Lab 3: A 1GHz Microstrip Solid-State Amplifier

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1. Introduction

The purpose of this lab is to design, build and test an amplifier at 1GHz frequency to achieve optimal gain. The amplifier consists three parts: the BJT transistor amplifier circuit, input and output matching networks. Through conjugate matching, we determined the stub lengths of the matching networks to reduce the reflections from input and output ports, and to maximize the transducer gain. Stability is also examined in designing to prevent oscillation of the network.

The amplifier circuit is designed and tuned for maximum simulated gain with ADS software, and then fabricated and tested using the VNA to measure the actual gain.

2. Design Procedures

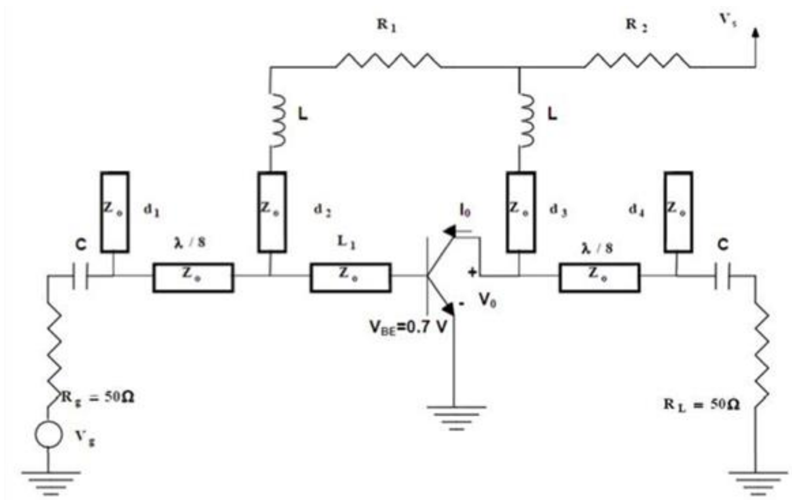


Fig 1: amplifier network schematics

Step 1: Separate the input or output networks, replace them by equivalent lumped element models and simulate the circuit at 1GHz on ADS. Detailed schematics for the input and output equivalent circuit are shown in section 3, Fig 3.3 and 3.6.

Step 2: Start by sweeping the length of the stubs which are closer to the transistor (e.g. d_2 or d_3), and disable the other ones further away from the input (d_1) or output (d_4) to the BJT. Results are shown in Figures in Section 3. Use the stubs closer to the transistor (d_2 and d_3) to tune the real part of input and output admittances (Y_{in} and Y_{out}). Find the lengths of d_2 when $Re\{Y_{in}\}=1$ and the lengths of d_3 when $Re\{Y_{out}\}=1$.

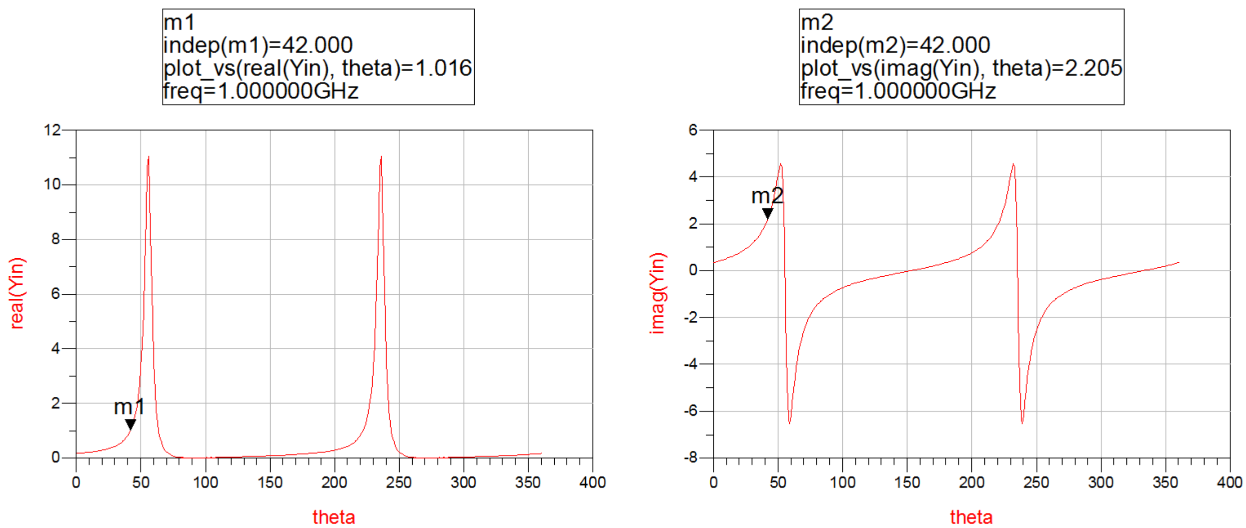
Step 3: Fix the lengths of d_2 and d_3 with values obtained from Step 2. Now, sweep d_1 and d_4 to have imaginary parts of Y_{in} and Y_{out} equals 0. Record the lengths of d_1 when $Im\{Y_{in}\}=0$ and the lengths of d_4 when $Im\{Y_{out}\}=0$.

Step 4: Validate the design by assembling together all 4 stubs (d_1 to d_4) with designed lengths. Record S parameters and shown in Fig 3.12 in Section 3.3.

3. Simulated Plots

3.1 Stub Length Tuning with Ideal Transmission Lines

3.1.1 Input Matching Network



Eqn Yin=(1-S(1,1))/(1+S(1,1))

Fig 3.1: Sweeping d_2 while d_1 disabled. d_2 = 42°, 64°, 222°, and 244° when Re{Y_{in}}=1.

By keeping L_1 = 25mm and the strip line between d_1 and d_2 at $\lambda/8$, we disable d_1 and sweep length of d_2 from 0° to 360°. The sweep yielded four possible solutions at 42°, 64°, 222°, and 244° when Re{Y_{in}}=1. We first chose the shortest length at 42°, but it resulted d_1=114° in the later simulation, which the stub length is too long and thus not desired. So we chose the second shortest stub length for d_2 at 64° to minimize the total stub length of d_1+d_2 for saving space. When keeping d_2 fixed at 64°, the shortest d_1 is found to be 76° shown as follows:

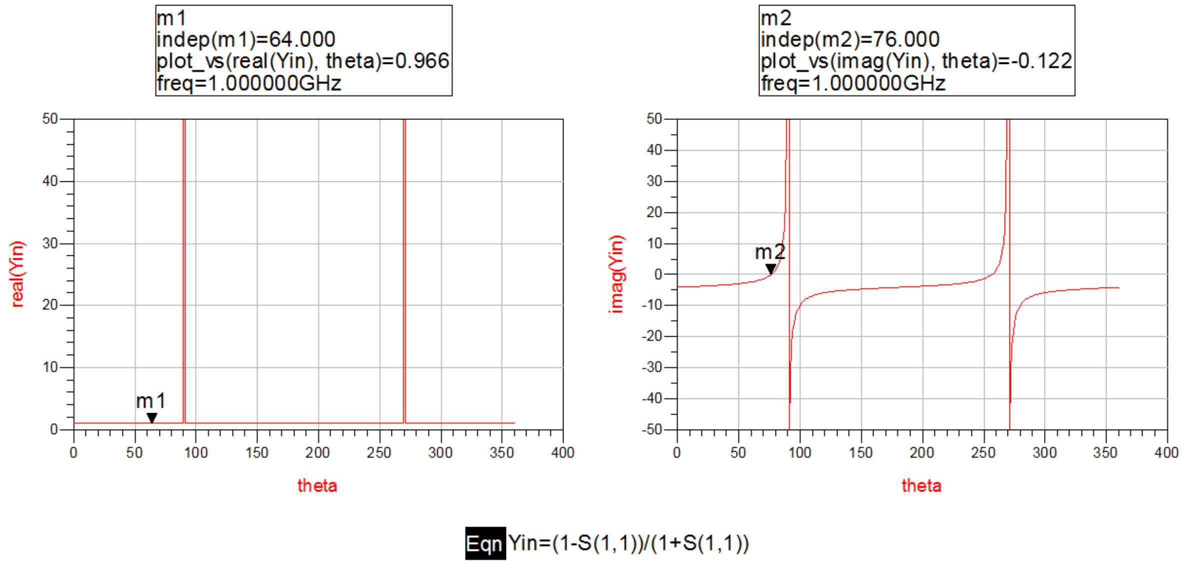


Fig 3.2: Sweeping d_1 while $d_2 = 64^o$. Imaginary part of Y_{in} is 0 when $d_1 = 76^o$

The final optimized input matching network is shown below:

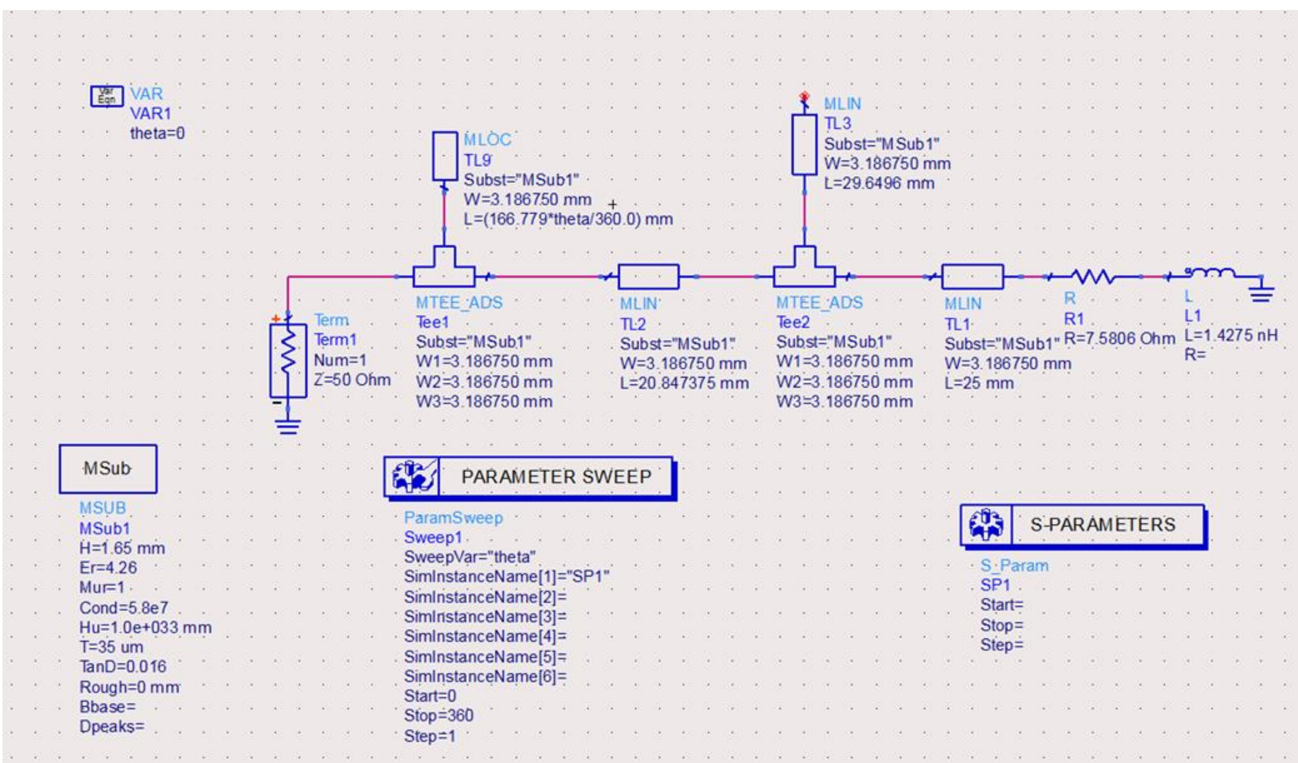


Fig 3.3: We relabelled d_1 as TL9, d_2 as TL3, and the stripline between d_1 and d_2 as TL2.

3.1.2 Output Matching Network

We find the optimized stub lengths for d_3 and d_4 following the similar procedures carried out previously in 3.1.1.

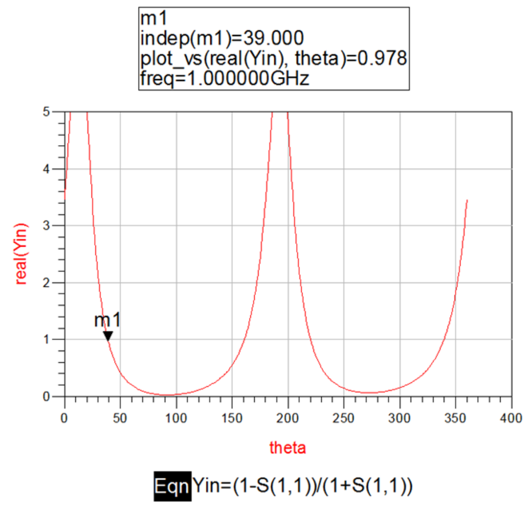


Fig 3.4: Sweeping d_3 while d_4 disabled. The shortest d_3 = 39^o when Re{Y_{in}}=1.

By keeping the strip line between d_3 and d_4 fixed at $\lambda/8$, we sweep length of d_3 from 0^o to 360^o. Again, the sweep yielded four different solutions when Re{Y_{out}}=1. We chose the shortest stub length for d_3 at 39^o to find the length d_4. By keeping d_3 fixed at 39^o, the shortest d_4 is found to be 76^o shown as follows:

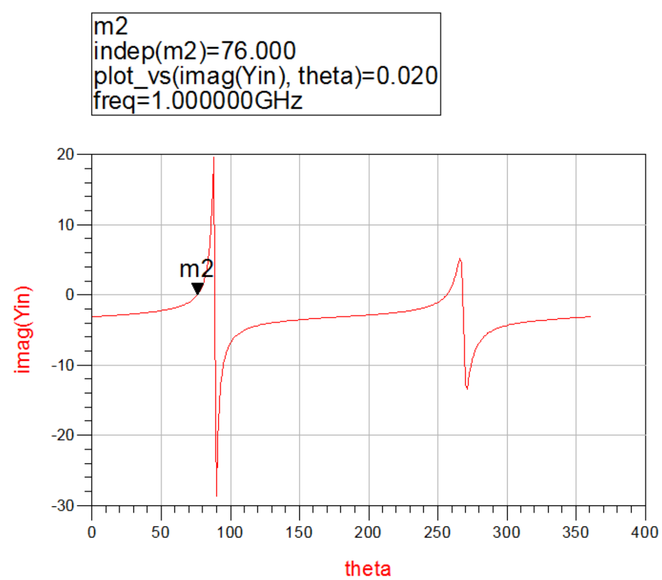


Fig 3.5: Sweeping d_4 while d_3 = 39^o. Imaginary part of Y_{out} is 0 when d_4 = 76^o

The final optimized input matching network is shown below:

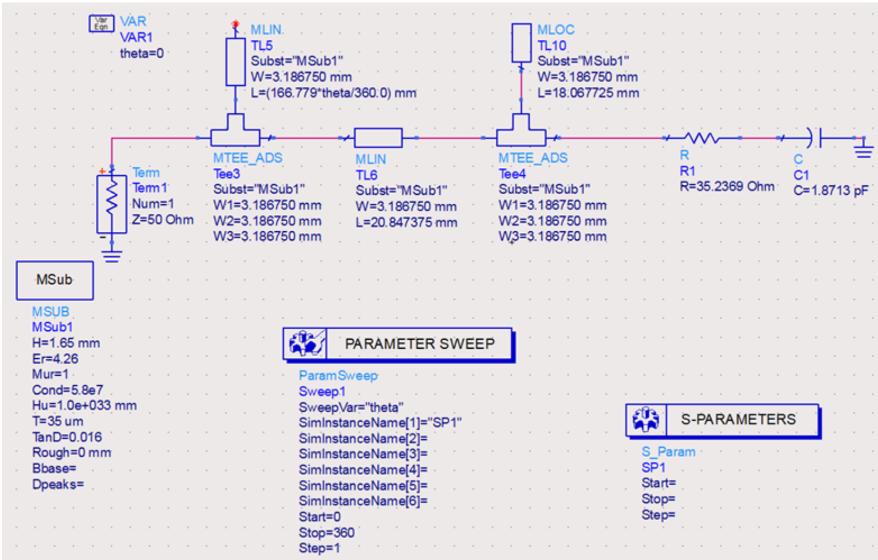


Fig 3.6: We relabelled d_3 as TL5, d_4 as TL10, and the stripline between d_3 and d_4 as TL6.

3.3 Stub Length Tuning with FR-4

We also simulated the network with lossy FR-4 microstrip lines on ADS following the same procedures in 3.2. The results are shown in the following plots:

For input network matching:

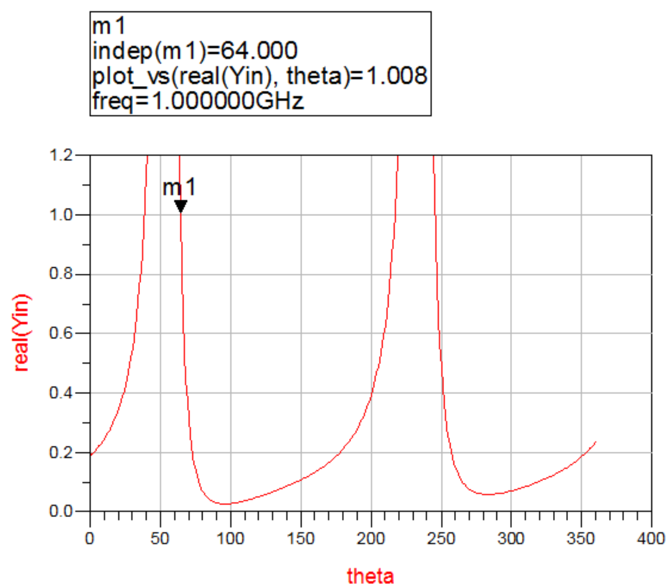


Fig 3.7: Sweeping d_2 while d_1 disabled. The second shortest $d_2 = 64^o$ when $Re\{Y_{in}\}=1$.

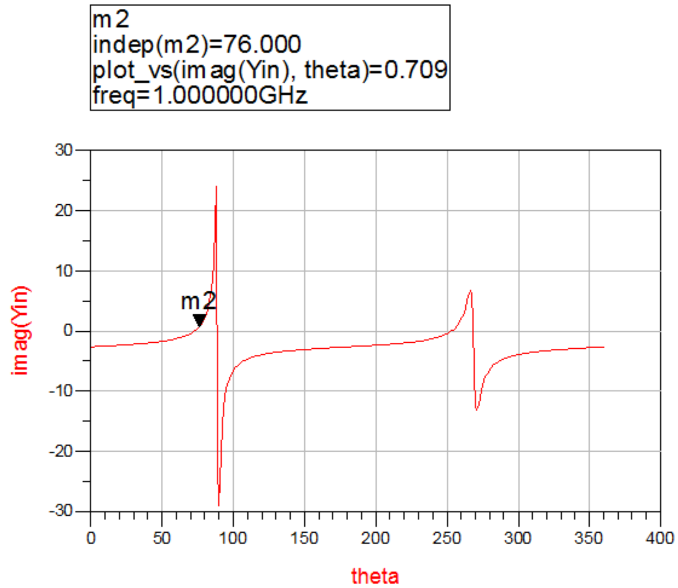


Fig 3.8: Sweeping d_1 while $d_2 = 64^o$. Imaginary part of Y_{in} is 0 when $d_1 = 76^o$

For output network matching:

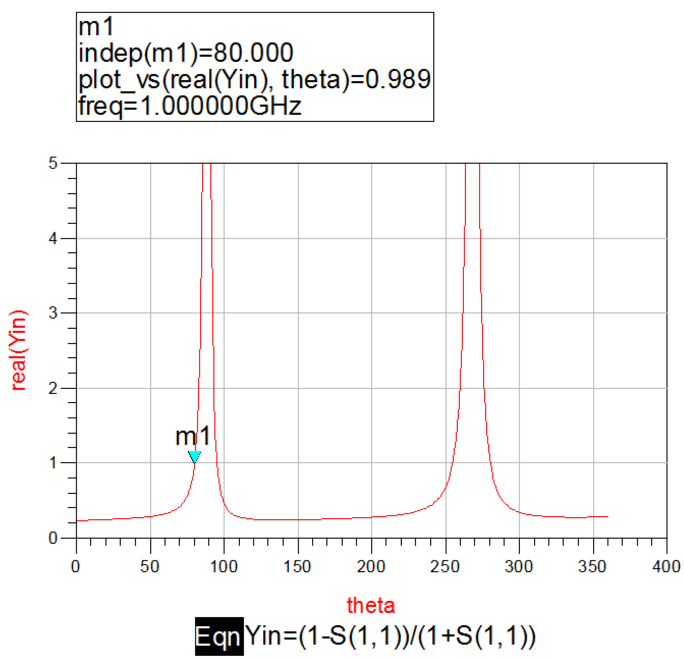


Fig 3.9: Sweeping d_3 while d_4 disabled. The shortest $d_3 = 80^o$ when $Re\{Y_{in}\}=1$.

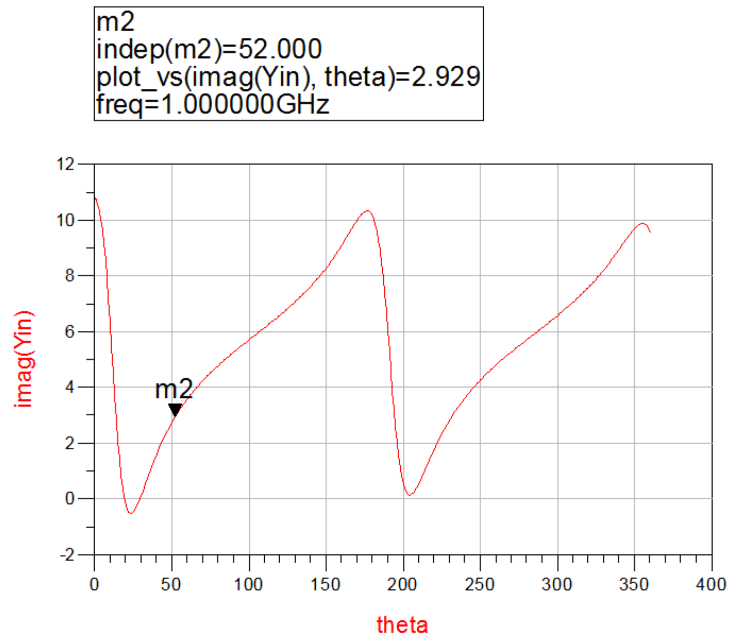


Fig 3.10: Sweeping d_4 while $d_3 = 80^o$. Imaginary part of Y_{out} is 0 when $d_4 = 52^o$

The resultant stub lengths are d_1=28.5mm, d_2=35.2mm, d_3=35.2mm and d_4=18.1mm.

The following is the final schematic for the amplifier network using optimized stub lengths:

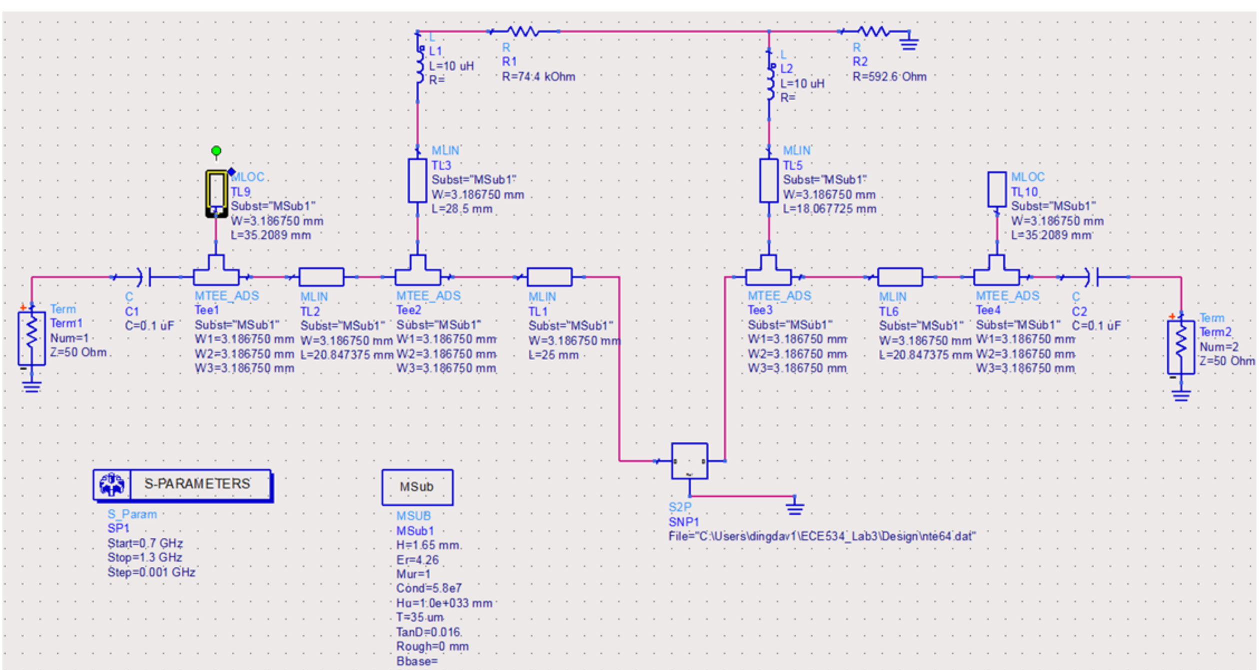


Fig 3.11: Final schematic for the amplifier network

The simulations for S-parameters are as follows:

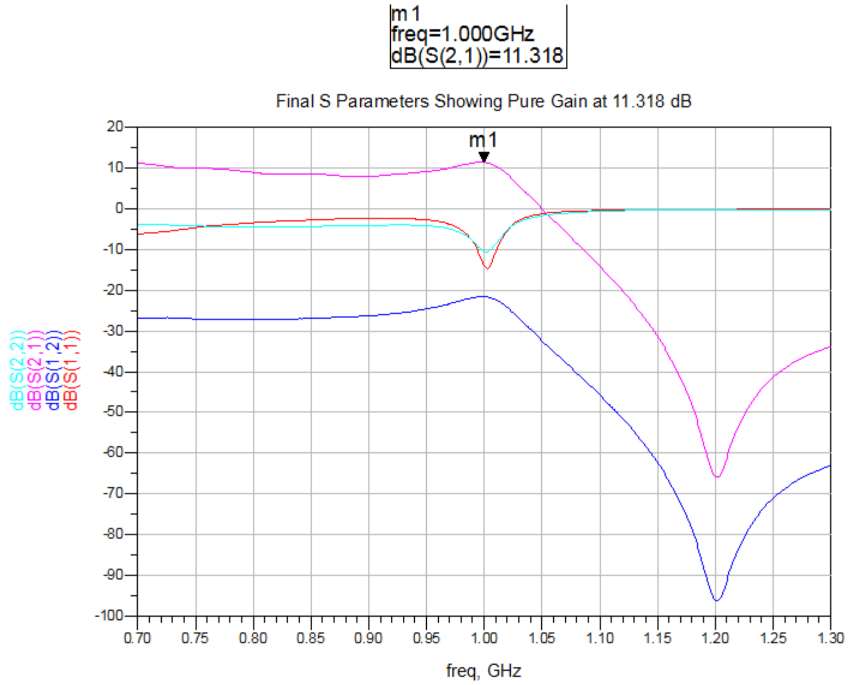


Fig 3.12: S-parameters on FR-4

4. Experimental Plots

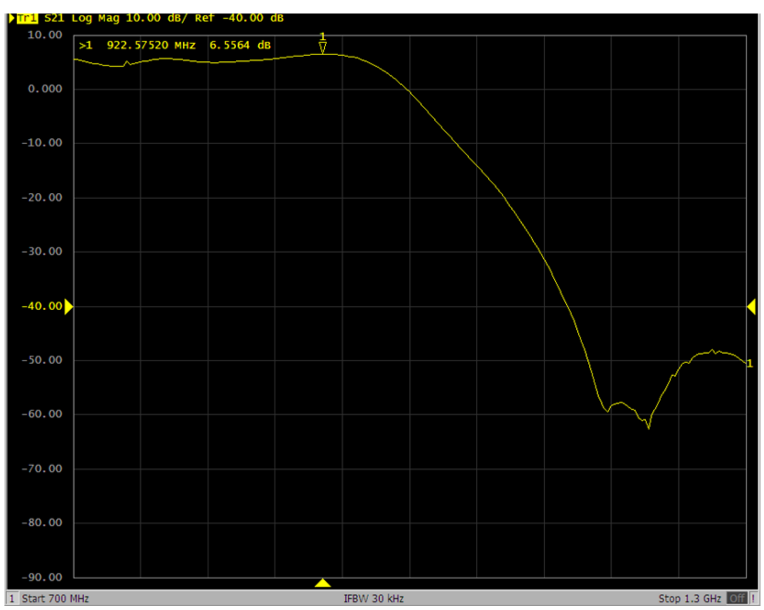


Fig 4.1: S21

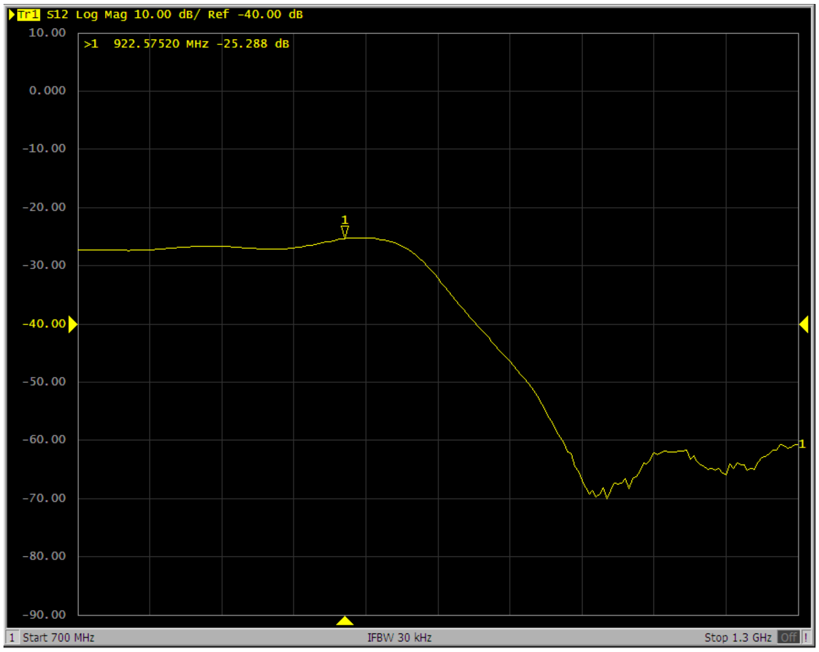


Fig 4.2: S12

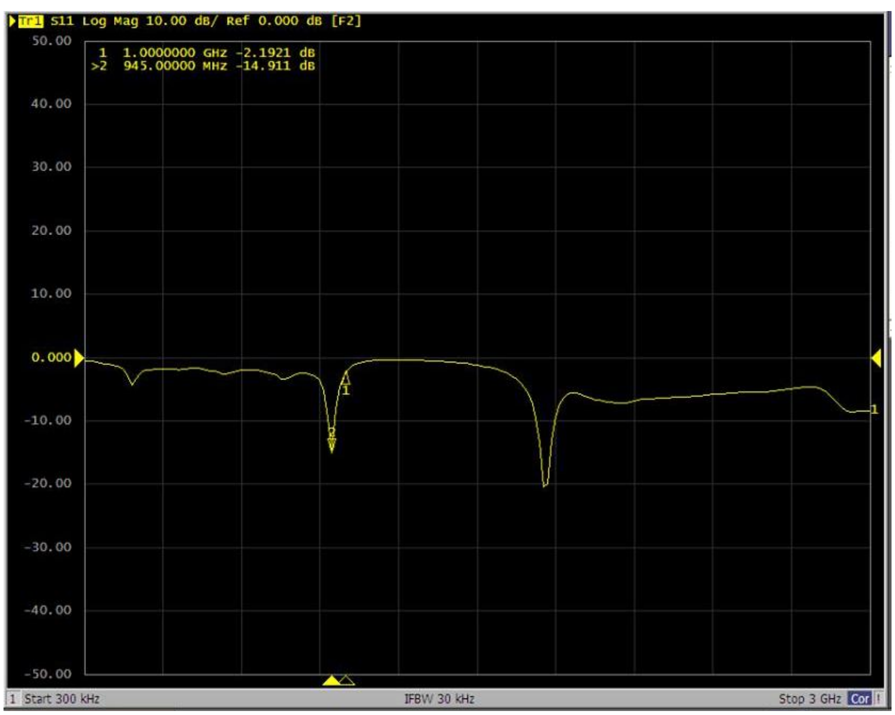


Fig 4.3: S11

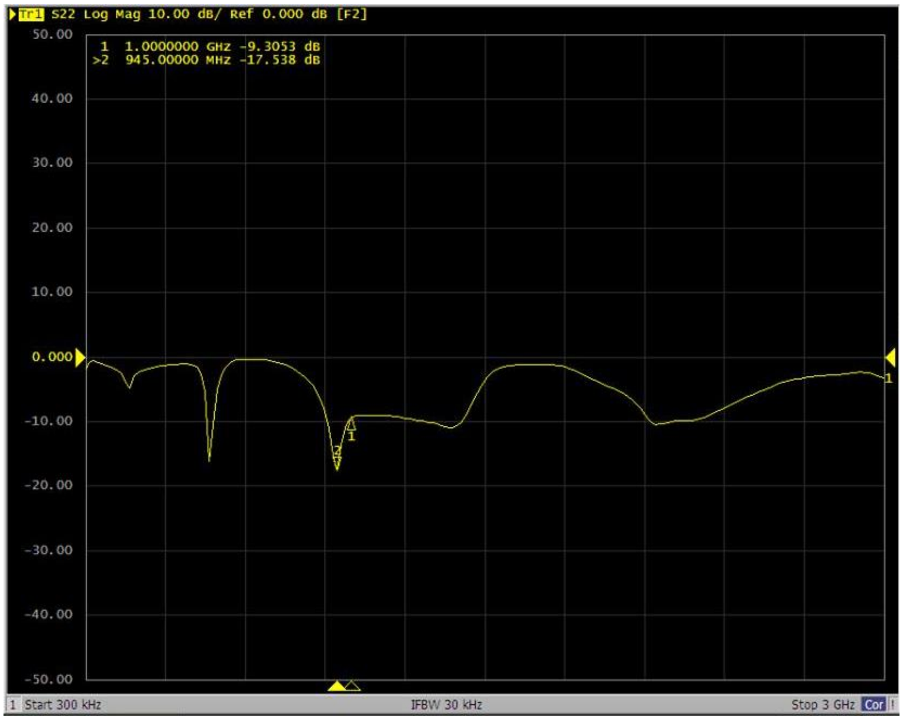


Fig 4.4: S22

5. Discussions

1. Biasing resistors R_1 and R_2 for an operating point of I_0=10mA, V_0=10V at V_S = 16V and h_{FE}= 80.

   The current into the base of BJT is $i_b = I_0/h_{FE}$=10mA/80=0.125mA.
   $V_x=V_0+I_0Z_0$=10.5V
   $R_1+2Z_0=(V_x-V_{BE})/i_b \Rightarrow R_1$=78.3kΩ
   $R_2=(V_S-V_x)/(I_0+i_b)$=543.21Ω

2. Stability factors K and Δ at 1 GHz

   From the data sheet, at 1 GHz, $S_{11}=0.4454\angle 161.638^o$, $S_{21}=3.6707\angle 53.358^o$, $S_{12}=0.08264\angle 46.371^o$, $S_{22}=0.37975\angle -51.66^o$

   $|\Delta|=|S_{11}S_{22}-S_{12}S_{21}|=0.1402<1$
   $K=\frac{1-|S_{11}|^2-|S_{22}|^2+|\Delta|^2}{2|S_{12}S_{21}|}=1.116>1$
   So the network is unconditionally stable at 1GHz.

3. Theoretical maximum transducer gain of the amplifier at 1 GHz

   At 1GHz,
   $B_1=1+|S_{11}|^2-|S_{11}|^2-|\Delta|^2=1.0345$
   $B_2=1+|S_{22}|^2-|S_{11}|^2-|\Delta|^2=0.9262$
   $C_1= S_{11}-\Delta S_{22}^*=0.49495\angle 159.265^o$
   $C_2= S_{22}-\Delta S_{11}^*=0.43803\angle -54.806^o$

   For stability, we only choose $|\Gamma_{in}|<1$ and $|\Gamma_{out}|<1$, or equivalently $|\Gamma_S|<1$ and $|\Gamma_L|<1$:
   $\Gamma_S=\frac{B_1-\sqrt{B_1^2-4|C_1|^2}}{2C_1}=0.74151\angle -159.265^o$
   $\Gamma_L=\frac{B_2-\sqrt{B_2^2-4|C_2|^2}}{2C_2}=0.7141\angle 54.806^o$
   $G_{T\max}=\frac{1}{1-|\Gamma_S|^2}\,|S_{21}|^2\,\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_S|^2}=27.57$ or 14.4dB

4. Input and output impedances of the transistor

   $\Gamma_{in}=\frac{Z_{in}-Z_0}{Z_{in}+Z_0}=\Gamma_S^* \Rightarrow Z_{in}=7.66+j8.94\ \Omega$
   $\Gamma_{out}=\frac{Z_{out}-Z_0}{Z_{out}+Z_0}=\Gamma_L^* \Rightarrow Z_{out}=35.68-84.97\ \Omega$

5. For choosing the stub lengths, why are there four options and are there benefits to one over the others?

   When finding the length of one stub using double stub tuning on admittance Smith chart, there are two options, which one of the solution is closer to the BJT than the other. For instance, the g=Re{Z_{in}'} circle intersects the rotated (by λ/8) g=1 circle at two different points. And also the full circle of the Smith chart represents 180^o or λ/2, by sweeping from 0° to 360°, we traversed through the full Smith chart twice, thus it creates two more options, where the second pair of solutions differ the first pair by λ/2.

   The longer than stubs are, the more conductor loss there are in the network. However, shorter stubs may be more susceptible to parasitic capacitance.

6. What will be the reactance of the capacitance C=0.1 μF at 1 GHz? Would this act as a good decoupling capacitor at this frequency?

   $Z_c = \frac{1}{j\omega C} = -j1.592\times10^{-3}\ \Omega$
   Since $|Z_c/Z_0|$<<1%, it acts as a short and is a good decoupling capacitor at 1GHz.

7. What will be the reactance of the inductance, L = 10 nH at 1GHz? Would this act as a good RF-choke at 1 GHz?

   $Z_c = j\omega L = j62.83\ \Omega$ which is not very large compare with R_1 or R_2.
   So it is not a good RF-choke at 1 GHz, an inductor with higher inductance is preferred to create high impedance.

6. Differences between Simulation and Measurement

The experimental plots and simulated plots agree with each other in general, however a few differences have been observed. The simulated plots have lower return loss and higher insertion loss around 1GHz. The most significant difference is in S_{21} such that the experimental plot has its maximum value 6.56dB at 922.6MHz comparing with the simulated plot which has maximum value11.3dB at 1GHz. The maximum value of the simulated S_{21} is much closer to the theoretical maximum transducer gain $G_{T\max}$=14.4dB.

The observed difference between the measured and simulated central frequency could be accounted by assuming that the two stubs are actually longer than what their physical length is. This is because each open-circuited stub induces a fringing field at its open end. This field can be modeled as a shunt fringing capacitance C_f attached to the open end. Equivalently, C_f can be accounted for by assuming that the open stub is actually longer than its physical length, since a short section of an open-circuited line behaves capacitively.

The discrepancy for the maximum value of S_{21} could be due to the non-ideal components used for constructing the circuit network. Each physical component has limited quality factor. The original inductor we used as RF-choke gave us negative dB values in S_{21}, but after replacing the inductor, we were able to achieve 6.56dB in S_{21}, and the gain is significantly improved. To achieve a higher gain, an inductor with higher inductance is needed, but it will also require the inductor to have larger size and it may also create some other undesired effects. Another source of the discrepancy may be caused by soldering and wiring. In the lab, we observed that the S-parameter values fluctuate when we touch or press the wires. Repositioning the wires could introduce parasitic capacitance that diminishes the effect of inductors.

7. Conclusion

In this lab, we designed, simulated, and tested a BJT amplifier network at 1GHz on microstrip. By examining the S-parameters, the amplifier network is determined to be unconditionally stable at 1GHz. There are some discrepancies between the simulated results and experimental results mainly due to the non-ideal components used to construct the network. By replacing the original inductor with a new one, we improved the transducer gain to 6.56dB, which is still lower than the simulated value of 11.4dB. However, it is possible to further improve the gain by using components with higher quality factors.