EHB 451E

Active Microwave Circuits

Term Project

6 GHZ Single Stage Low Noise Amplifier Design

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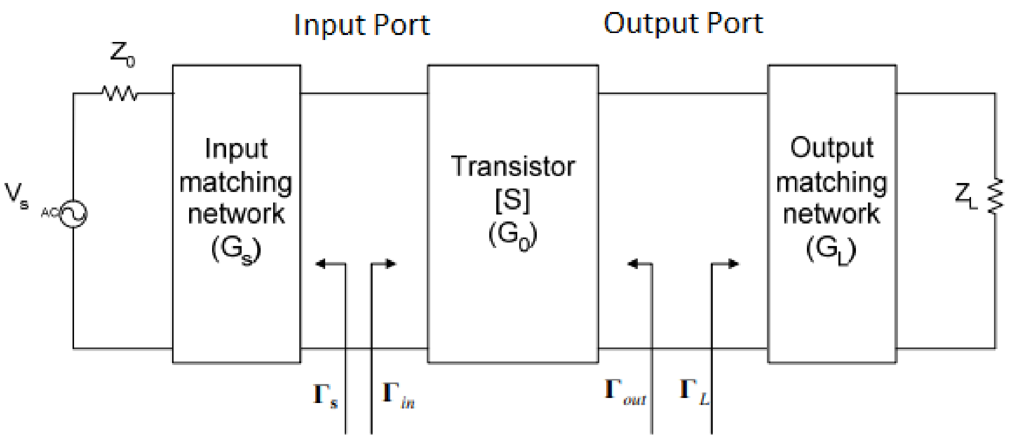


Figure 1.1: A general amplifier two-port network [1].

Istanbul Technical University

2019

İçindekiler

1. INTRODUCTION

A low-noise amplifier (LNA) is an amplifier that is used to amplify signals with very low strength, usually from an antenna [2]. Input signal of these amplifiers are very low – powered, barely recognizable, and they should be amplified without significant degrade on signal to noise ratio. Otherwise important information might be lost. LNA's are one of the most important circuit components present in signal receivers.

A typical LNA may supply a power gain of 100 (20 dB) while decreasing the signal-to-noise ratio by less than a factor of two (a 3 dB noise figure (NF)) [3]. The goal of this project is to achieve somewhat close power gain and a noise figure with the amplifier that will be made.

Low noise amplifiers are a vital part of low noise blocks. A low noise block (LNB) is the receiving device mounted on satellite dishes used for satellite TV reception, which collects the radio waves from the dish and converts them to a signal which is sent through a cable to the receiver inside the building [4]. A cross-section across a low-noise block downconverter can be seen in Figure 1.2.

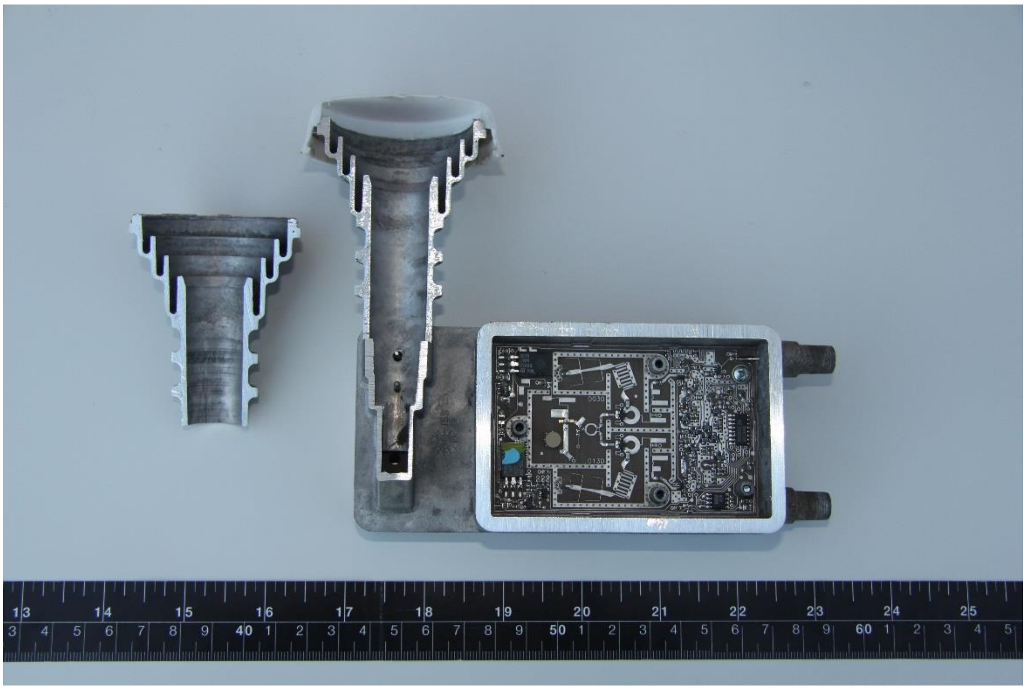


Figure 1.2: Low Noise Downconverter.

A low noise downconverter includes a low noise amplifier, a frequency mixer, a local oscillator and an intermediate frequency (IF) amplifier.

Low noise blocks are firstly branched with their RF/Input frequency band. They can be single dual or triple band designed. Also, the gain of these blocks can be fixed number with a single stage pass, or between a range with step by step design.

In this project, the motivation of the design it to make a low noise amplifier where to be used in 6 GHz center frequency. For the chosen transistor FHX76LP the noise figure minimum value is given as 0.3 dB at 6 GHz. The design will focus on to develop a LNA with around 0.6 dB noise figure, and the maximum gain that is achievable at this Noise Figure. Coming up; in the Design part we will make the calculations and simulations. The expected result is that, with the quality of this LNA satisfying the standards in the industry and being able to use in a low noise block. In Figure 1.3 the transistor physical structure can be examined.

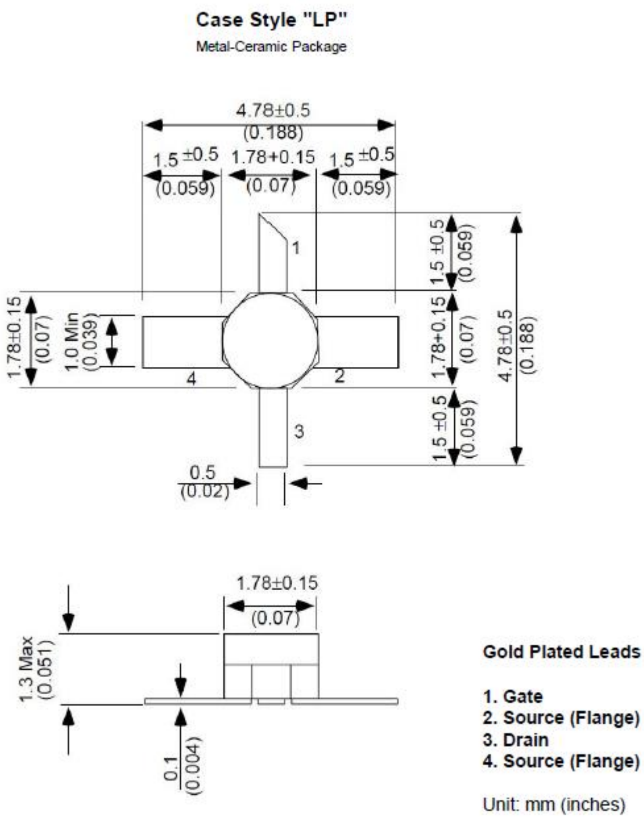


Figure 1.3: Physical Structure of FHX76LP.

2. DESIGN

For the 6 GHz low noise amplifier design, the transistor is chosen as the “FHX76LP” super low noise HEMT designed in “Sumitomo Electric” with features like low noise figure, high associated gain and high reliability [5].

Before getting into any calculation, the first problem that is encountered is the dataset scale in the datasheet of the transistor. S parameters are only given in 1 GHz strides, which can be seen in Figure 2.1.

S-PARAMETERS

V_{DS} = 2V, I_{DS} = 10mA

FREQUENCY	S11		S21		S12		S22	
(MHZ)	MAG	ANG	MAG	ANG	MAG	ANG	MAG	ANG
1000	.987	-14.8	5.535	164.2	.014	80.2	.585	-11.4
2000	.965	-29.4	5.463	148.8	.027	70.2	.567	-22.9
3000	.925	-44.6	5.334	133.2	.041	57.7	.538	-34.7
4000	.878	-58.3	5.154	118.8	.049	50.0	.511	-45.2
5000	.828	-72.9	5.019	104.3	.059	40.6	.480	-56.4
6000	.776	-87.8	4.825	89.8	.067	32.4	.446	-68.4
7000	.719	-102.8	4.606	75.6	.075	23.2	.413	-80.6
8000	.669	-116.6	4.354	61.9	.079	15.2	.394	-92.6
9000	.631	-129.4	4.130	49.5	.083	6.3	.374	-102.4
10000	.590	-141.7	3.982	37.0	.086	.2	.365	-112.5
11000	.548	-155.3	3.849	24.7	.088	-7.6	.335	-121.9
12000	.507	-169.6	3.689	12.4	.091	-14.2	.323	-134.1
13000	.482	177.0	3.545	-.2	.095	-20.8	.313	-145.0
14000	.459	164.7	3.425	-11.9	.096	-28.7	.315	-155.9
15000	.439	152.3	3.330	-24.4	.098	-36.4	.324	-165.4
16000	.419	138.7	3.264	-37.1	.102	-44.1	.322	-174.3
17000	.404	123.9	3.238	-50.3	.103	-54.6	.321	175.4
18000	.383	107.3	3.176	-63.5	.108	-63.4	.316	165.3
19000	.377	93.2	3.101	-78.0	.105	-74.5	.320	153.2
20000	.348	76.5	3.028	-92.3	.110	-87.6	.301	146.1

Figure 2.1: S Parameters of the FHX76LP

To enrich this data, a simple curve fitting algorithm is written as a solution. First a 2^{nd} degreed polynomial is drawn with curve fitting tool.

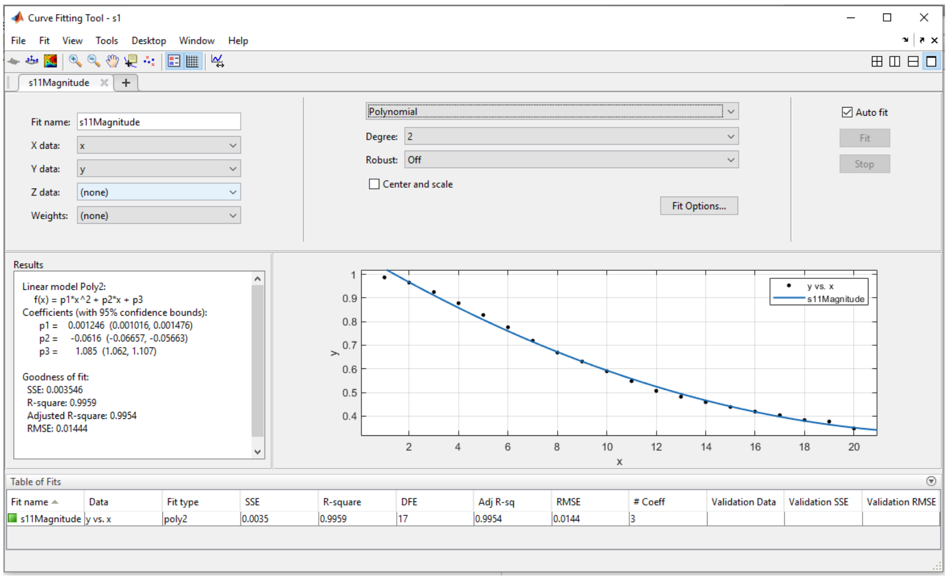


Figure 2.2: First trial for curve fitting, 2^{nd} degree polynomial

```
fittedmodel =

     Linear model Poly2:
     fittedmodel(x) = p1*x^2 + p2*x + p3
     Coefficients (with 95% confidence bounds):
       p1 =    0.001246  (0.001016, 0.001476)
       p2 =     -0.0616  (-0.06657, -0.05663)
       p3 =       1.085  (1.062, 1.107)
>> goodness

goodness =

  struct with fields:

           sse: 0.0035
       rsquare: 0.9959
           dfe: 17
    adjrsquare: 0.9954
          rmse: 0.0144

>> output

output =

  struct with fields:

        numobs: 20
      numparam: 3
     residuals: [20×1 double]
      Jacobian: [20×3 double]
      exitflag: 1
     algorithm: 'QR factorization and solve'
    iterations: 1
```

Figure 2.3: Coefficients, goodness and output for 2^{nd} degree polynomial.

Although this curve in Figure 2.2, had a value of R-Square really close to 1, which means our curve is really good for this dataset; it had a problem for cutoff frequencies. Below 1 GHz and over 20 GHz is not reflecting the truth for the S11 magnitude. Moreover, another curve can be found in Figure 2.4, which is chosen to kind of solve this issue.

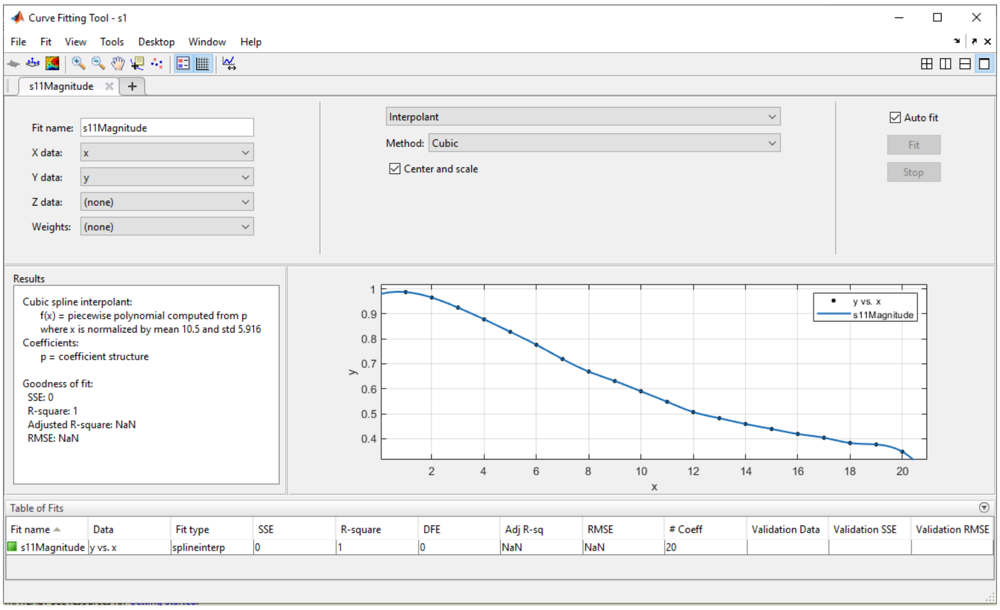


Figure 2.4: Second trial for curve fitting, a cubic spline interpolant.

This curve in Figure 2.4 is chosen with the reasoning of goodness in the fit, and the expected values of S parameter magnitudes in the results. The attributes, goodness and output for this curve can be seen in Figure 2.5.

```
s11Magnitude =

     Cubic spline interpolant:
       s11Magnitude(x) = piecewise polynomial computed from p
       where x is normalized by mean 10.5 and std 5.916
     Coefficients:
       p = coefficient structure
>> goodness

goodness =

  struct with fields:

           sse: 0
       rsquare: 1
           dfe: 0
    adjrsquare: NaN
          rmse: NaN

>> output

output =

  struct with fields:

       numobs: 20
     numparam: 20
    residuals: [20×1 double]
     Jacobian: []
     exitflag: 1
```

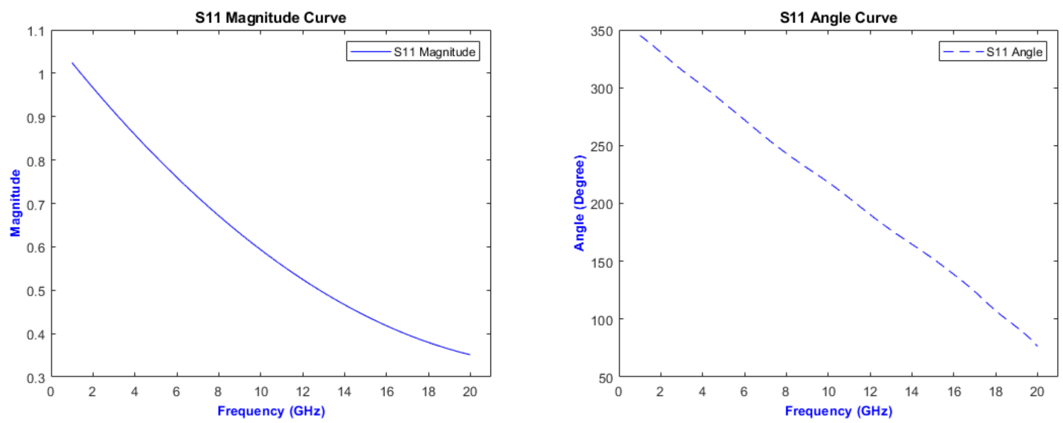
Figure 2.5: Attributes, goodness and output for the cubic spline interpolant.

After the selection of the curve type, the algorithm in Figure 2.6 is used in S11, S12, S21 & S22 magnitudes and angles. For each S parameter the x & y are updated from the table.

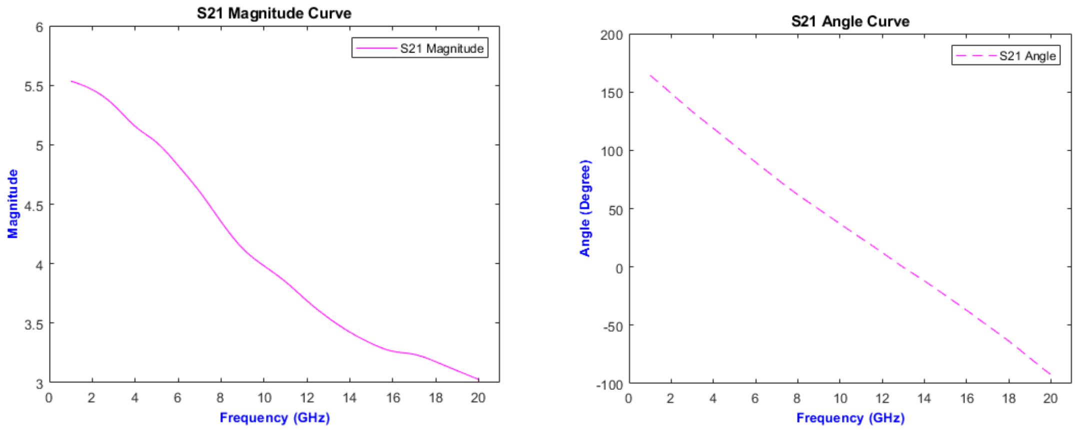
```
x = [ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20];

y = [ .987  .965 .925 .878  .828 .776  .719  .669  .631 .590 .548 .507 .482  .459
.439 .419  .404 .383 .377  .348 ];

plot(s11Magnitude, 'b');
xlim([0 21]);
title('S11 Magnitude Curve')
legend("S11 Magnitude");
xlabel('Frequency (GHz)', 'FontSize',10,'FontWeight','bold','Color','b')
ylabel('Magnitude', 'FontSize',10,'FontWeight','bold','Color','b')

Results=zeros(1,200);

for counter = 10:200

        Results(counter-9) = s11Magnitude(counter/10);

end



Temp = transpose(Results);

dlmwrite('S11Magnitude.txt',Temp);
```

Figure 2.6: The simple algorithm from MATLAB, together used with curve fitting tool.

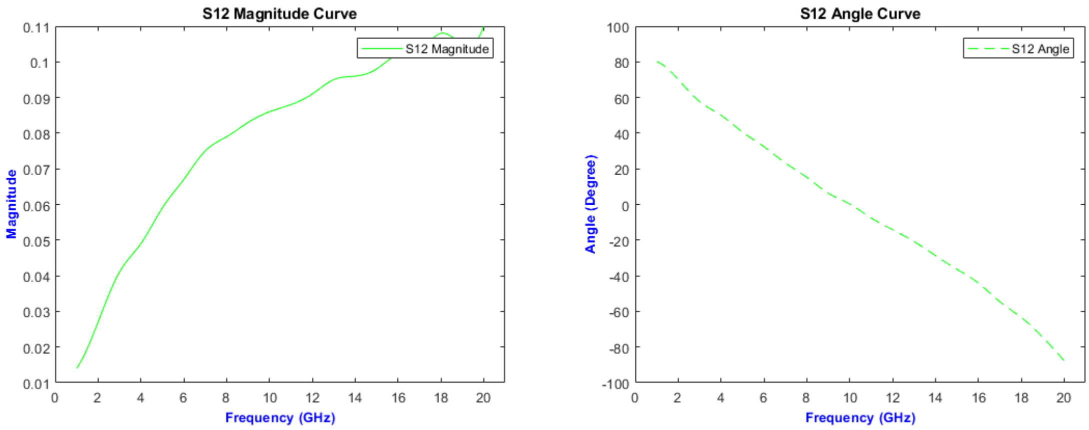
From this algorithm and the curve fitting tool in MATLAB, the results can be seen in Figure 2.7.



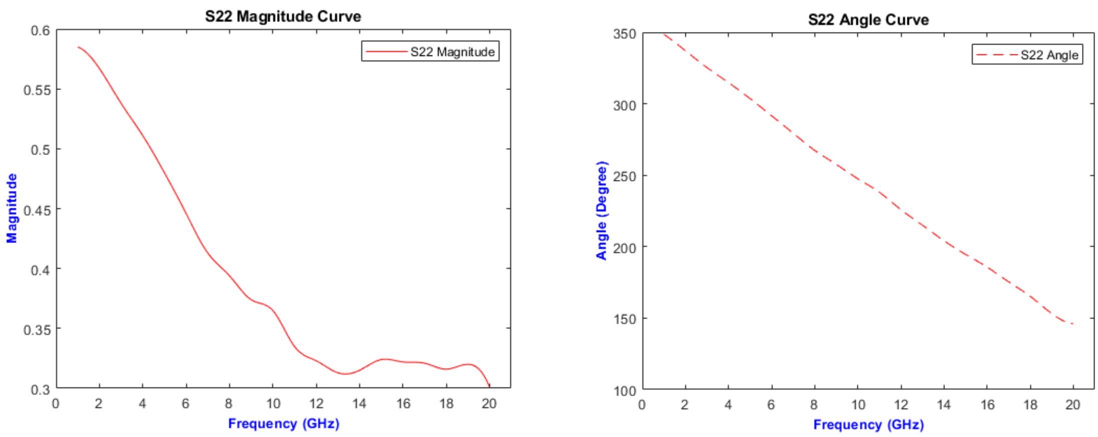
(a)



(b)



(c)



(d)

Figure 2.7: S Parameter Magnitude – Angle Fitted Curves (a) S11, (b) S21, (c) S12, (d) S22.

From these curves, the dataset for S parameters are enriched to 100 MHz strides. The idea behind this procedure is to get a more precise result in simulation.

Our design goal was to make a low noise amplifier at 6 GHz with a 0.6 dB Noise Figure. From the datasheet of the transistor, or Figure 2.1:

$S_{11} = 0.776 \angle -87.8$

$S_{12} = 0.067 \angle 32.4$

$S_{21} = 4.825 \angle 89.8$

$S_{22} = 0.446 \angle -68.4$

Using these S parameters, K and Δ is found as:

$\Delta = | S_{11} * S_{22} - S_{12} * S_{21} | = 0.64 \angle\ 220.2$

$K = (1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2) / (2| S_{12}\ S_{21}|^2) = 1.8683$

From these solutions we can safely say that our transistor at 6 GHz is unconditionally stable; as" $\Delta < 1$ & $K > 1$".

The Noise Parameters are given in the datasheet, also it can be seen in Figure 2.8.

NOISE PARAMETERS

V_{DS} = 2V, I_{DS} = 10mA

Freq. (GHz)	Γ opt (MAG)	Γ opt (ANG)	NFmin (dB)	Rn/50
2	0.79	12.5	0.28	0.24
4	0.62	30.0	0.29	0.20
6	0.50	54.1	0.30	0.16
8	0.41	83.6	0.32	0.12
10	0.35	117.3	0.35	0.08
12	0.32	153.8	0.40	0.06
14	0.30	-168.0	0.48	0.06
16	0.29	-129.5	0.60	0.09
18	0.29	-91.8	0.72	0.14
20	0.29	-56.3	0.91	0.19

Figure 2.8: Noise Parameters of FHX76LP.

As it was pointed out before, the noise figure for 6 GHz is given as F_{min} = 0.3 dB. Also $\Gamma_{opt} = 0.50 \angle 54.1$ and $R_N/Z_0 = 0.16$ where Z_0 = 50 ohms. Because 0.6 dB noise figure is the upper tolerance limit and the design goal, the constant noise figure circle should be drawn for F = 0.6 dB. From the lecture notes, we learned the equations as:

$F = 10^{0.06} = 1.148$

$F_{min} = 10^{0.03} = 1.071$

$N = [\ (F-F_{min}) / 4(R_N/Z_0)\ ]\ .\ |1 + \Gamma_{opt}|^2 = 0.2199$

$CF = \Gamma opt / (N + 1) = 0.409 \llcorner 54.1$ *(This is on the same line as Γopt, expected to)*

$RF = [\ N*(N + 1- |\Gamma opt|^2)\ ]^{0.5} / (N+1) = 0.3786$

These results drawn on a Smith Chart can be seen in Figure 2.9.

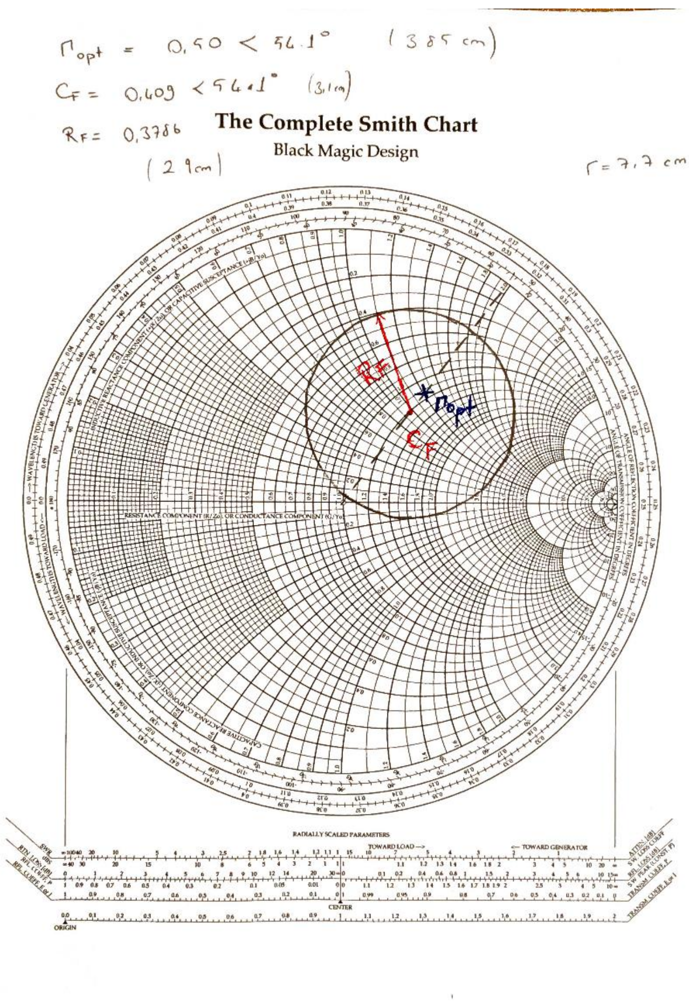


Figure 2.9: Constant Noise Figure Circle for F = 0.6 dB.

Any Γ value that is taken on this circle will give F = 0.6 dB to us. From this point on we need to consider the gain circles for out design.

From our textbook, we know that if “S_{12}” can be set equal to zero, the design becomes much simpler. The standart parameter to be checked for this procedure is called “Universal Figure of Merit” and can be shown in the Figure 2.10 [6]:

$$U = \frac{|S_{12}||S_{21}||S_{11}||S_{22}|}{(1-|S_{11}|^2)(1-|S_{22}|^2)}$$

Figure 2.10: Universal Figure of Merit

From this equation;

$U = 0.0137$

The condition to be met was, as in Figure 2.11;

$$\frac{1}{(1+U)^2} < \frac{G_T}{G_{TU}} < \frac{1}{(1-U)^2}$$

Figure 2.11: Condition between U and Transducer Power Gain & it's unilateral value.

From this equation;

$0.973 < G_T / G_{TU} < 1.027$

And in dB form;

$-0.11\ dB < G_T / G_{TU} < 0.115\ dB$

For the G_T gain calculation, this range is acceptable; so we can continue the design in unilateral case.

For $S_{12} = 0$;

$\Gamma_L = transpose\ (\Gamma out) = transpose\ (S_{22}) = 0.446 \angle 68.4$

$G_{Lmax} = 1 / (1-|S_{22}|^2) = 1.2483$

$G_{Lmax} = 0.9632\ dB$

To achieve G gain, we need two more results where;

$G\ (dB) = G_L\ (dB) + G_O\ (dB) + G_S\ (dB)$

From this point on G_O and G_S as;

$G_O = |S_{21}|^2 = 23.28$

$G_O = 13.66\ dB$

Now the G_S calculation and the tangent constant gain circle to the chosen noise figure circle.

$G_{Smax} = 1 / (1-|S_{11}|^2) = 2.51$

$G_{Smax} = 4\ dB$

$G_{MAX}\ (dB) = G_{Lmax}\ (dB) + G_O\ (dB) + G_{Smax}\ (dB) = 0.9632 + 13.66 + 4 = 18.62\ dB$

This is our maximum gain, the upper limit that can be achieved.

The tangent G_S circle is drawn on Smith Chart in Figure 2.12.

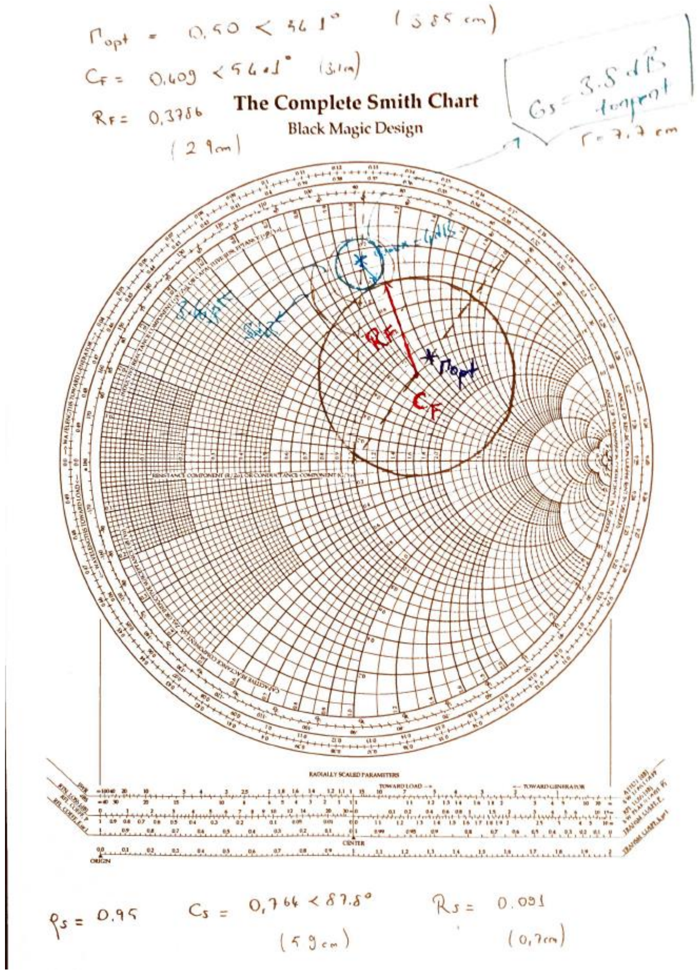


Figure 2.12: The tangent constant gain circle to the noise figure circle.

This circle in Figure 2.12 is drawn by hand, with the search of tangent circle calculated repeatedly. For “*G_S = 3.8 dB*" and “*$\Gamma_S = 0.69 \angle 84$* “is the interception point. From this point forward, if we choose a “*Γ_S”* in a smaller valued gain circle, our noise figure goal of “F = 0.6 dB" will not be met.

At this point, we will need a matching circuit to match the designed amplifier to the transmission line. A matched circuit general plan can be seen in Figure 2.13.

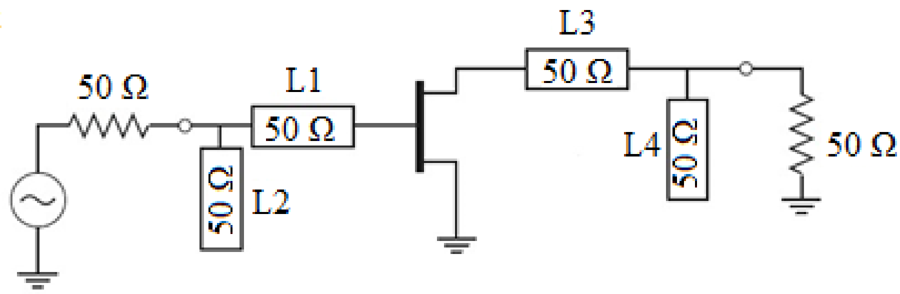
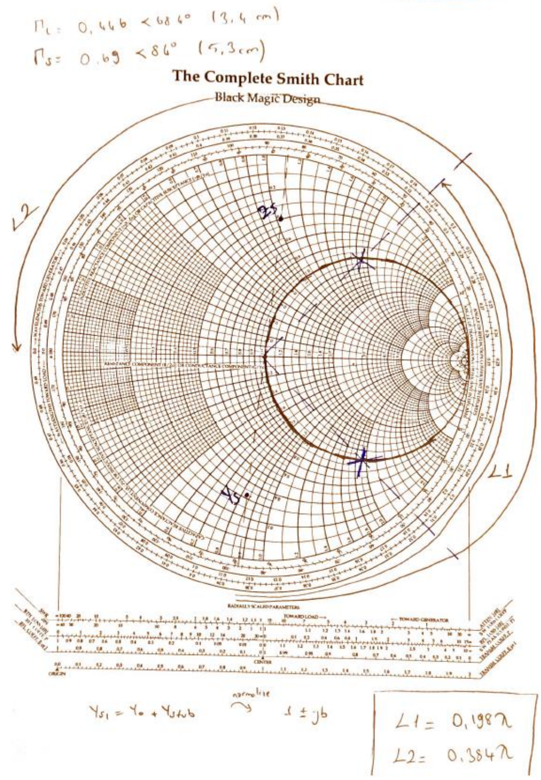
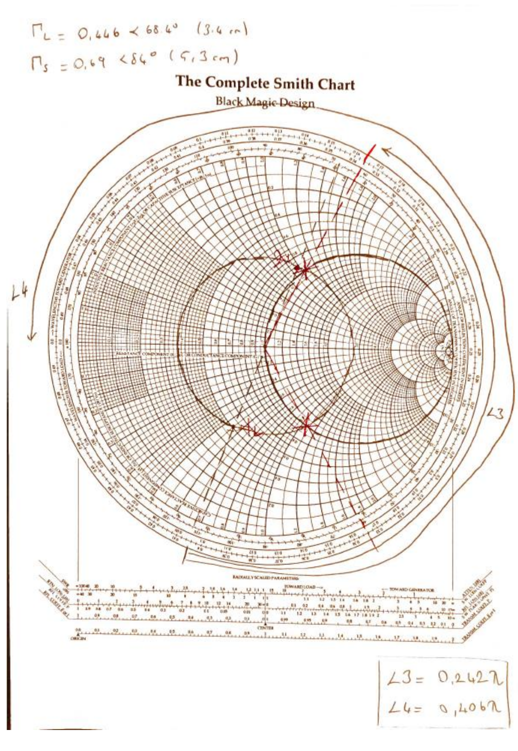


Figure 2.13: The matching circuit and the lengths L1, L2, L3, L4.

All the calculations and drawing can be found in Figure 2.14.



(a)



(b)

Figure 2.14: The length of matching circuits (a) Z_S (b) Z_L.

From the calculations in smith chart the lengths in the matching circuit is find as:

*L1 = 0.198 * λ cm*

*L2 = 0.384 * λ cm*

*L3 = 0.242 * λ cm*

*L4 = 0.406 * λ cm*

Using this matching circuit, we complete our design calculations.

The transmission line is chosen as a micro strip line called “Duroid”. This material, and its attributes are taken from the “Rogers Corporation – RT/Duroid 5880” datasheet [7].

For this substrate, the attributes are taken as:

H (Substrate Thickness) = 0.254 mm

Er (Relative Dielectric Constant) = 2.2

Mur (Relative Permeability) = 1

Cond (Conductivity) = 5.96E+7 {Copper}

T (Conductor Thickness) = 8 µm {Taken at the minimum end}

TanD (Dielectric Loss Tangent) = 0.0009

Now we can move on to the simulation.

3. SIMULATION

We used “Advanced Design System 2016” for simulating our design in the computer environment.

First of all, we need to see if the curve that we fitted is adequate for the design.

In this interest, we simulate our transistor with the estimated S parameters, and do a 1 GHz – 20 GHz swipe to see if we match the figures in 2.7.

The circuit can be seen in Figure 2.15, and the simulation results is drawn on 2.16.

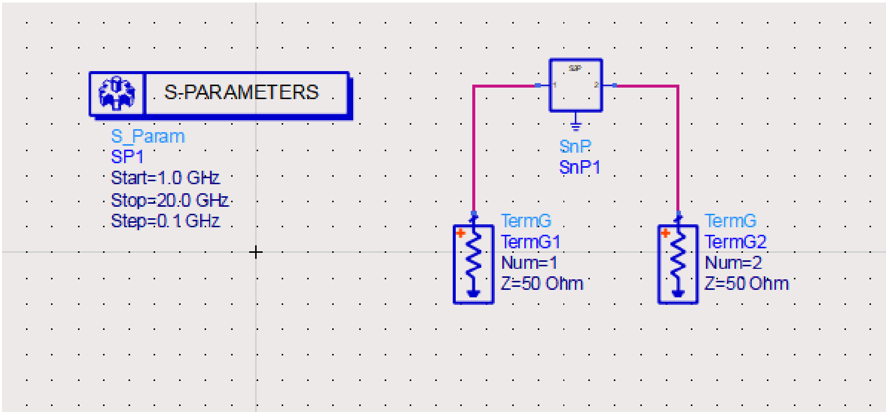
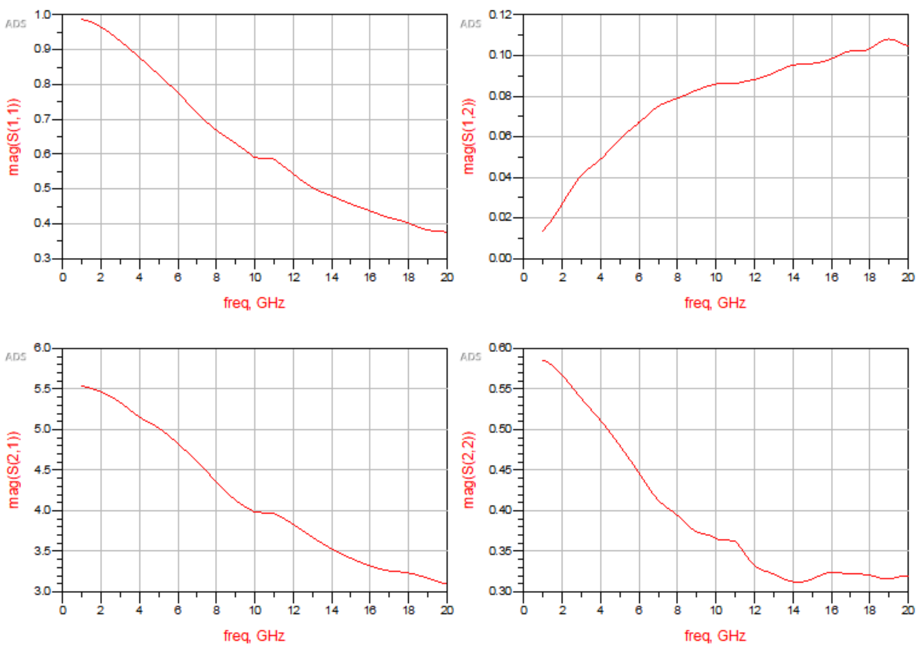
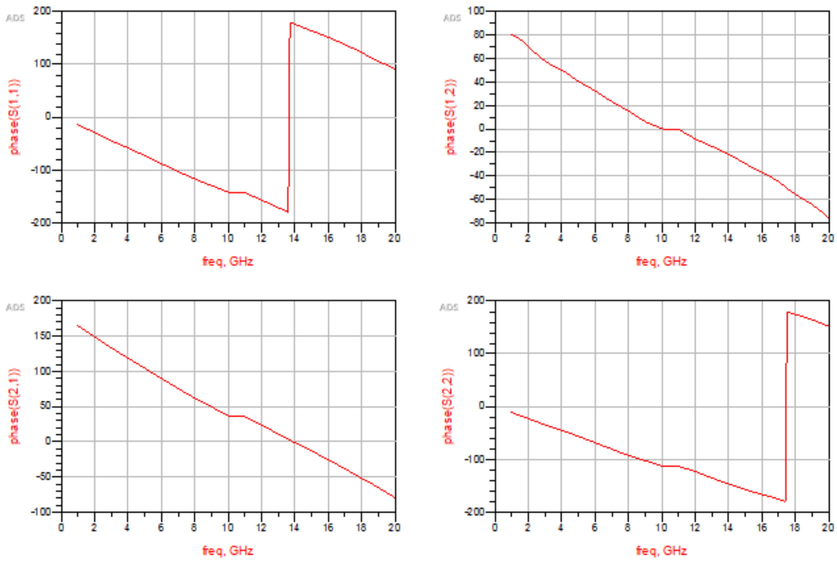


Figure 2.15: S Parameter Controller Circuit



(a)



(b)

Figure 2.16: Magnitude (a) and Phase (b) of simulated S parameters.

The magnitude plots are really close to the fitted curve, but there is a discontinuity in the phase plots. This is just because of the axis values, in fact, it is almost the same as the fitted curve.

Secondly, as we calculated the transmission line lengths, we will need the width of the lines for the $Z_0 = 50\ \Omega$. For this, we use a sweep tuning. This tuning circuit and the tuned variable can be seen in Figure 2.17. The result is given in Figure 2.18.

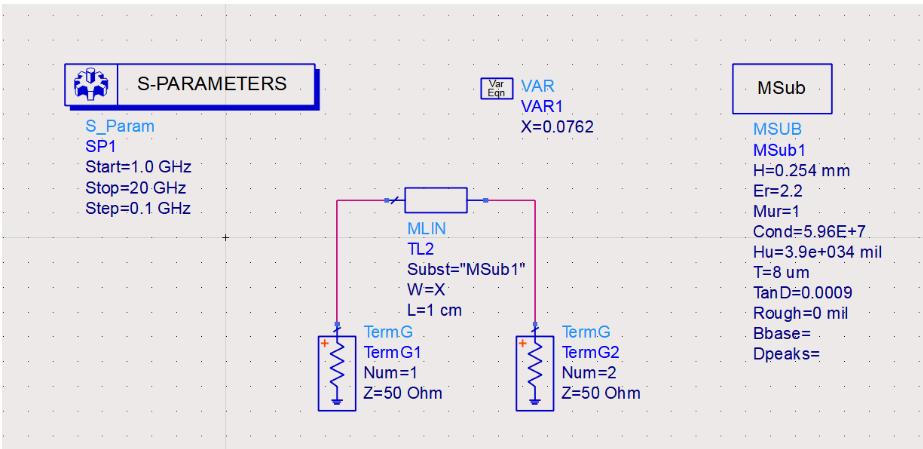


Figure 2.17: Width tuning sweep circuit.

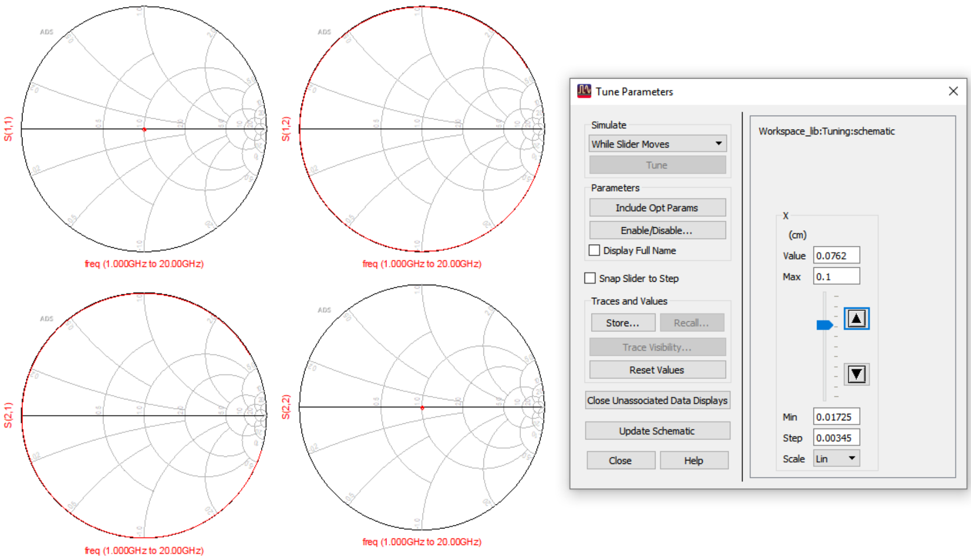


Figure 2.18: Simulation result for the tuning.

For "*W = 0.0762 cm*" chosen, the S11 and the s22 are at the center of the smith chart. So for this width selection, we satisfy $Z_0 = 50\ \Omega$.

Now we know the width and the length of our matching circuit elements. The low noise amplifier circuit is given in the Figure 2.19.

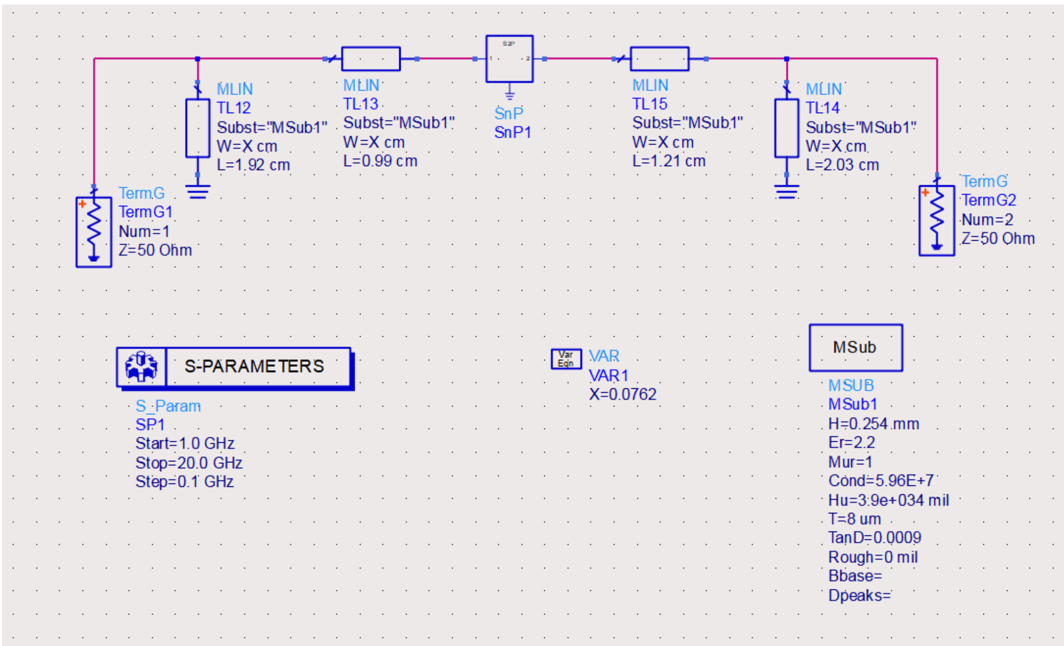


Figure 2.19: Complete Circuit.

For the given circuit, the gain plot looks like Figure 2.20.

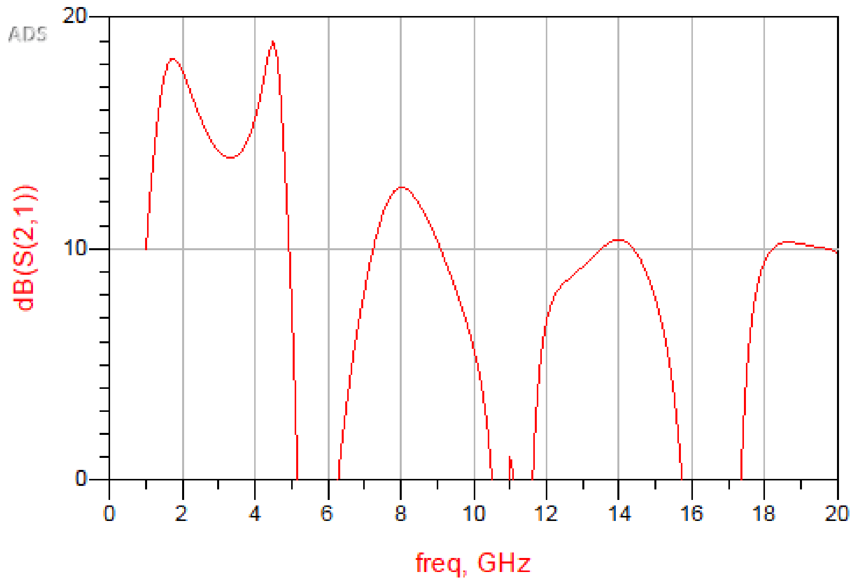


Figure 2.20: Gain of the amplifier.

This figure is, well, not what we expected for the 6 GHz range. From this point, the matched circuit lengths are the first thought to be changed. After some fine tuning in the lengths, circuit in Figure 2.21 is made.

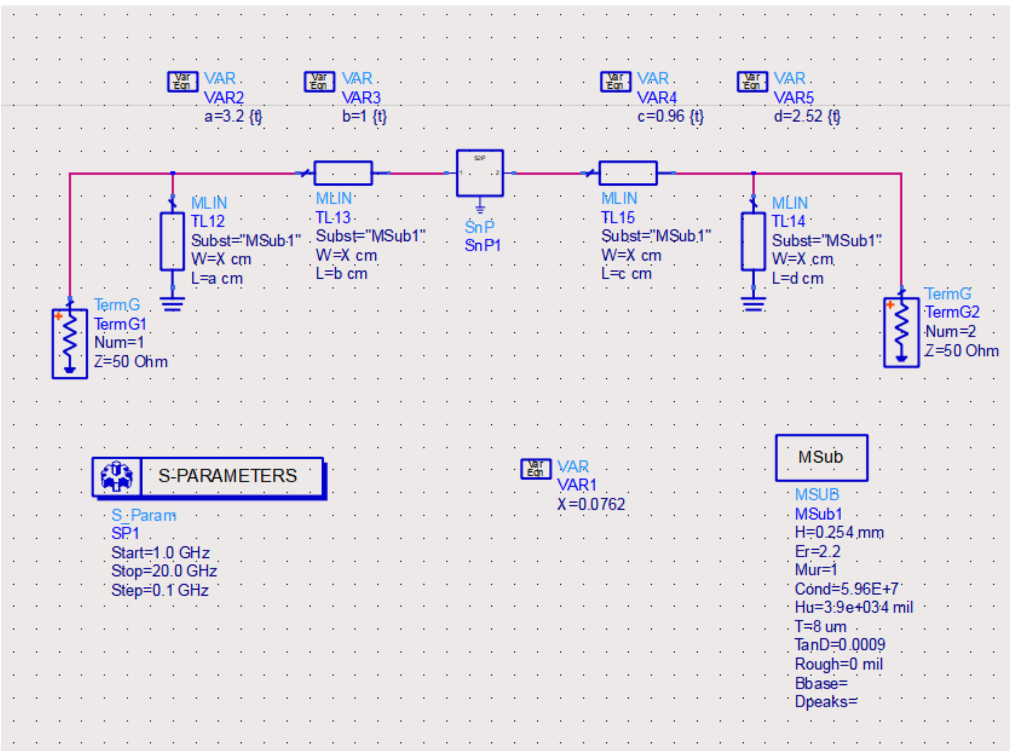


Figure 2.21: Fine-tuned circuit.

In this circuit, the length of the matching circuits are chosen in final as:

L1 = 3.2. cm

L2 = 1 cm

L3 = 0.96 cm

L4 = 2.52 cm

The new gain plot and the according tuning is given in Figure 2.22.

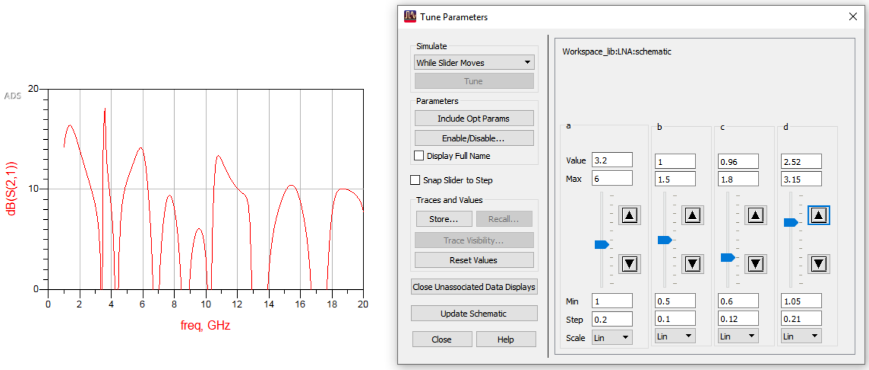


Figure 2.22: Fine-tuned gain plot.

In the Figure 2.22 the gain at 6 GHz is read as 14.08 dB. In our calculations we found “G_{MAX} *(dB) = 18.62 dB"* so this result is not unreal or unexpected. For the chosen noise figure “*F = 0.6 dB*”, an expected gain simulation is made.

4. RESULTS AND POTENTIAL FUTURE WORK

We begin our road for a low noise amplifier design, at 6GHz with a selected noise figure value. Our tradeoff was to get a little better gain, not using Γ_S equal to Γ_{opt} and not setting the goal for minimum noise figure.

In the book there is a quote from another book called "Avantek Microwave Semiconductors Data Book 1989" which gives an instance of a 4GHz low noise block example. This example can be seen in Figure 3.1.

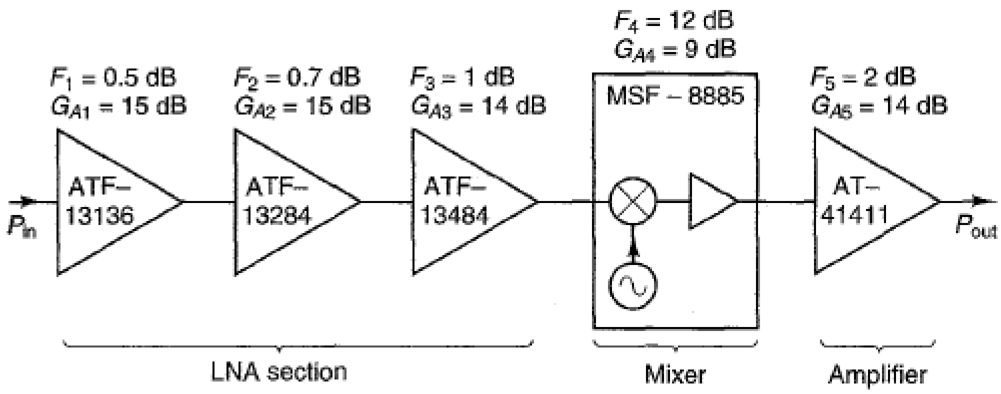


Figure 3.1: A 4-GHz LNB, consisting 2 LNA's and one general purpose amplifier [6].

From this example, it can be guessed that our design probably can be used in a front end in a Low Noise Block. Our design had the 0.6 dB noise figure and around 17 dB gain.

The first element has to have a really low noise figure as it effects all the blocks noise the most. 0.6 dB should not be that bad.

Also a 5.7 to 6 GHz, C band to UHF Band Low Noise Block called "BDC 5760-5200" does have a noise figure total of 3.5 dB and gain of 24 dB. This also supports that our design, can be used in a cascaded amplifiers system to form a Low Noise Block.

5. BIBLIOGRAPHY

[1] Url 1 - http://www.iitg.ac.in/engfac/krs/public_html/lectures/ee441/lecture_slides_5.pdf

[2] Url 2 - https://www.techopedia.com/definition/8101/low-noise-amplifier-lna

[3] Url 3 - https://en.wikipedia.org/wiki/Low-noise_amplifier

[4] Url 4 - https://en.wikipedia.org/wiki/Low-noise_block_downconverter

[5] Url 5 - https://www.sedi.co.jp/file.jsp?/pdf/FHX76LP_ED1-3.pdf

[6] Book - Microwave Transistor Amplifiers: Analysis and Design (page: 239, page: 321)

[7] Url 6 - https://rogerscorp.com/-/media/project/rogerscorp/documents/advanced-connectivity-solutions/english/data-sheets/rt-duroid-5870---5880-data-sheet.pdf