ENGR 470 - Microwave Engineering

Lab 5 – Microwave Amplifier Design

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March 30, 2017

1. Actual circuit board layout

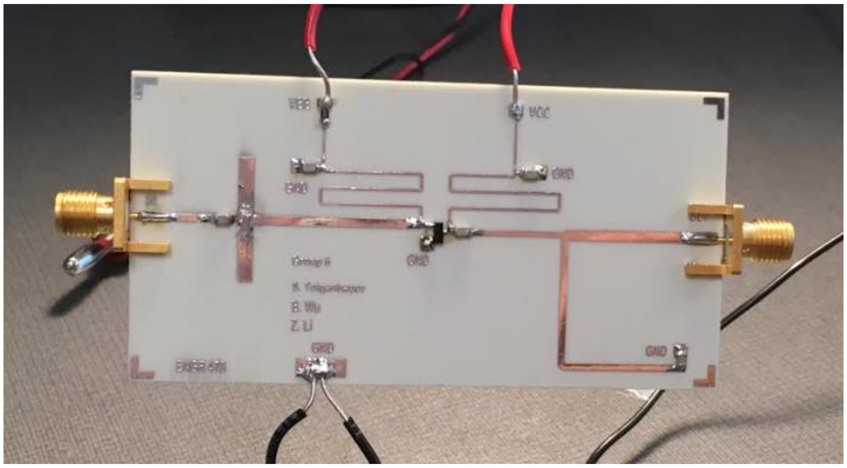


Figure 1 Microwave amplifier circuit layout

2. Performance summary

Table 1 Results Summary

	Required value	Calculated value	Simulated value	Experimental value
Mid-band transducer grain at $f_c = 1\ GHz$	>14.5 dB	14.32 dB	14.54 dB	13.892367 dB
$\lvert S_{11}\rvert\ at\ 0.9\ GHz$	<-11 dB	\	-15.16 dB	-16.716867 dB
$\lvert S_{11}\rvert\ at\ 1.1\ GHz$	<-11 dB	\	-15.34 dB	-11.953149 dB
$\lvert S_{22}\rvert\ at\ 0.9\ GHz$	<-11 dB	\	-12.65 dB	-16.003258 dB
$\lvert S_{22}\rvert\ at\ 1.1\ GHz$	<-11 dB	\	-13.07 dB	-12.766315 dB
Stability factor 1	\	1.012	\	\
Δ	\	0.4536 - 0.2276i	\	\
Stable?	Yes			
Γ_S for maximum unilateral transducer power gain ($= S_{11}$)	\	-0.099 - 0.092i	\	\
Γ_L for maximum unilateral transducer power gain ($= S_{22}$)	\	0.314 - 0.185i	\	\
G_{tran} maximum unilateral transducer gain	\	14.327	\	\
Γ_S for simultaneous conjugate match ($= \Gamma_{in}^*$)	\	-0.7110 + 0.2618i = 0.7577(159.77)	\	\

Γ_L for simultaneous conjugate match ($= \Gamma_{out}^*$)	\	0.6583 + 0.4855i = 0.8179(36.4)	\	\
G_{tran} maximum bilateral transducer gain	\	15.5784 dB	\	\

1 Conjugate matching circuit (see Attachment)

2 Smith Chart with conjugate matching circuit (see Attachment)

3 Amplifier design using transmission line (see Attachment)

4 Amplifier design using microstrip (see Attachment)

5 The gain, input return loss, and output return loss (see Attachment)

6 Circuit board design in CAD (see Attachment)

7 Results discussion

7.1 Conjugate matching

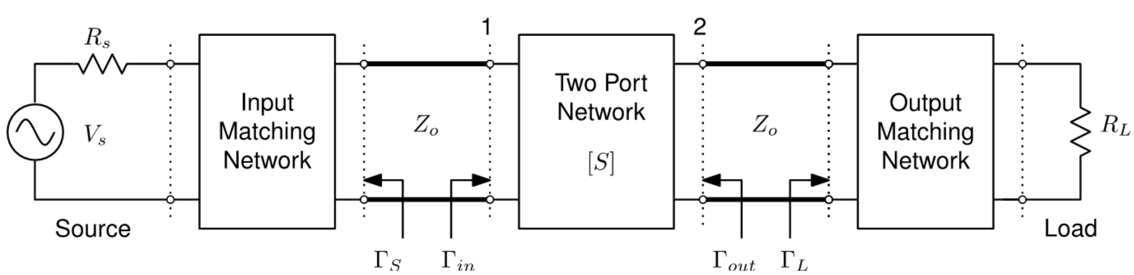


Figure 2 Matching circuit

Conjugate Matching was achieved by simultaneously solving the below two equations:

$$\Gamma_{in} = \Gamma_S^* = \left(\frac{S_{11} - \Delta\Gamma_L}{1 - S_{22}\Gamma_L}\right)$$

$$\Gamma_L = \Gamma_{out}^* = \left(\frac{S_{22} - \Delta\Gamma_S}{1 - S_{11}\Gamma_S}\right)^*$$

Where $\Delta = S_{11}S_{22} - S_{12}S_{21}$. When it is bilateral, the above two equations yield:

$$\Gamma_S = \frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2C_1}$$

$$\Gamma_L = \frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2C_2}$$

where:

$$B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2$$

$$B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2$$

$$C_1 = S_{11} - \Delta S_{22}^*$$

$$C_2 = S_{22} - \Delta S_{11}^*$$

The results were calculated in the Matlab Script. Define the available power gain as:

$$G_A = \frac{1 - |\Gamma_S|^2}{|1 - S_{11}\Gamma_S|^2} |S_{21}|^2 \frac{1}{1 - |\Gamma_{out}|^2}$$

When it is under conjugate matching, $|\Gamma_{out}| = |\frac{S_{22} - \Delta\Gamma_S}{1 - S_{11}\Gamma_S}|$, $|\Gamma_S| = |\frac{S_{11} - \Delta\Gamma_L}{1 - S_{22}\Gamma_L}|$, the results are summarized in Table 1.

Also define the stability condition K as:

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

When $K > 1$ and $|\Delta| < 1$, we conclude that the design is unconditionally stable.

With all these formulas and the available S parameters provided for the transistor operated at 1 GHz with $V_{CE} = 6$ V and $I_C = 20$ mA, the calculated Γ_S, Γ_L, and G_A are implemented in our design, and the Attachment Figure 1 shows our conjugate matching circuit design. The corresponding Smith's Chart can be found in Attachment Figure 2.

7.2 7.2. Transmission line implementation of microwave amplifier

In Lab 4 of the course, we were asked to design a microwave amplifier using transmission lines and microstrips. We first needed to determine which specific type of matching to use for our design. The two options were single stub or double stub matching. We chose to use single stub matching first as the complexity in double stub was slightly harder but gives the same result. There were guidelines that needed to be met, such as achieving a mid-band transducer gain of greater than 14.5 dB. The S_{11} and S_{22} port also needed to be less than -11dB. The advice given to us, was to utilize the optimizer in AWR. The optimizer was able to tweak the electrical length of the input, output, and give us an approximate range of values to use.

The next step was to change the transmission line into microstrip design. This was easy to do, as we can substitute each transmission line with the corresponding microstrip component. The more difficult part was trying to junction together the parts using the microstrip junctions. The junction area needed to include a short microstrip line on either end. The addition of these junction microstrips threw us off and a new optimizer sequence needed to be performed. From there, we continued to further improve the circuit design by tweaking the length and width of each value and adjusting each value by hand if necessary. Making certain again that the mid-band transducer gain, port S_{11}, and port S_{22} meet specification.

In Attachment Figure 5, the gain of the microstrip and transmission design are similar, both designs meet the specification of greater than 14.5 dB. Testing the microstrip design, our experimental value was 13.89 dB, this was lower than the simulated and calculated value. We suspect that some interference or circuitry design caused this.

The input return loss of the transmission design in Attachment Figure 6 shows a more stable plot than the microstrip design. The transmission line is able to work in any frequency between 0.9 GHz to 1.5 GHz. The return loss in these frequency gives a value of less than -11 dB. The microstrip has an input return loss of -19.33 dB at 1 GHz. The microstrip design however has a more limited area of frequency it can use. Looking at Table 1, the simulated results of port S_{11} have all met the specifications at the specified frequencies. The experimental values were also able to meet specifications but the value at 1.1 GHz appears to be greater than the simulated value of -15.34 dB at -11.95 dB. We speculate that there was either some circuitry errors or some interferences from the board that caused this error.

The output return loss graph in Attachment Figure 7 compares the value of the transmission line to the microstrip design. The two share quite a resemblance, but the microstrip design is able to give a lower gain at the same frequencies. Similar to port S_{11} at 1.1 GHz, port S_{22} the experimental value is greater than the simulated value of -12.76 dB at -13.07 dB.

Also, the bias line design here is very critical. We use the capacitor with $\mathrm{C} = 33$ pF as the DC blocking capacitor here as its reactance at $\mathrm{f} = 1$ GHz is about only 5 Ω, which is behaving like a short circuit. With the aid of quarter-wave transformer, the bias line at operation frequency will behave like an open circuit due to the impedance inverting. We also add a DC-bias resistor whose resistance is about 51 kΩ at the base of the transistor in order to provide some margin to the bias current. The following figure shows our DC bias line design.

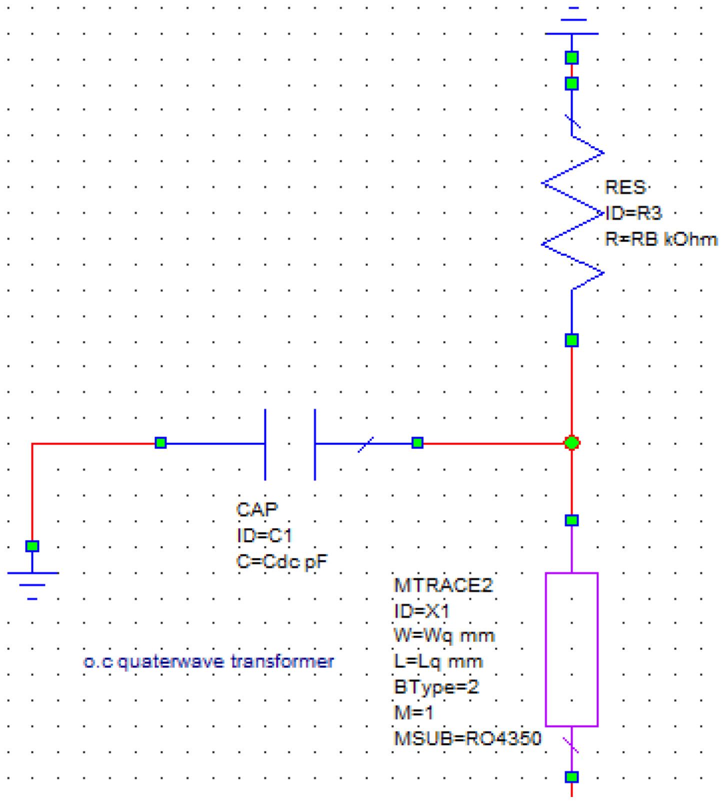


Figure 3 DC bias line design at the base of the transistor

7.3 7.3. Microstrip implementation of microwave amplifier

By using TXLine we can convert transmission line model to microstrip. The substrate requirements are listed below.

Table 2 Substrate requirements

Substrate name	RO4350
Thickness	0.762 mm
Copper thickness	35.5 µm
Permittivity	3.7
Loss tangent	0.0031
Characteristic impedance	50 Ω
Characteristic impedance of quarter-wave transformer	100 Ω

For instance, Figure 4 below shows how to convert the quarter-wave transformer from transmission line to microstrip design.

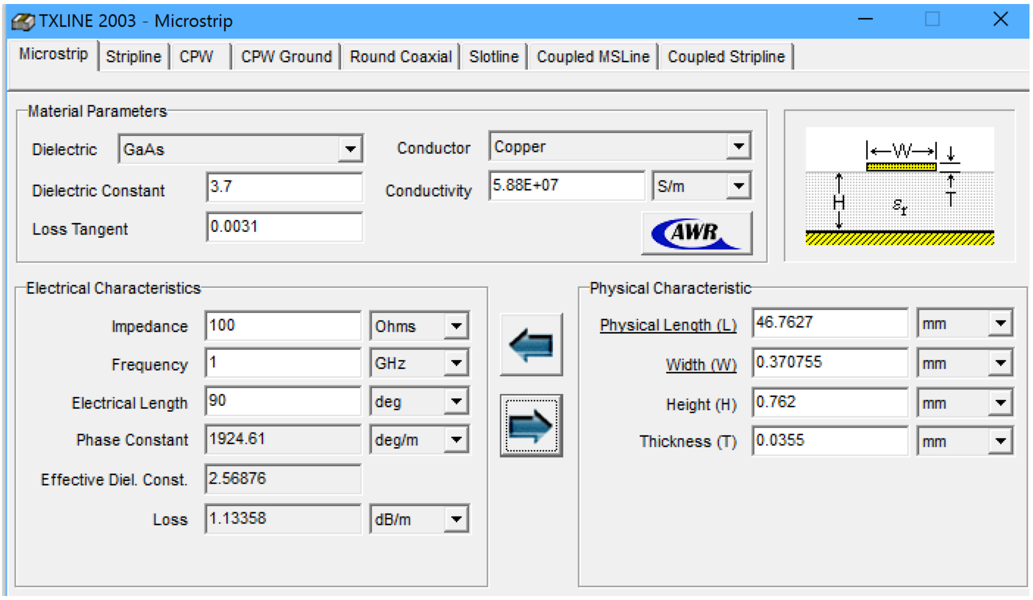


Figure 4 Using TXLine to convert quater-wave transformer from transmission line model to microstrip

The final circuit design can be found in Attachment Figure 8.

8 Matlab calculation

```
% Lab 4
% read pozar textbook pg 567, 572

% Unconditionally Stable
% K >1
% |delta|<1

% ----------------------------------------------------------------------------
% ! Filename:        BFR520K.S2P                                 Version:   2.1
% ! Philips part #: BFR520                                       Date: Sep 1991
% ! Bias condition: Vce=6V, Ic=20mA
% !
% #   MHz   S   MA   R   50
% ! Freq         S11             S21             S12             S22      !GUM [dB]
%    40     .743  -18.7  33.272  161.4    .009   81.0    .918  -11.1 !    41.9
%   100     .627  -41.8  27.392  141.4    .020   72.1    .792  -23.2 !    35.2
%   200     .447  -66.7  19.114  121.4    .033   68.1    .607  -31.5 !    28.6
%   300     .342  -82.4  14.179  110.6    .043   68.6    .503  -33.4 !    24.8
%   400     .278  -94.3  11.131  103.5    .053   69.6    .446  -33.1 !    22.2
%   500     .237 -102.7   9.118   98.7    .063   71.1    .414  -32.7 !    20.3
%   600     .209 -109.7   7.724   94.8    .073   71.7    .395  -32.2 !    18.7
%   700     .185 -116.5   6.708   91.5    .083   72.7    .384  -31.7 !    17.4
%   800     .164 -122.5   5.920   88.7    .094   73.0    .377  -31.1 !    16.2
%   900     .148 -129.1   5.307   85.9    .104   73.2    .371  -30.8 !    15.2
%  1000     .135 -137.3   4.799   83.4    .114   73.2    .365  -30.5 !    14.3
```

```matlab
%  1200    .126 -152.3   4.058   79.2    .134   73.0    .354  -30.7 !    12.8
%  1400    .125 -161.6   3.545   75.4    .156   72.3    .345  -32.1 !    11.6
%  1600    .111 -166.7   3.132   71.7    .175   71.4    .347  -32.7 !    10.5
%  1800    .099 -178.7   2.813   68.6    .195   70.9    .348  -33.6 !     9.6
%  2000    .101  163.6   2.574   65.1    .215   69.6    .339  -33.4 !     8.8
%  2200    .126  151.0   2.382   62.3    .235   68.5    .322  -33.7 !     8.1
%  2400    .147  149.6   2.244   58.9    .256   67.3    .305  -36.4 !     7.5
%  2600    .147  151.2   2.082   56.3    .273   65.9    .295  -40.3 !     6.9
%  2800    .143  144.3   1.983   54.0    .292   65.0    .297  -42.4 !     6.4
%  3000    .157  131.2   1.884   51.0    .312   63.6    .290  -42.0 !     6.0
% ! Noise data:
% ! Freq.     Fmin        Gamma-opt         rn
%   500       1.45     .194     27.0       .250
%   900       1.60     .164     49.0       .260
%  1000       1.65     .166     55.0       .280
%  2000       2.20     .165   -175.0       .180
% ---------------------------------------------------------------------------

close all
clear all

% parameter at 1GHz
S11 = -0.099 - 0.092i;
S12 = 0.0329 + 0.109i;
S21 = 0.552 + 4.77i;
S22 = 0.314 - 0.185i;

% Unliteral Assumption: S12 = 0
gamma_out_unl = S22;
gamma_L_unl = conj(gamma_out_unl);
gamma_in_unl = S11;
gamma_S_unl = conj(gamma_in_unl);
Gtran_max_unl = 10*log10(((1-abs(gamma_S_unl)^2)/(abs(1-
S11*gamma_S_unl))^2)*(abs(S21))^2*(1-(abs(gamma_L_unl))^2)/((abs(1-
S22*gamma_L_unl)))^2);

% Biliteral Assumption for simultaneous conjugate match: S12 ~= 0
delta = S11*S22-S12*S21;
K = (1-(abs(S11))^2-(abs(S22))^2+(abs(delta))^2)/(2*abs(S12*S21));

B1 = 1 + (abs(S11)^2) - (abs(S22))^2 - (abs(delta))^2;
B2 = 1 + (abs(S22)^2) - (abs(S11))^2 - (abs(delta))^2;
C1 = S11 - delta * conj(S22);
C2 = S22 - delta * conj(S11);

gamma_S1 = (B1 + sqrt(B1^2-4*(abs(C1))^2))/(2*C1);
gamma_S2 = (B1 - sqrt(B1^2-4*(abs(C1))^2))/(2*C1);

if abs(gamma_S1)>1
    gamma_S = gamma_S2;
else
    gamma_S = gamma_S1;
end

gamma_L1 = (B2 + sqrt(B2^2-4*(abs(C2))^2))/(2*C2);
gamma_L2 = (B2 - sqrt(B2^2-4*(abs(C2))^2))/(2*C2);
```

```
if abs(gamma_L1)>1
    gamma_L = gamma_L2;
else
    gamma_L = gamma_L1;
end

if K>1 && abs(delta)<1
    disp('Unconditionally Stable');
    Gtran_max = 10*log10((abs(S21)/abs(S12))*(K-sqrt(K^2-1)));
else
    disp('Not Stable');
end
```

Attachment

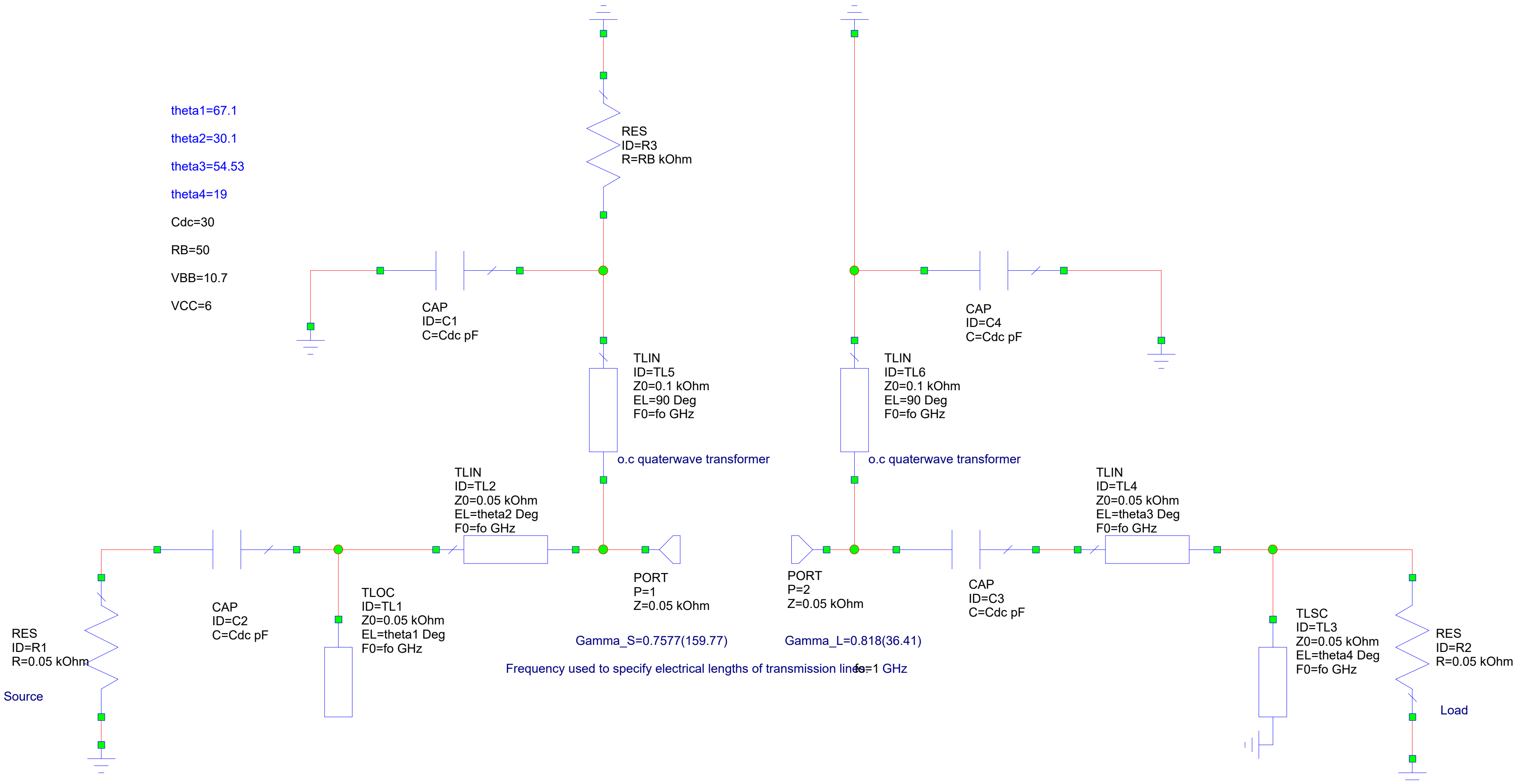


Figure 1. Conjugate Matching

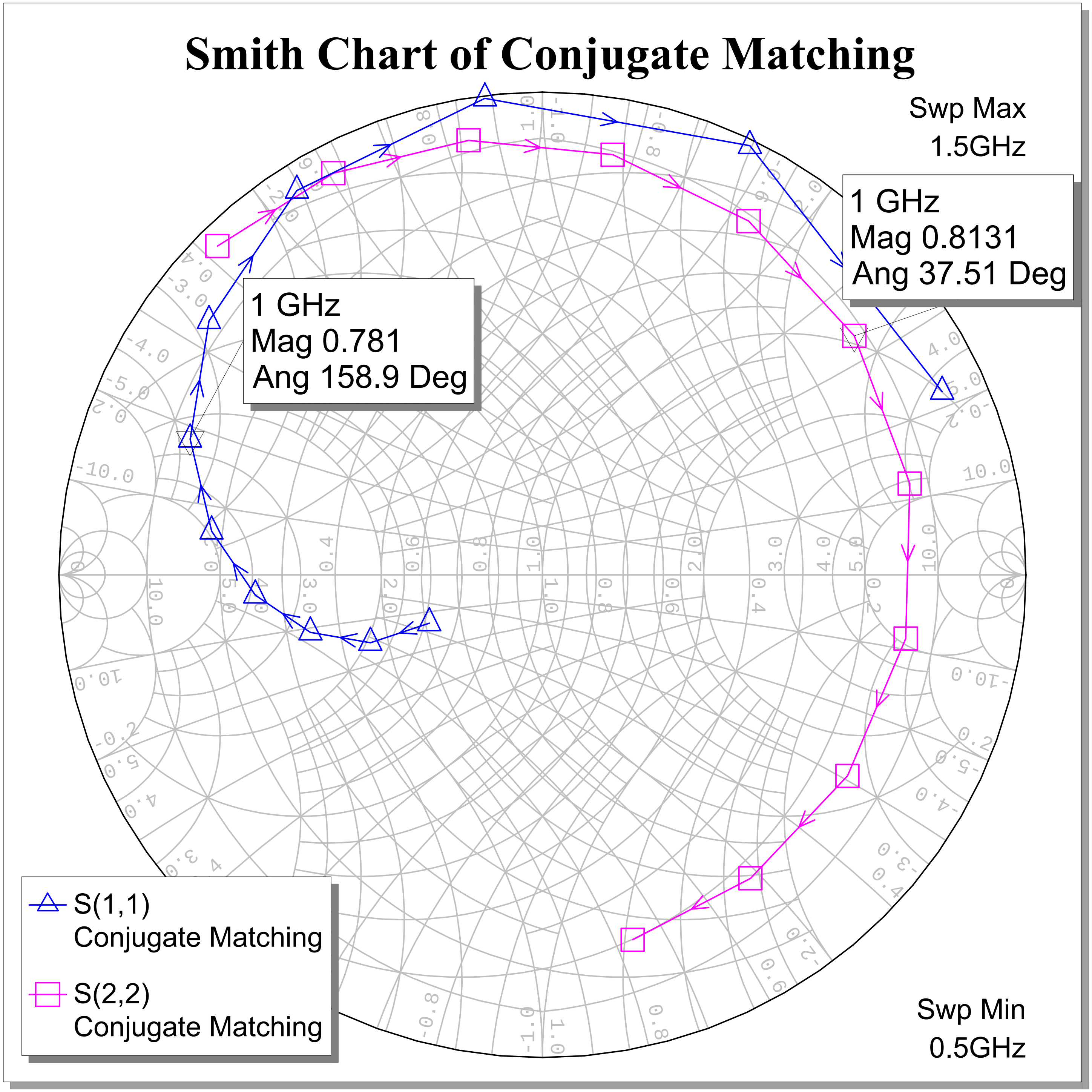


Figure 2. S11 and S22 of Conjugate Matching Cricuit

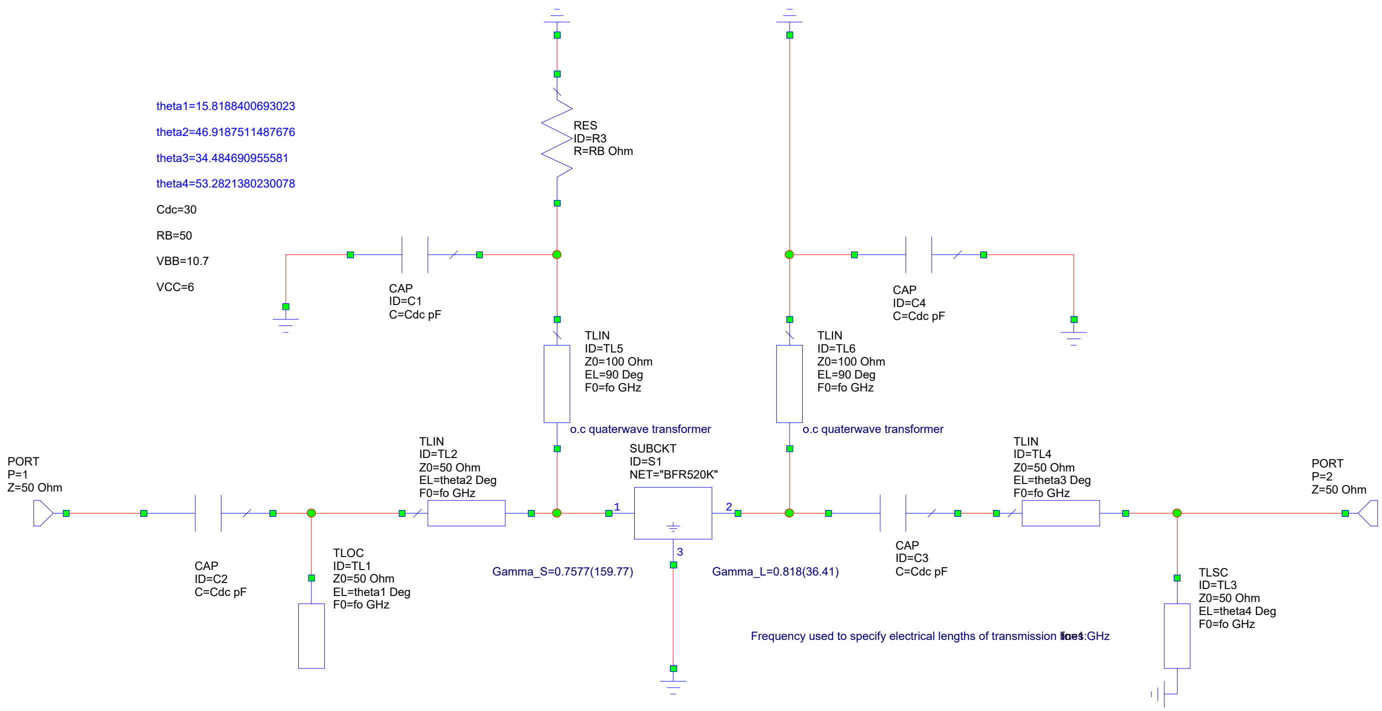


Figure 3. Transmission Line Design of Microwave Amplifier

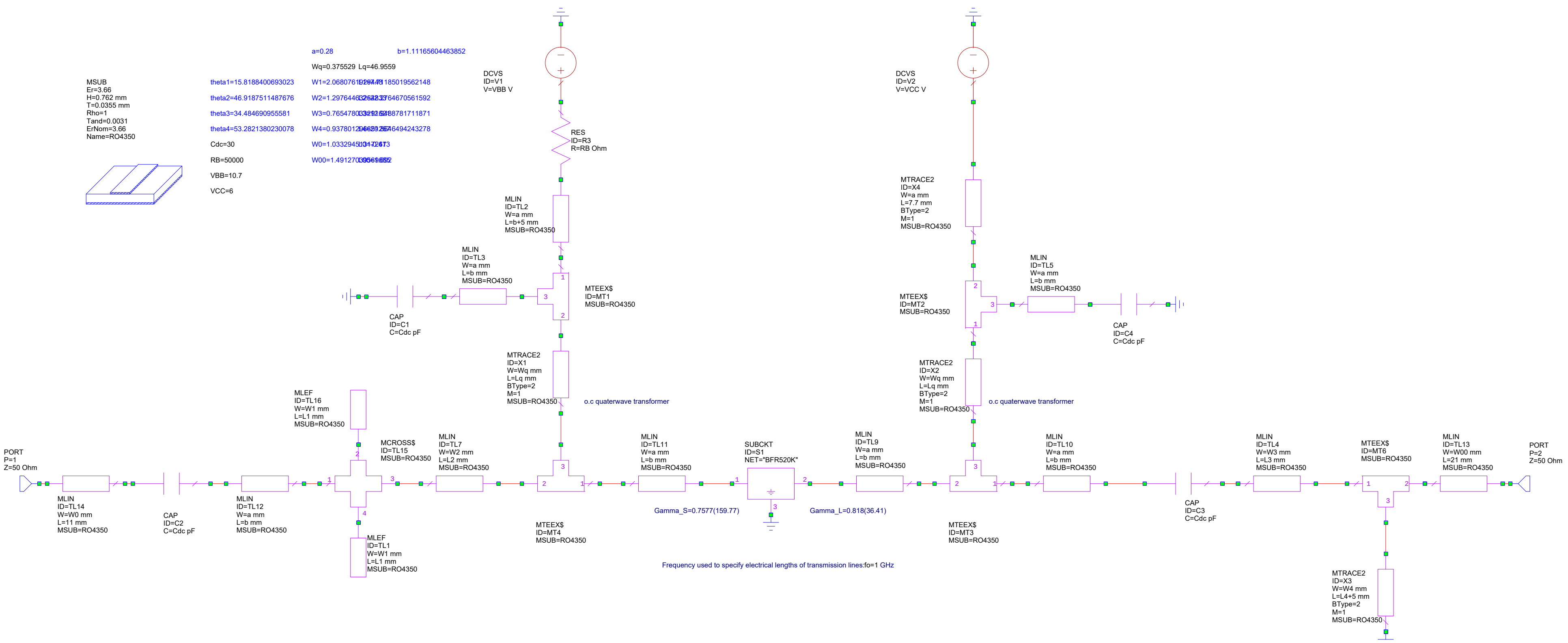
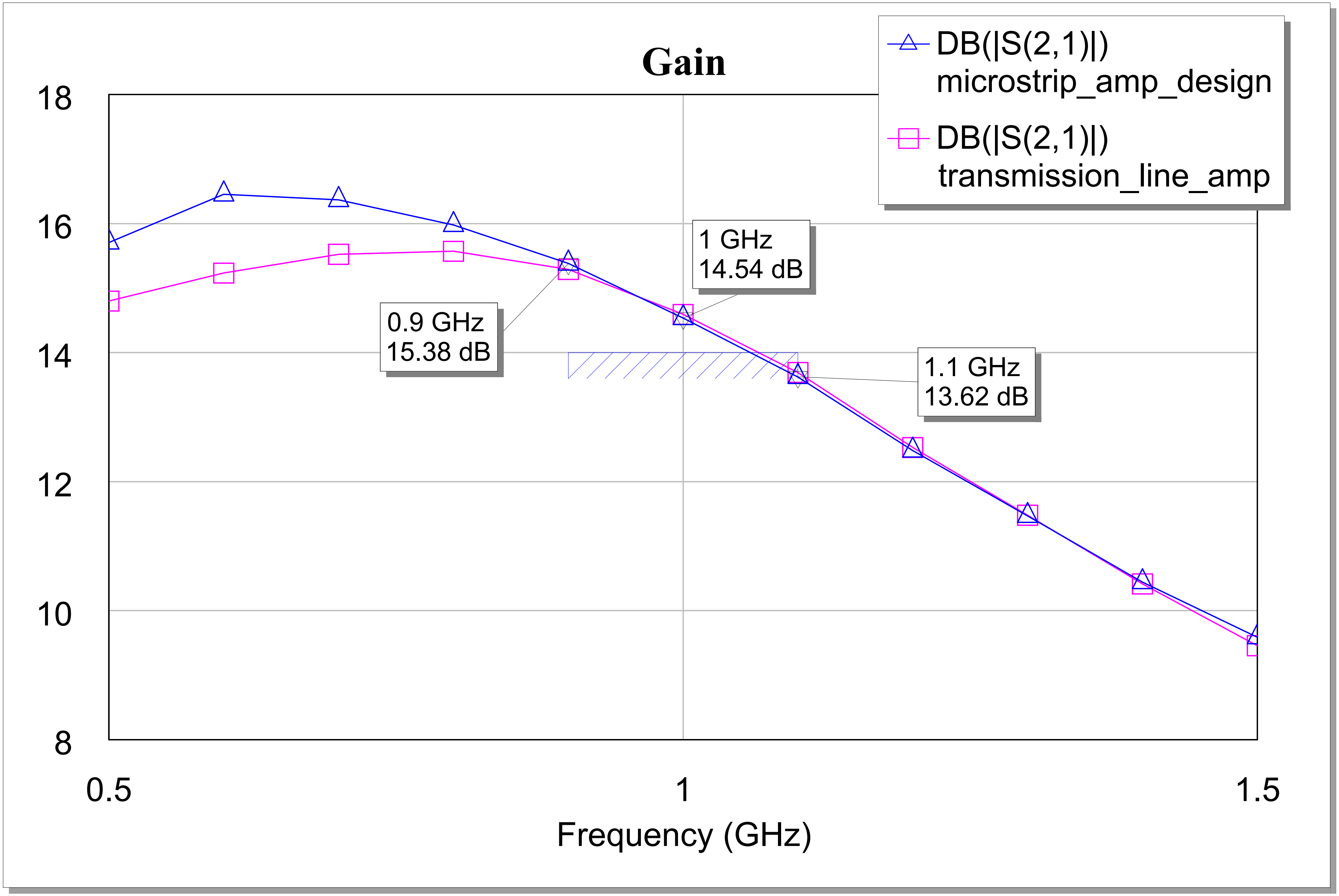


Figure 4. Microstrip Design of Microwave Amplifier



Attachment Figure 5. Gain of Transmission Line Design vs. Microstrip Design

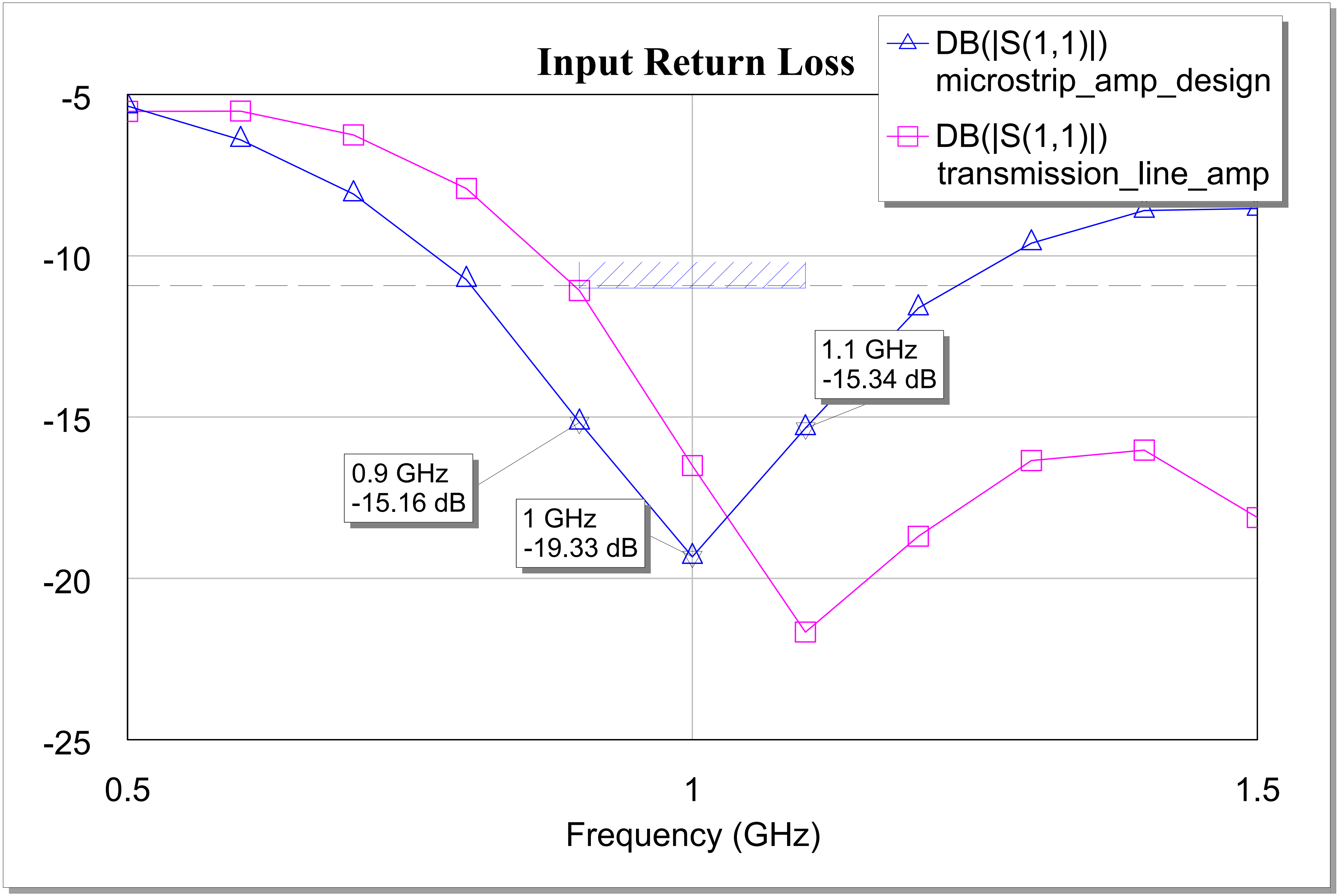


Figure 6. S11 of Transmission Line Design vs. Microstrip Design

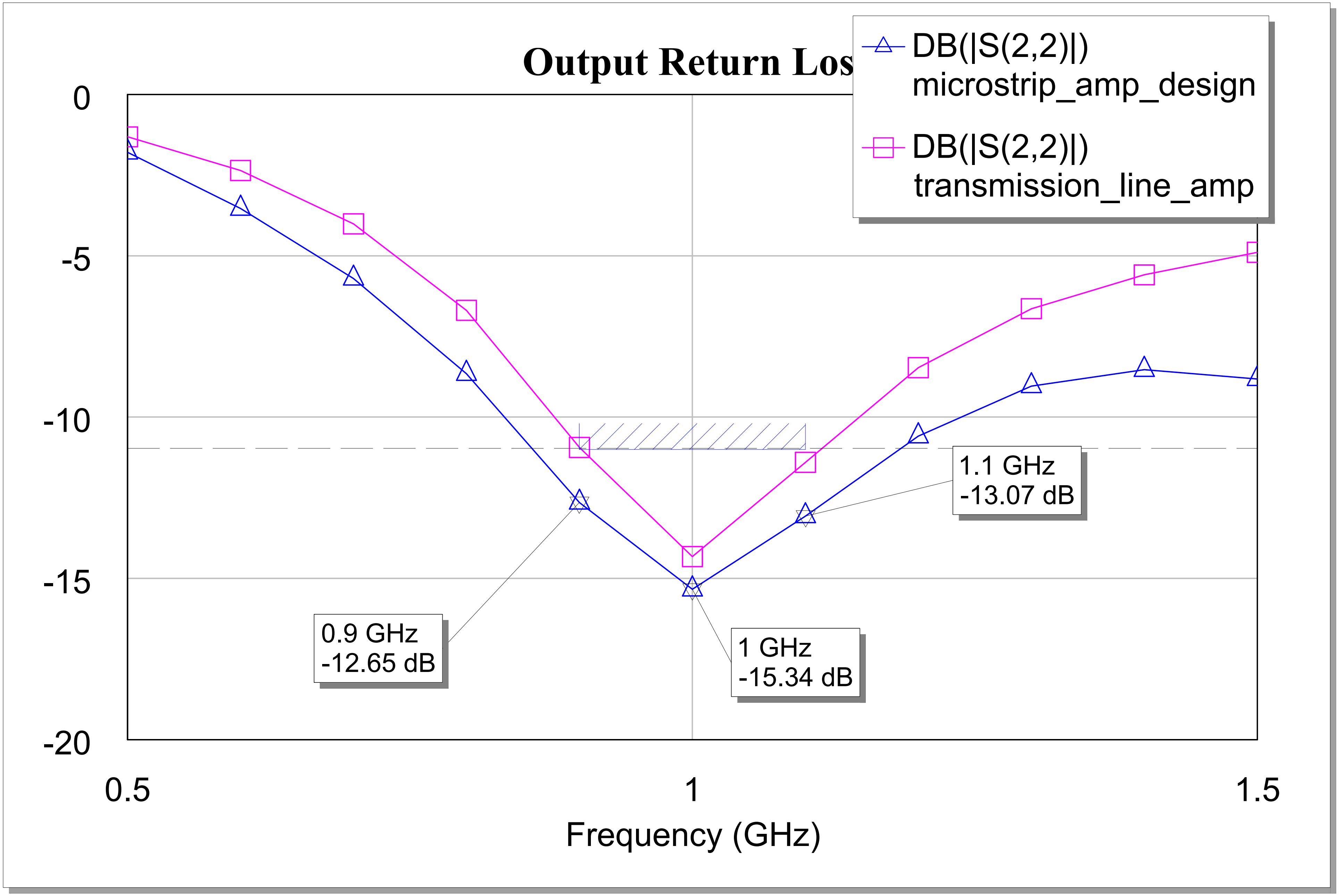


Figure 7. S22 of Transmission Line Design vs. Microstrip Design

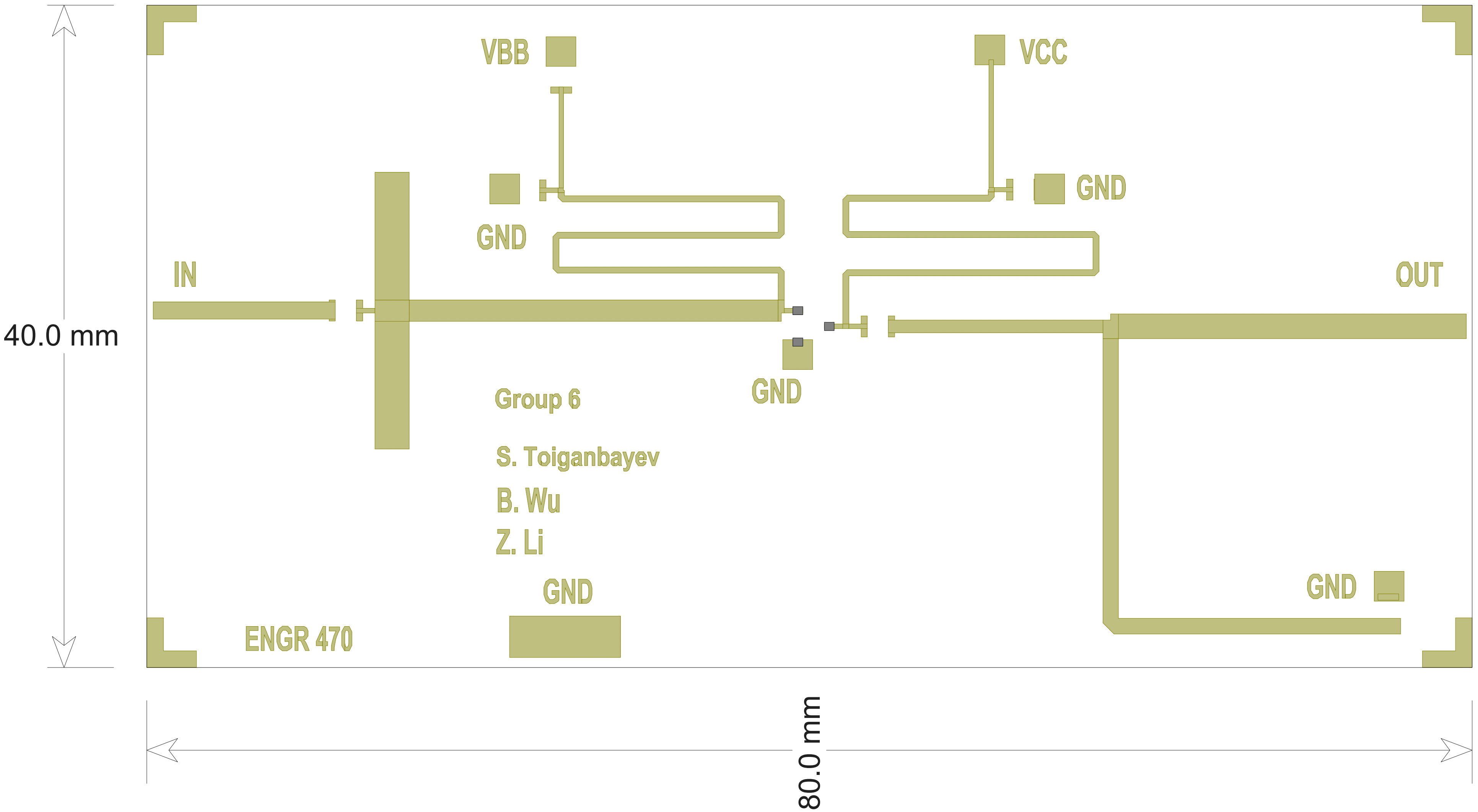


Figure 8. Circuit Layout Design