	82.6129	15.3689	125.7103	0.752	-6.9114
2	0.937	-23.3933	0.0106	76.453	9.4586	99.2192	0.7393	-11.4135
3	0.923	-33.3482	0.0155	70.5348	6.4791	83.289	0.7389	-15.9214
4	0.9112	-42.9261	0.0199	64.8894	4.778	71.3844	0.7428	-20.5725
5	0.8998	-51.9749	0.0238	59.5998	3.6889	61.5361	0.7489	-25.2954
6	0.8886	-60.4061	0.0272	54.7094	2.936	53.0005	0.7561	-30.0308
7	0.8778	-68.1855	0.0301	50.2303	2.3879	45.4324	0.764	-34.7338
8	0.8676	-75.3158	0.0326	46.1533	1.9744	38.6403	0.7723	-39.3687
9	0.8582	-81.823	0.0347	42.4566	1.6541	32.5007	0.7806	-43.9077
10	0.8496	-87.7471	0.0364	39.1116	1.4012	26.9251	0.7891	-48.3294
11	0.8418	-93.1344	0.0378	36.0872	1.1982	21.8451	0.7974	-52.6182
12	0.8349	-98.0333	0.039	33.3522	1.0332	17.2054	0.8056	-56.7631
13	0.8287	-102.491	0.04	30.877	0.8976	12.9604	0.8136	-60.7574
14	0.8232	-106.553	0.0408	28.6341	0.785	9.0718	0.8214	-64.5975
15	0.8183	-110.000	0.0414	26.5986	0.6909	5.507	0.8289	-68.2823

Table 1 The S-parameters of a GaAs MESFET from 0 to 15 GHz.

Defining:

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (1)$$

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{21}S_{12}|^2} \quad (2)$$

a transistor is unconditional stable if $|\Delta| < 1$ and $|K| > 1$.

The values of $|\Delta|$ and K are calculated from the S-parameters in Table 1. These results are listed in Table 2. Observing Table 2, the MESFET is unconditionally stable in the frequencies ranging from 3 GHz to 15 GHz. In the range of $f < 3$ GHz, the amplifier is only conditionally stable and the stability in this region will be monitored from the values of Γ_{in} and Γ_{out} .

It is desired to conjugate match the amplifier to maximize the amplifier transducer gain. Observing Fig. 3, $\Gamma_{in} = \Gamma_S^*$ will yield maximum power transfer from the input matching circuit to the transistor. Also, $\Gamma_{out} = \Gamma_L^*$ will provide maximum power transfer from the transistor to the output matching circuit. Therefore, a simultaneously conjugate match requires $\Gamma_{in} = \Gamma_S^*$ and $\Gamma_{out} = \Gamma_L^*$. Solving this relations lead to [3]:

$$\Gamma_S = \frac{B1 - \sqrt{B1^2 - 4|C1|^2}}{2C1} \quad (3)$$

$$\Gamma_L = \frac{B2 - \sqrt{B2^2 - 4|C2|^2}}{2C2} \quad (4)$$

Where,

$$B1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2$$

$$B2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2$$

$$C1 = S_{11} - \Delta S_{22}^*$$

$$C2 = S_{22} - \Delta S_{11}^*$$

Frequency (GHz)	$ \Delta $	K
1	0.783	0.713
2	0.781	0.923
3	0.766	1.012
4	0.767	1.085
8	0.731	1.439
12	0.709	1.947
15	0.703	2.407

Table 2 The calculated $|\Delta|$ and K for the MESFET.

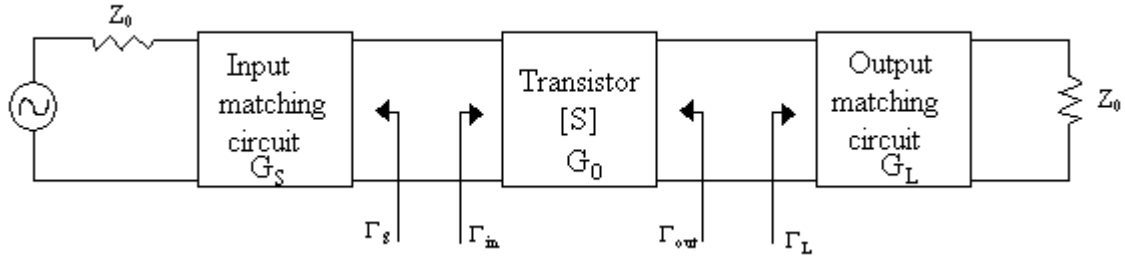


Fig. 3 The general transistor amplifier circuit (Source from [3]).

From (3) and (4), and Table 1 it is found that $|\Gamma_S| = 0.89$, and $|\Gamma_L| = 0.51$ at 4 GHz.

The transducer gain (G_T) of the amplifier is defined as the product of the gain at the source (G_S), the transistor gain (G_0), and the gain at the load (G_L). Thus, the transducer gain can be expressed as:

$$G_T = G_S * G_0 * G_L \quad (5)$$

where for a conjugate matched amplifier,

$$G_L = \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2} \quad G_0 = |S_{21}|^2 \quad G_S = \frac{1}{1 - |\Gamma_S|^2}$$

where it has been assumed that $\Gamma_{in} = \Gamma_S^*$ and $\Gamma_{out} = \Gamma_L^*$. From (5), the expected maximum transducer gain $G_T = 22.03$ dB.

The input and output matching circuits are designed using L-section networks. These networks are to be designed such that they have the proper Γ_S or Γ_L at the amplifier end, and are matched to the source or load impedance, respectively at the other end. The source L-section network is illustrated in Fig. 4a. Given Γ_L and Γ_S from (3) and (4), the normalized load impedance Z_L and the normalized source impedance Z_S can be calculated as:

$$\begin{aligned} Z_L &= (1+\Gamma_L)/(1-\Gamma_L) \\ &= 1.134+j1.224 \\ Y_L &= 1/Z_L = 0.407-j0.44 \end{aligned}$$

$$\begin{aligned} Z_S &= (1+\Gamma_S)/(1-\Gamma_S) \\ &= 0.36+j2.256 \\ Y_S &= 1/Z_S = 0.069-j0.432. \end{aligned}$$

The line lengths of the open-stubs and the through transmission line are determined using Smith chart. The Smith chart is shown in Fig. 4b.

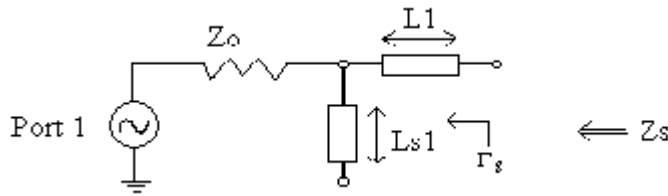


Fig. 4a Source L-section matching network with an open circuit stub.

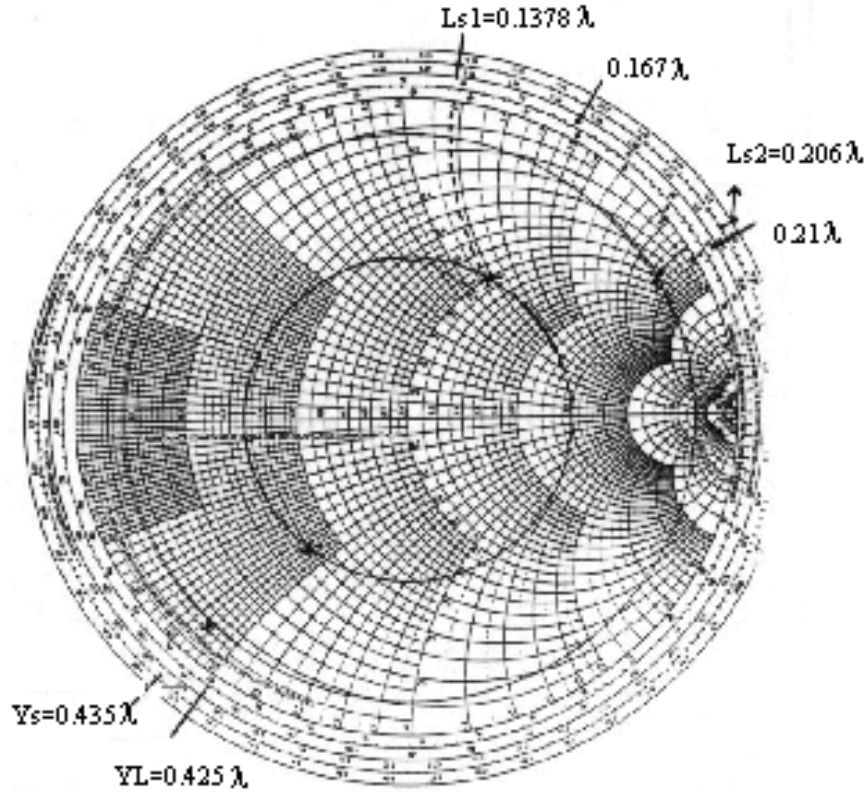


Fig. 4b The simultaneously conjugate match amplifier design using Smith chart.

For the input matching network, the normalized source admittance Y_s ($0.069-j0.432$) is first found on the Smith chart. Then one moves along the VSWR circle toward the load a length of 0.225λ ($0.435\lambda-0.21\lambda$) at which point the $r=1$ circle is intercepted. The normalized admittance of this point is $1+j3.6$. For the input admittance of the open stub to be $+j3.6$, the required open-circuit stub length is $L_{s2}= 0.206\lambda$, as shown in Fig. 4b. A similar technique provides the line lengths of 0.258λ and the open stub length of 0.1378λ for the output matching network. The physical transmission line lengths are then calculated as:

$$\lambda = \frac{v}{f_c} = \frac{3 \times 10^8}{(\sqrt{9.8})(4 \times 10^9)} = 23.9579 \text{ mm}$$

$$L1 = 0.258\lambda = 6.1811 \text{ mm}$$

$$L_{s1} = 0.1378\lambda = 3.301 \text{ mm}$$

$$L2 = 0.225\lambda = 5.3905 \text{ mm}$$

$$L_{s2} = 0.206\lambda = 4.9353 \text{ mm},$$

where the dielectric constant for the transmission line model is assume to be 9.8. These lengths will be modified for the microstrip model for which the proper effective dielectric constant is used.

Results

The amplifier and the matching network were analyzed using HPADS. Initially, ideal transmission lines were used for the analysis. The schematic circuit of the design and the S-parameters plot are shown in Fig. 5 and in Fig. 6, respectively. Notice from Fig. 6 that the transducer gain (S21) of the amplifier was above 0 dB from 8.5 GHz to 12 GHz. In order to improve the out-of-band response, a maximally flat low pass filter was design with a cut-off frequency of 5 GHz and an insertion loss of 20 dB at 8 GHz. This low pass filter can be designed using a fifth-order ladder circuit that was discussed in [3]. The element values for the ladder circuits were $g_1=0.618$, $g_2=1.618$, $g_3=2.0$, $g_4=1.618$, and $g_5=0.618$. The physical capacitors and inductors are calculated [3]:

$$C_k = \frac{g_k}{R_0 \omega_c} \quad (6)$$

$$L_k = \frac{R_0 g_k}{\omega_c} . \quad (7)$$

This results in $C_1=0.3934$ pF, $L_2=2.575$ nH, $C_3=1.2732$ pF, $L_4=2.575$ nH, and $C_5=0.3934$ pF. The lumped circuit representing the fifth-order maximally flat low pass filter is illustrated in Fig. 7. The S-parameters of the filter is shown in Fig. 8.

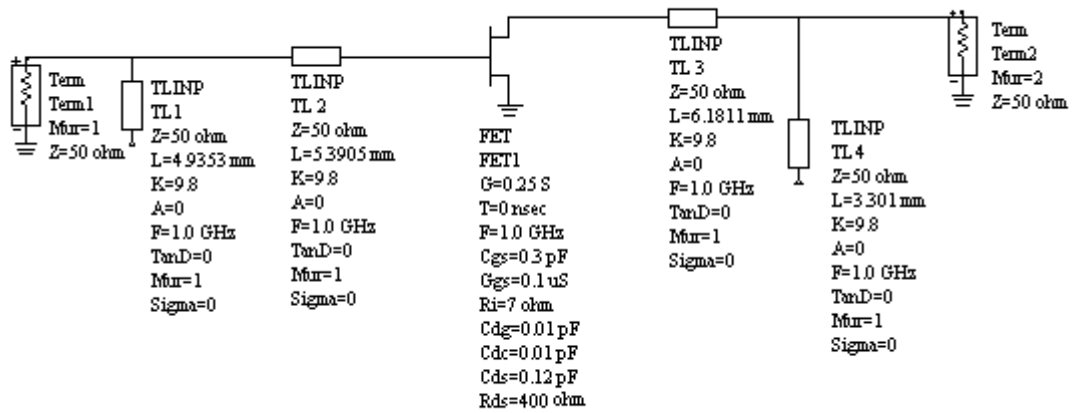


Fig. 5 The schematic circuit of the conjugate match MESFET amplifier.

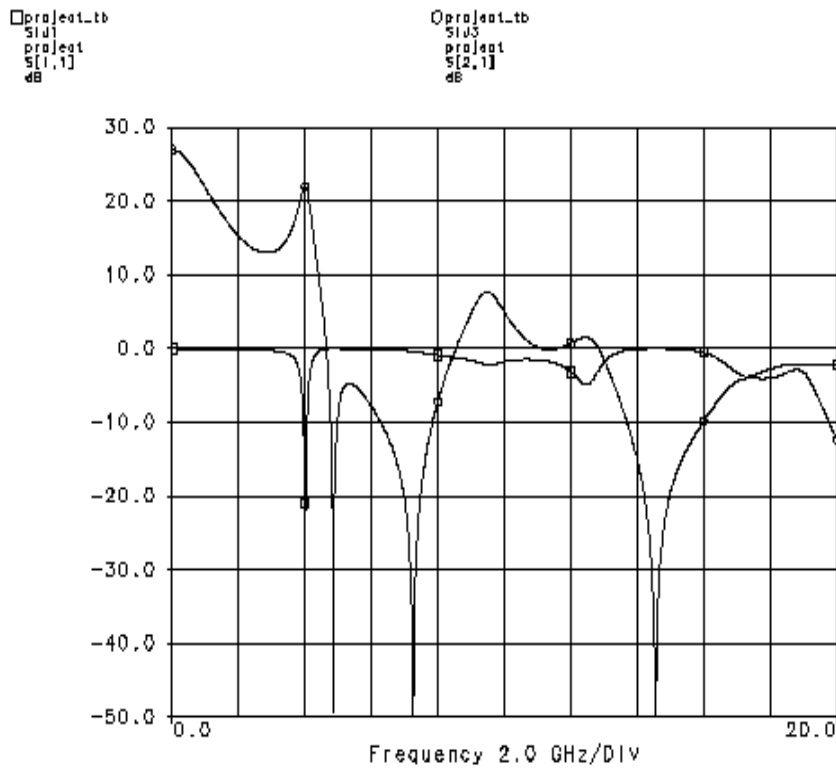


Fig. 6 The S-parameters of the conjugate match MESFET amplifier.

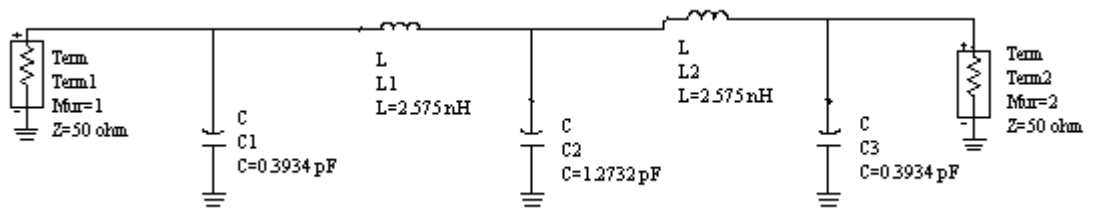


Fig. 7 The lumped circuit model of the maximally flat low pass filter.

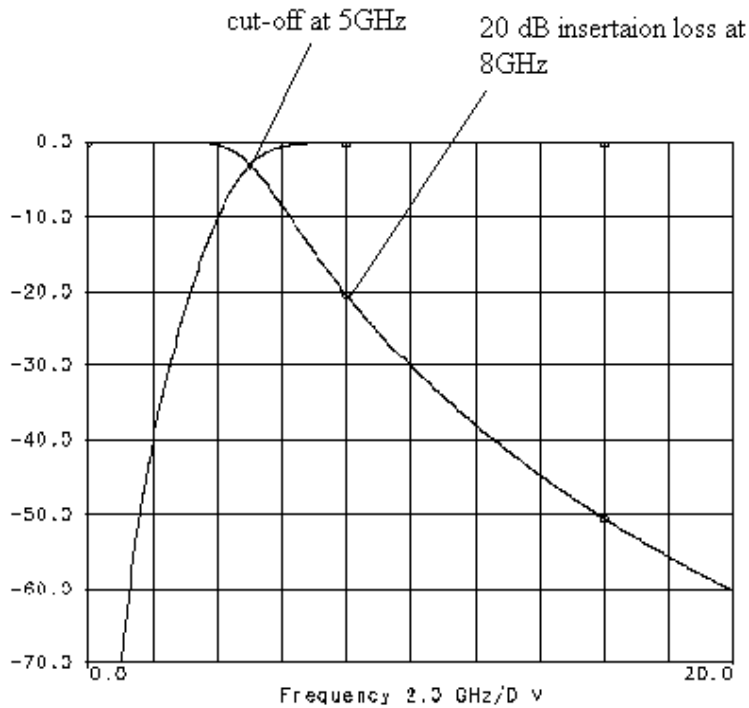


Fig. 8 The S-parameters of the maximum flat low pass filter design.

The low pass filter is then cascaded with the MESFET amplifier. The conjugate match schematic circuit is illustrated in Fig. 9 and the S-parameters are plotted in Fig. 10. Comparing the results in Fig. 10 with the results in Fig.6, it is observed that the maximum transducer gain (S_{21} at $f_c = 4$ GHz) of the amplifier design with the low pass filter did not change with the inclusion of the low pass filter. However, the transducer gain of the amplifier design with the low pass filter has been reduced to below 0 dB from 8.5 GHz to 12 GHz, as shown in Fig. 10.

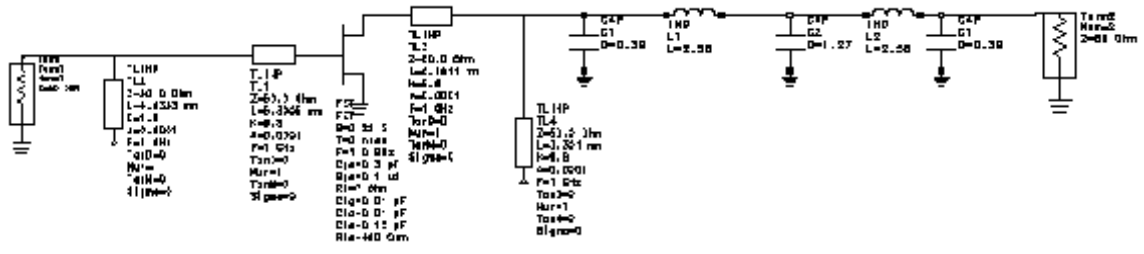


Fig. 9 The design for the MESFET amplifier with the maximally flat low pass filter.

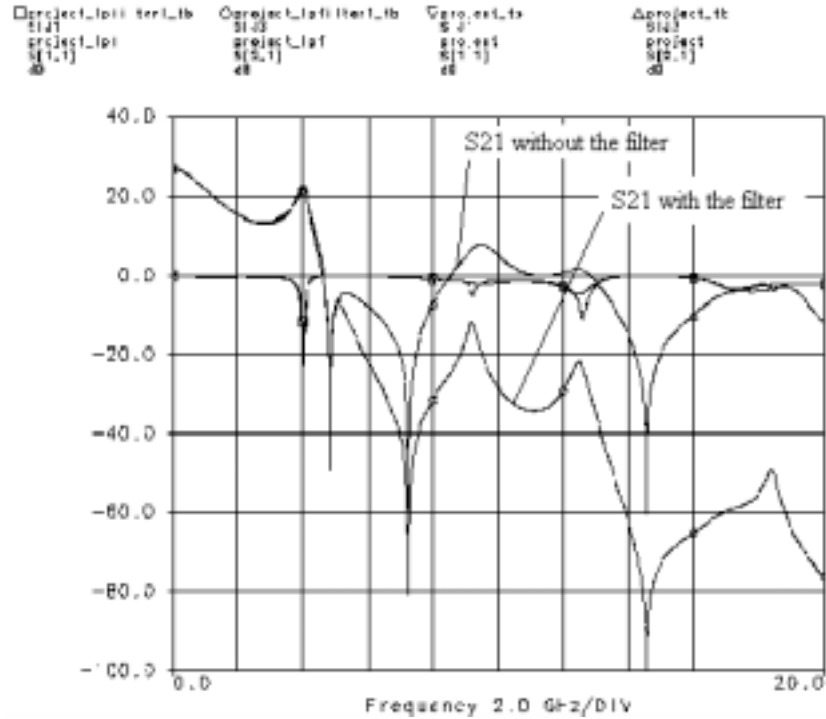


Fig. 10 The final amplifier design with and without the low pass filter.

The final part of the design is to use microstrip line for the matching network of the MESFET amplifier. To this end, the lengths and the widths of the microstrip lines were calculated using Linecalc from *Eesof*.

The schematic circuit of the amplifier designed via microstrip line is illustrated in Fig. 11. The S-parameters of this design is illustrated in Fig. 12. Compared on this figure are the S-parameters of the circuit in Fig.11 with and without the low pass filter of Fig. 7. Again the low pass filter improved the behavior of the out-of-band response without adverse affects of the performance at the resonant frequency.

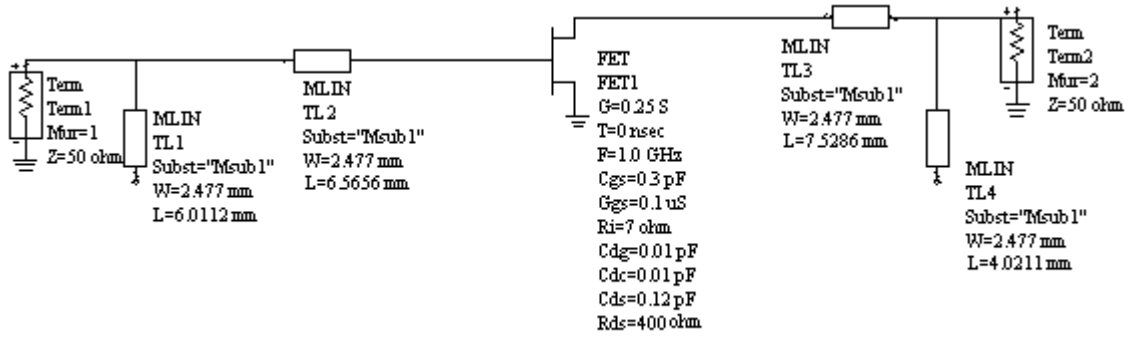


Fig. 11 The schematic circuit of the microstrip line amplifier design.

A comparison of the transducer gain between the transmission line design and the microstrip line design is provided in Table 3. Notice that the percent error of the transducer gain for the transmission line and microstrip line designs were less than three percent as compared to the calculated transducer gain. However, the resonant frequency of the amplifier has shifted from 4 GHz to 3.9 GHz. This was due to the parasitic capacitance (because of the fringing effects) of the open-stub microstrip. To improve the design further, the resonant frequency was tuned back to 4GHz by shortening the open circuit stub. The final S-parameter plot is shown at Fig.13.

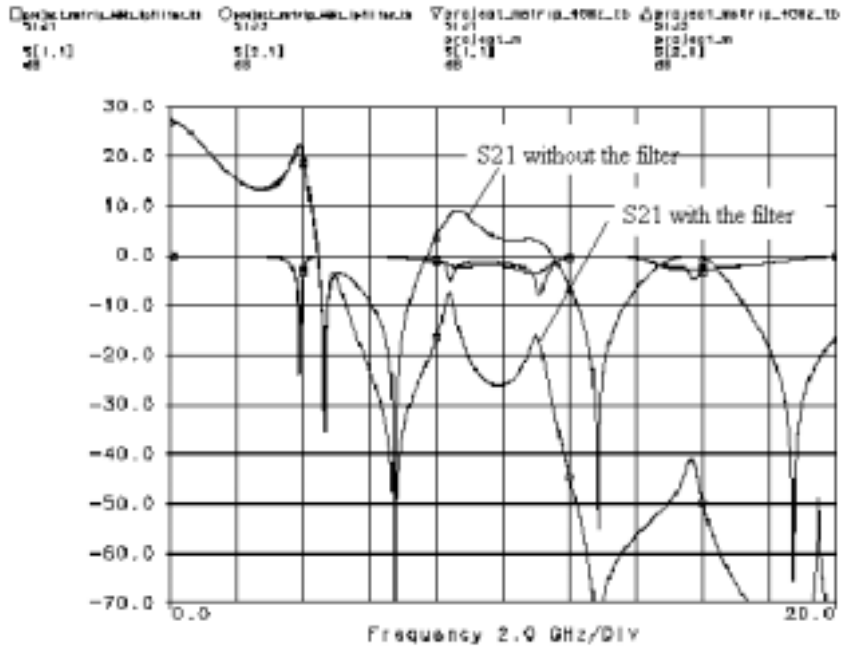


Fig. 12 A Comparison of the final amplifier design in microstrip line with and without the low pass filter.

MESFEET	Transmission line ($f_c = 4\text{GHz}$)		
$G_T(S_{21})\text{dB}$	<i>Calculated value</i>	<i>Measured value</i>	<i>Percent error</i>
	22.03	21.80	1.04
MESFET	Microstrip line ($f_c = 3.9\text{GHz}$)		
$G_T(S_{21})\text{dB}$	<i>Calculated value</i>	<i>Measured value</i>	<i>Percent error</i>
	22.03	21.5	2.41

Table 3 A comparison of the MESFET amplifier design in transmission line and microstrip line at $f_c = 4\text{GHz}$

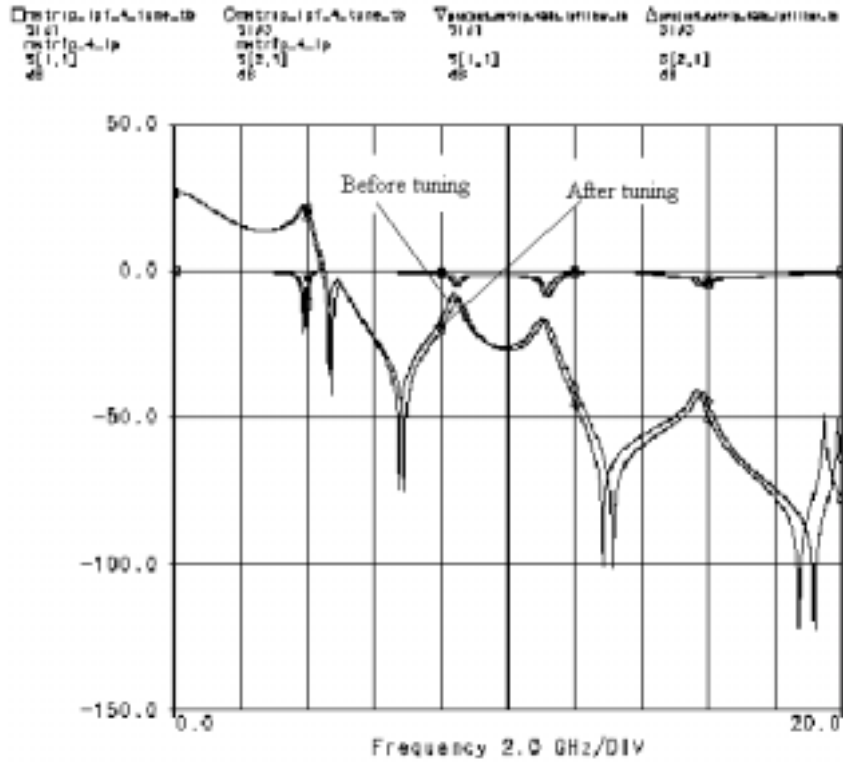


Fig. 13 A comparison between the amplifier design before and after tuning.

Conclusion

In this paper, the design of a conjugate match GaAs MESFET amplifier was presented. To this end, conjugate matched source and load networks were designed using L-sections with open stub tuners. Stability was verified over the band of interest. Initially the matching networks were designed using ideal transmission line model and excellent results were realized. Interestingly, the transducer gain (S_{21}) of the MESFET amplifier design was above 0 dB at the frequency range from 8.5 GHz to 12 GHz. This could cause a problem if the amplifier were operated from 0 GHz to 20 GHz. A solution to this problem was to design a low pass filter that cascaded with the output of the MESFET amplifier. In order not to affect the transducer gain, a maximally flat low pass filter was used instead of an equal-ripple low pass filter for the filter design.

The matching networks were subsequently designed using microstrip line. Due to parasitic effects, it was observed that the resonant frequency shifted downwards. This was mainly due to the fringing of the open circuit stubs, which results in an effective capacitive loading.

To further improve the amplifier design, the resonant frequency was tuned back to 4 GHz by shortening the line length of the open circuit stub. In practice, we also needed to consider others effects such as surface mode loss, dielectric loss, and conductor loss for amplifier designs using microstrip line.

Finally, the applications of MESFET amplifiers are not limited only in signal applications; they are also widely been used in designing oscillators. Further applications of MESFET amplifiers are discussed in [3].

References

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