Lab Project 2: Design Low Noise Amplifier (LNA)

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Design and optimize a microwave amplifier with the specified characteristics, using both Lumped and distributed elements.

Discuss the difference between the outputs of the lumped and distributed element amplifiers.

Find the better of the two, while operating at frequency of 3.2 Ghz.

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5/8/2009

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Project Objectives

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Design Procedures

- Evaluate Rollet's stability factor: if K< 1 design for specific gain or noise resistively load the drain if k>1 conjugate match.
- If K< 1 plot stability circles.
- Design for specific gain: plot gain circles
- Design for low noise: plot noise circles and terminate drain for best match.
- Resistively load: add a series resistor to the drain and conjugate match both ports.

Specifications

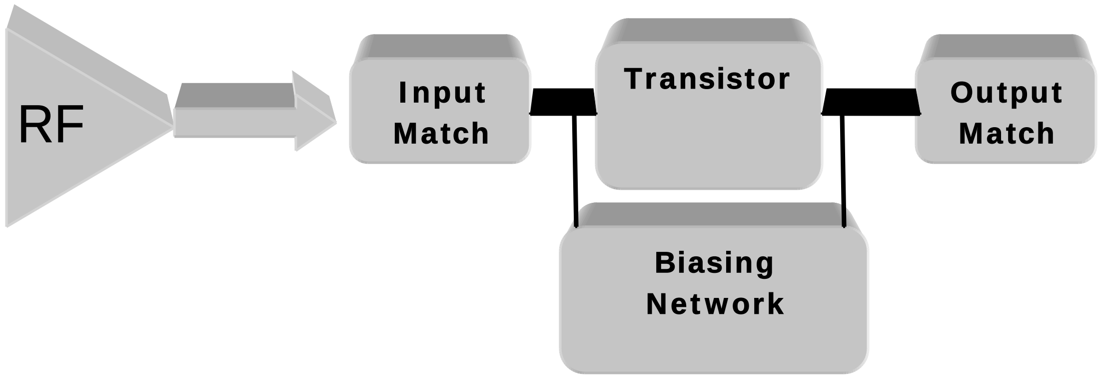
Transistor – low Noise L to Ku-Band GaAs MESFET (NE76038)

- Vg 0.7V
- Vd 0.5V
- Id 6.77mA

Transmission line

- Relative dielectric constant (ϵ_r) = 3.48
- Substrate Thickness (H) = 762 µm
- Metal Thickness (T) = 35 µm
- Rho = 0.7
- Tand = 0.004
- ϵ_r Nom = 3.48

RF Amplifier



Typical Diagram of RF Amplifier

Using this typology we have to:

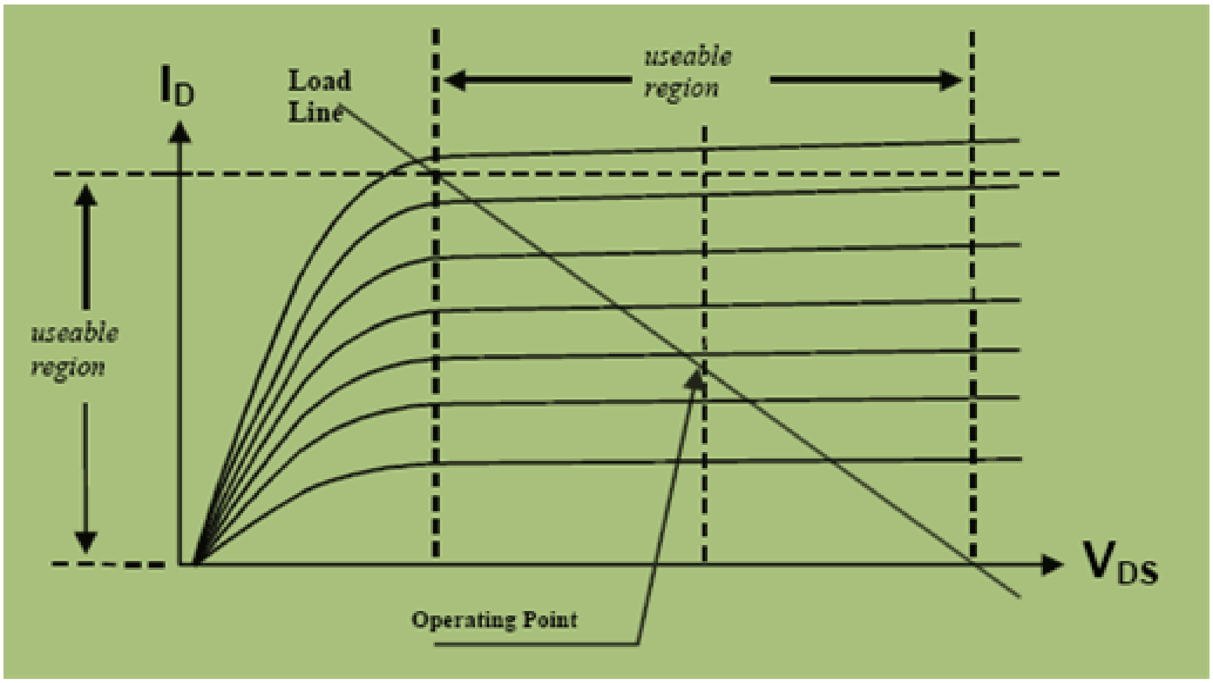
- Design a microwave transistor.
- Design a DC biasing circuit.
- Design the Input Output Matching circuits based on amplifier (low noise).

The design method is based on using S parameter for the ZM1 (Input matching circuit) and ZM2 (Output Matching circuit), the design will encompass:

- Obtain transistor static IV curve.
- Using IV curve, design the bias circuit.
- Obtain S parameters for the designed bias values.
- Using IV curves, define the optimum load line for maximum output power and determine the resistance value, RL, corresponding to this load line.
- Design ZM2 for maximum output power.
- Determine S_{11} with ZM2 at output and design input matching circuit, ZM1,for zero reflection.

IV Curve of Transistor

The IV curve of transistor, as the starting point for the design is as follows:



Design Environment using Microwave office

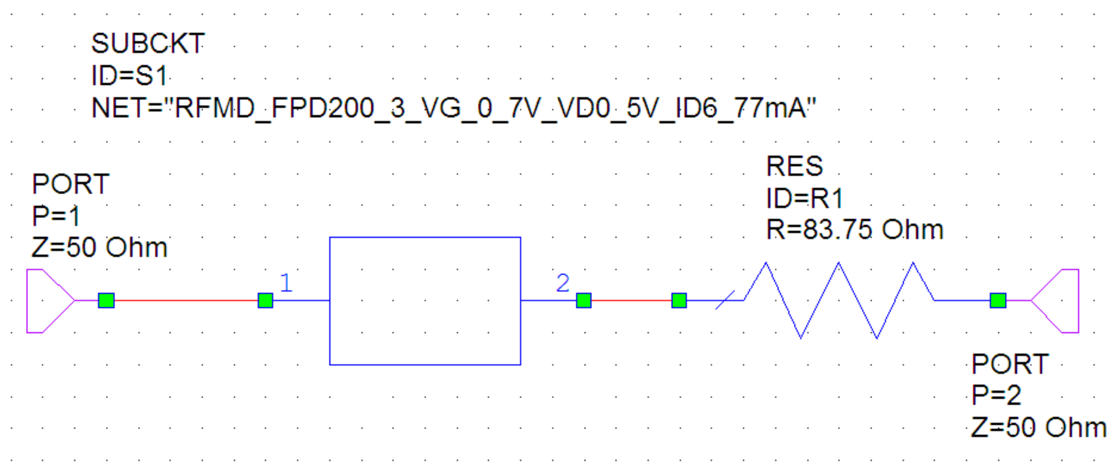
Microwave office (AWR) is used to design the low noise amplifier.

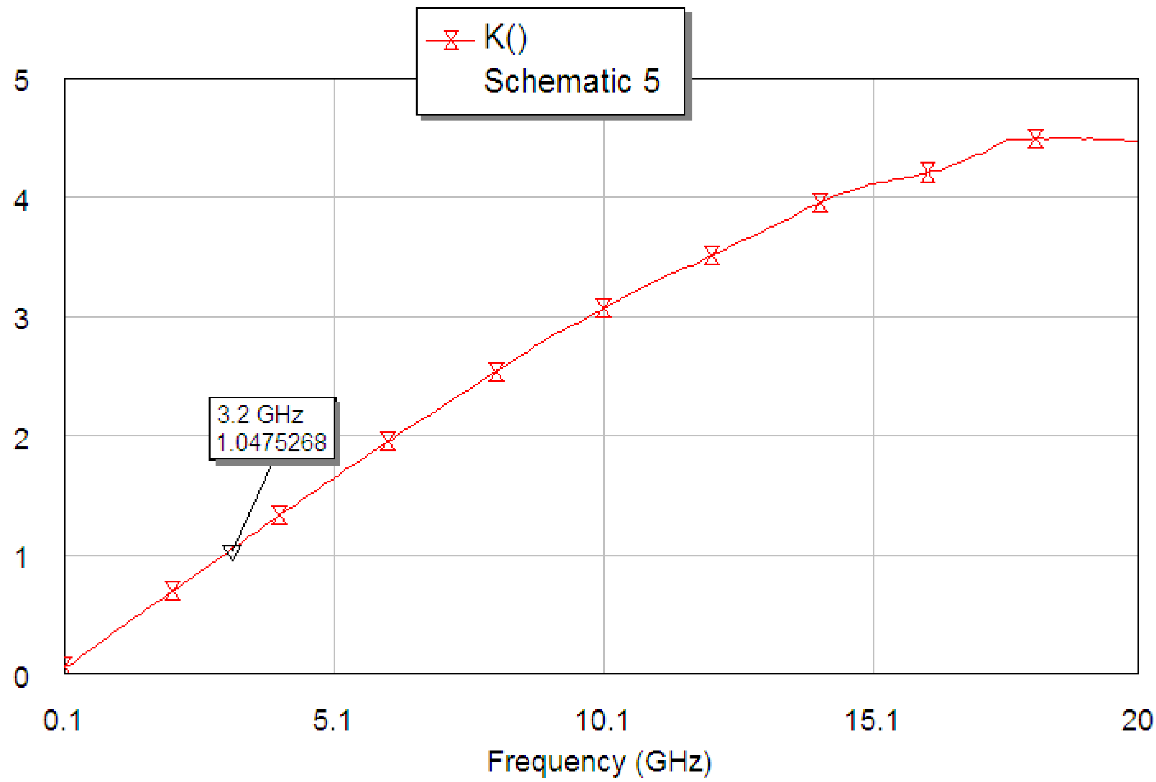
Amplifier design using Lumped Elements

At First stabilize series resistance:

- Convert S parameter to Z parameter.
- Add series resistance to real part of transistor Z_{22}.
- Check K
- Design for simultaneous conjugate match.

Adding resistance 83.7539 Ohm for K of 1.05 for stability. The circuit is shown below:

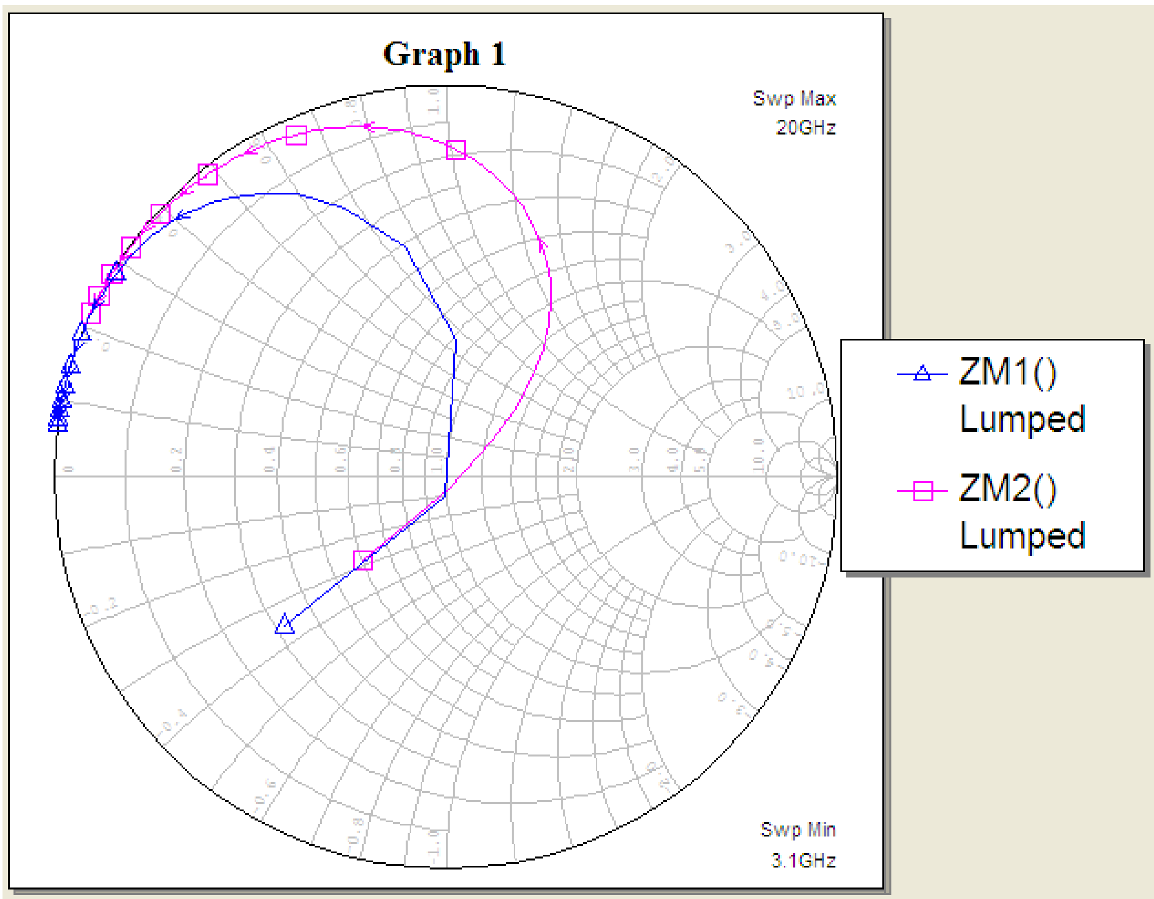



K()
Schematic 5
5
4
3
2
1
0
3.2 GHz
1.0475268
0.1
5.1
10.1
15.1
20
Frequency (GHz)

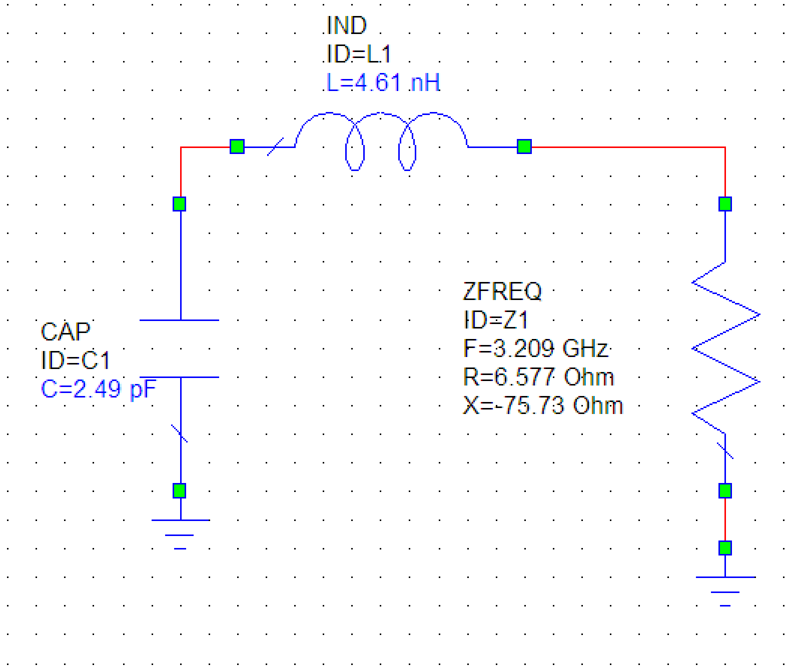
Conjugate matching using matched network technique

- Using match functions (ZM_1 and ZM_2) to find impedance match.
- Take a conjugate value and enter as a frequency dependent resistor.
- Add series Inductance L_1 to reach the unity admittance circle.
- Add Shunt capacitance C_1.

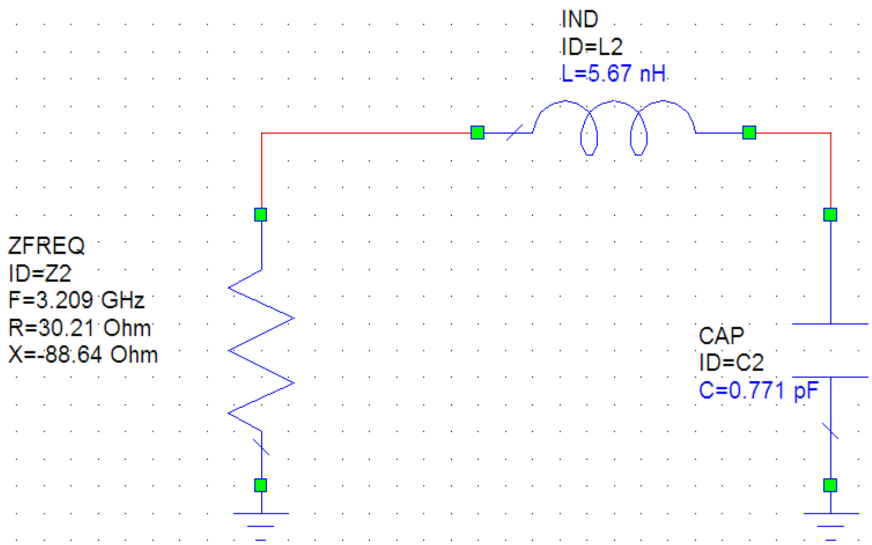
Smith Chart ZM_1 and ZM_2 before matching



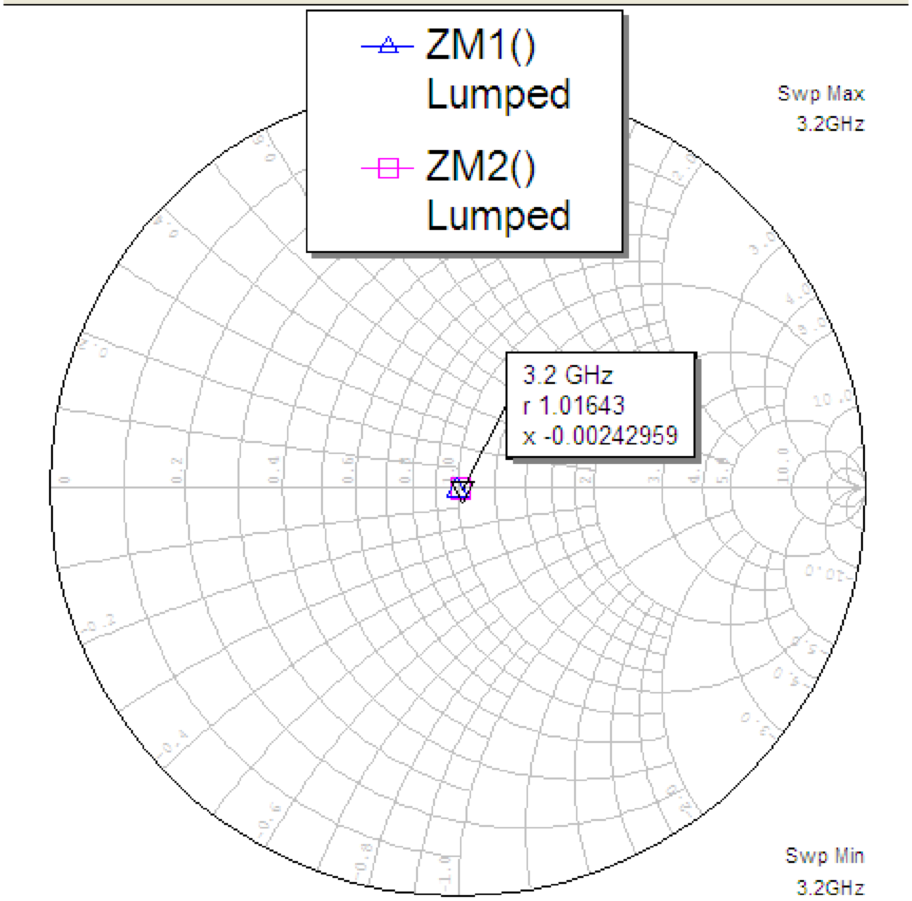
Input Matching (ZM_1)



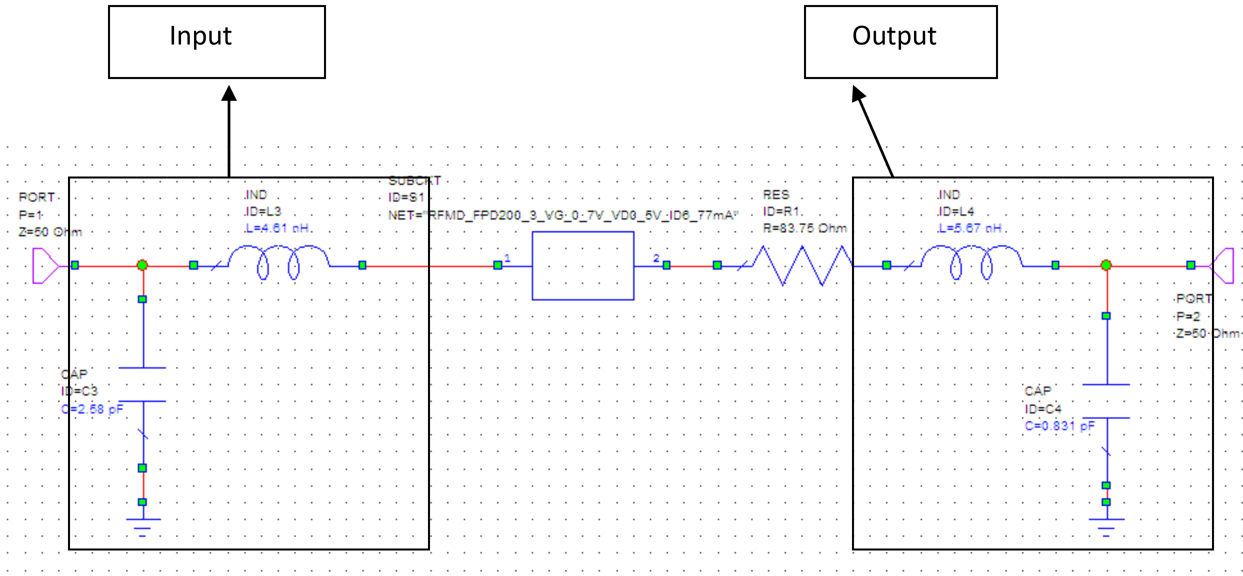
Output Matching (ZM_2)



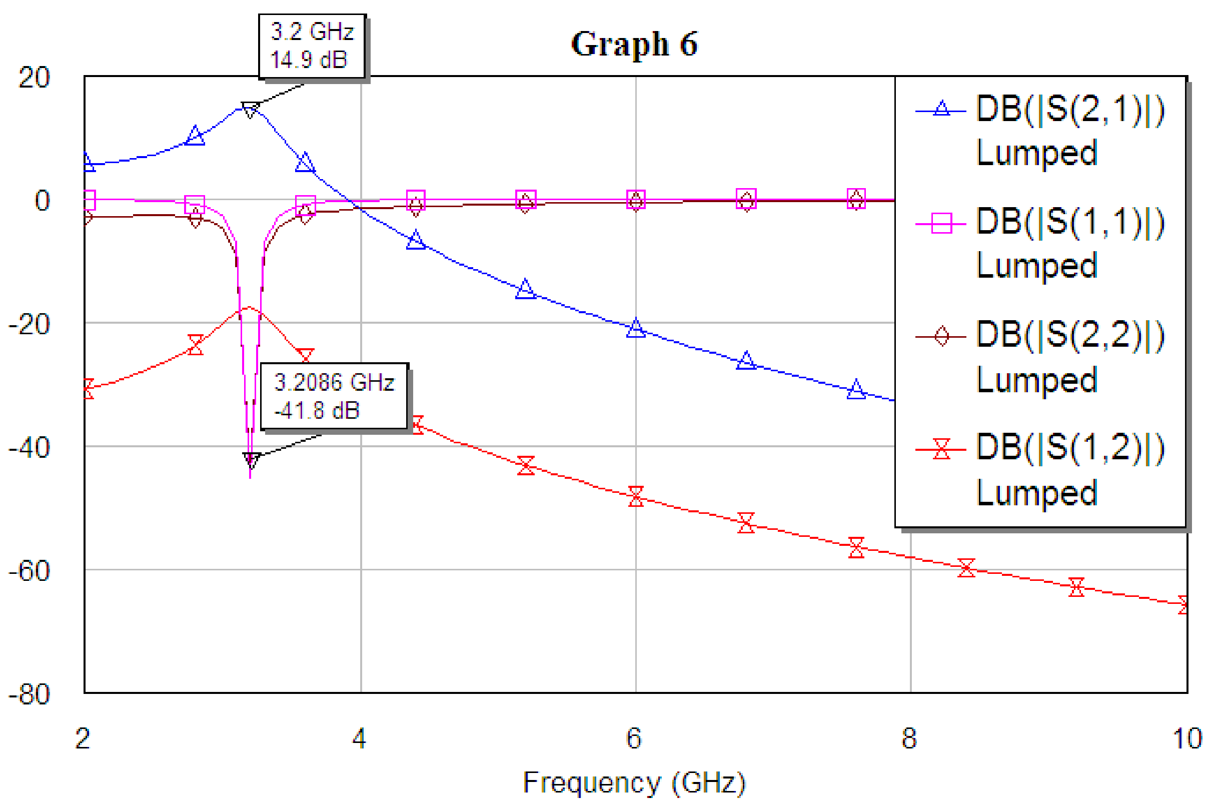
After matching by correcting the values of Inductors and Capacitors, the Smithchart will look like:



Add Input and Output match network to the circuit



Frequency Response of the circuit



Result

We get the following results;

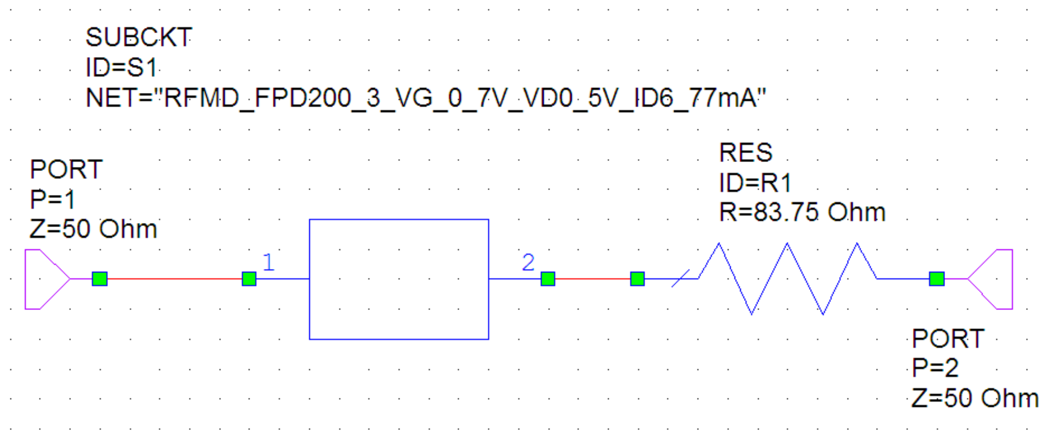
1. A gain of 14.9 db in our amplifier design using lumped elements at 3.2 GHz.
2. Higher gain as compared to gain obtained in distributed element (using resistance of ~87 ohm).
3. The calculations done by hand (as shown in Analytical calculations) are same as the one exhibited in the AWR.

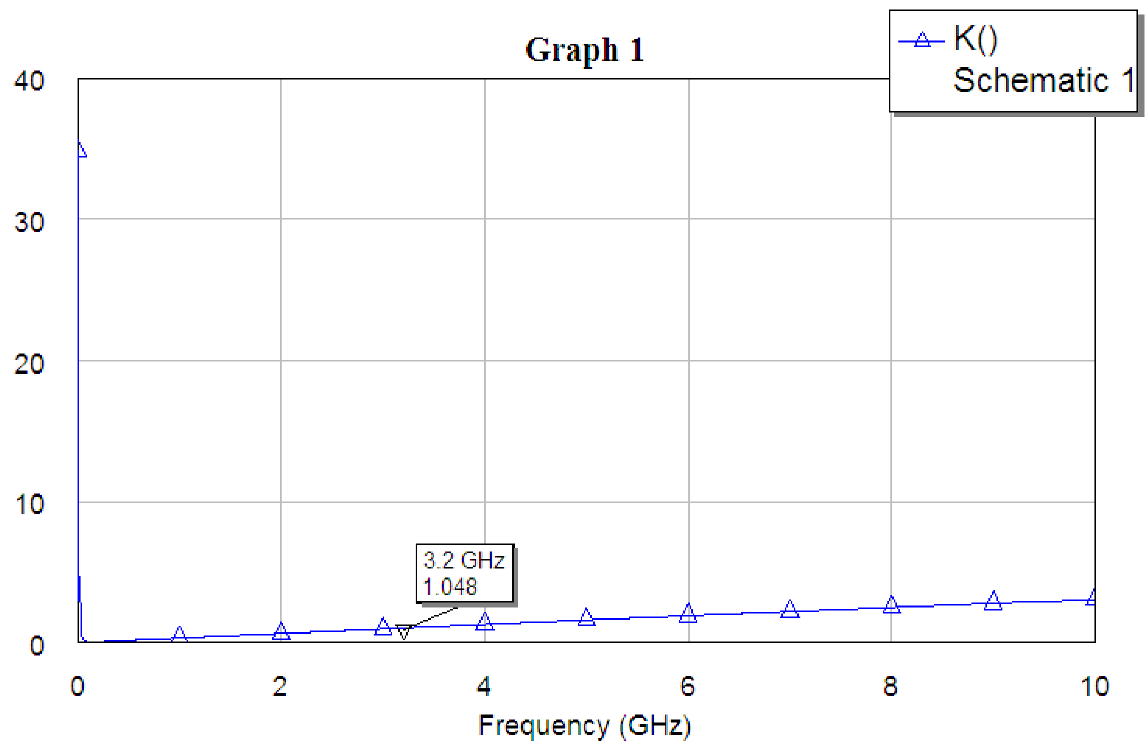
Amplifier designing using distributed element

Steps taken:

- Convert S parameter to Z parameter.
- Add resistance to real part of Z_{22}.
- Check K.
- Design for conjugate match.

Adding resistance 83.7539 Ohm for K of 1.05 for stability. The circuit is shown below:

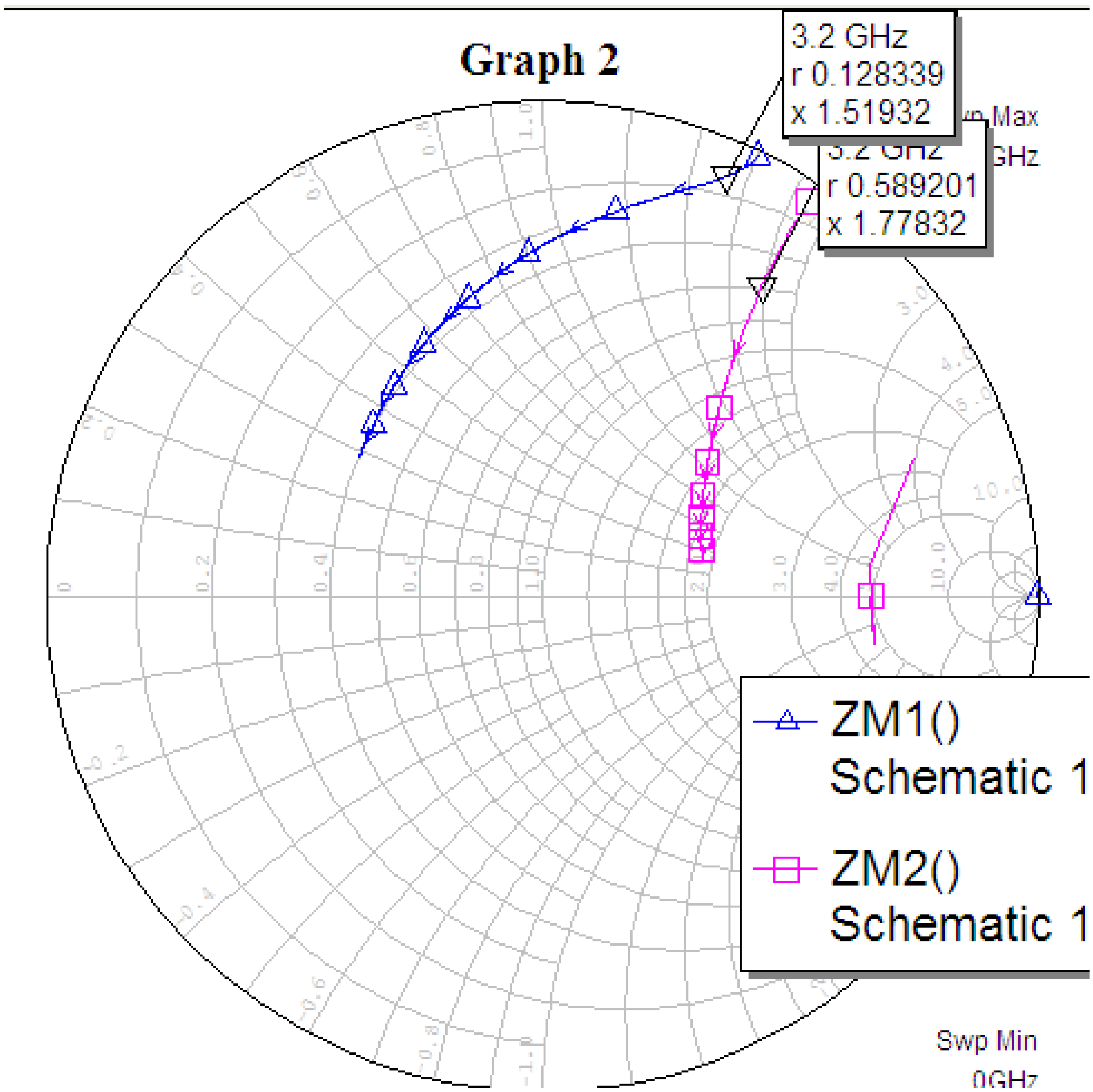




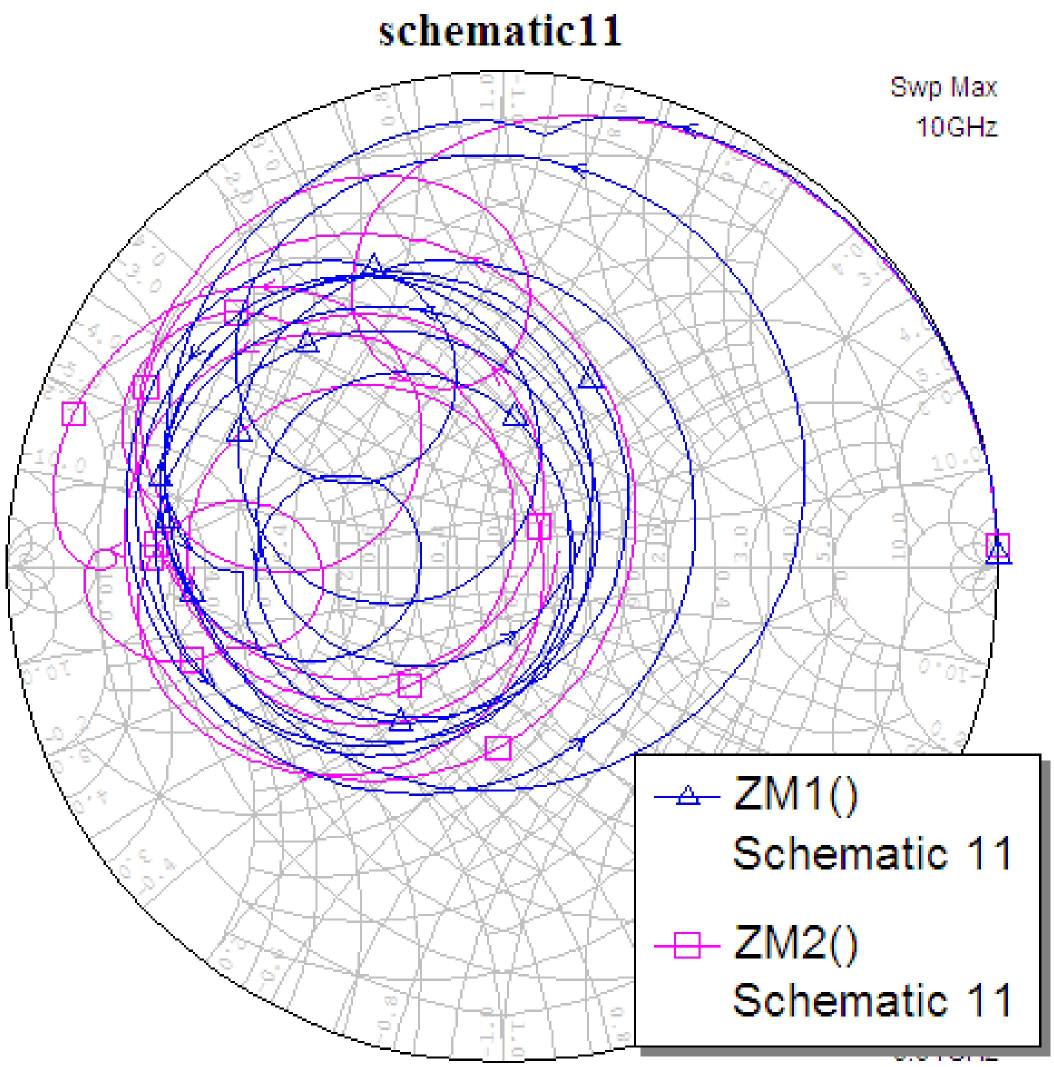
Conjugate matching using matched network technique

- Use conjugate match function (ZM1 and ZM2) to find impedance match.
- Take a conjugate value and enter as a frequency dependent resistor.
- Add CPW1 to reach the unity admittance circle.
- Add CPW2 to reach the 50 ohm point.

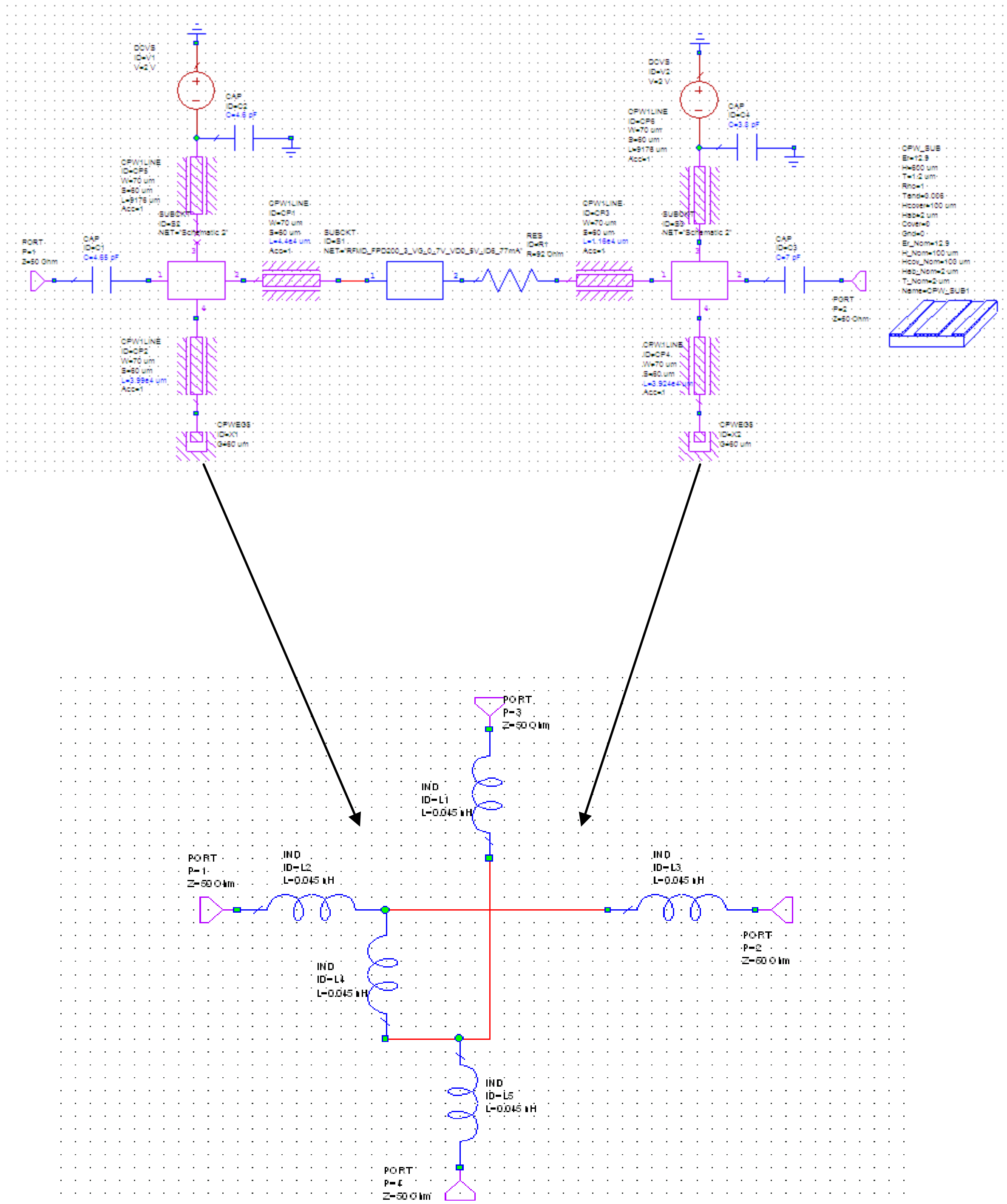
Smithchart before Matching



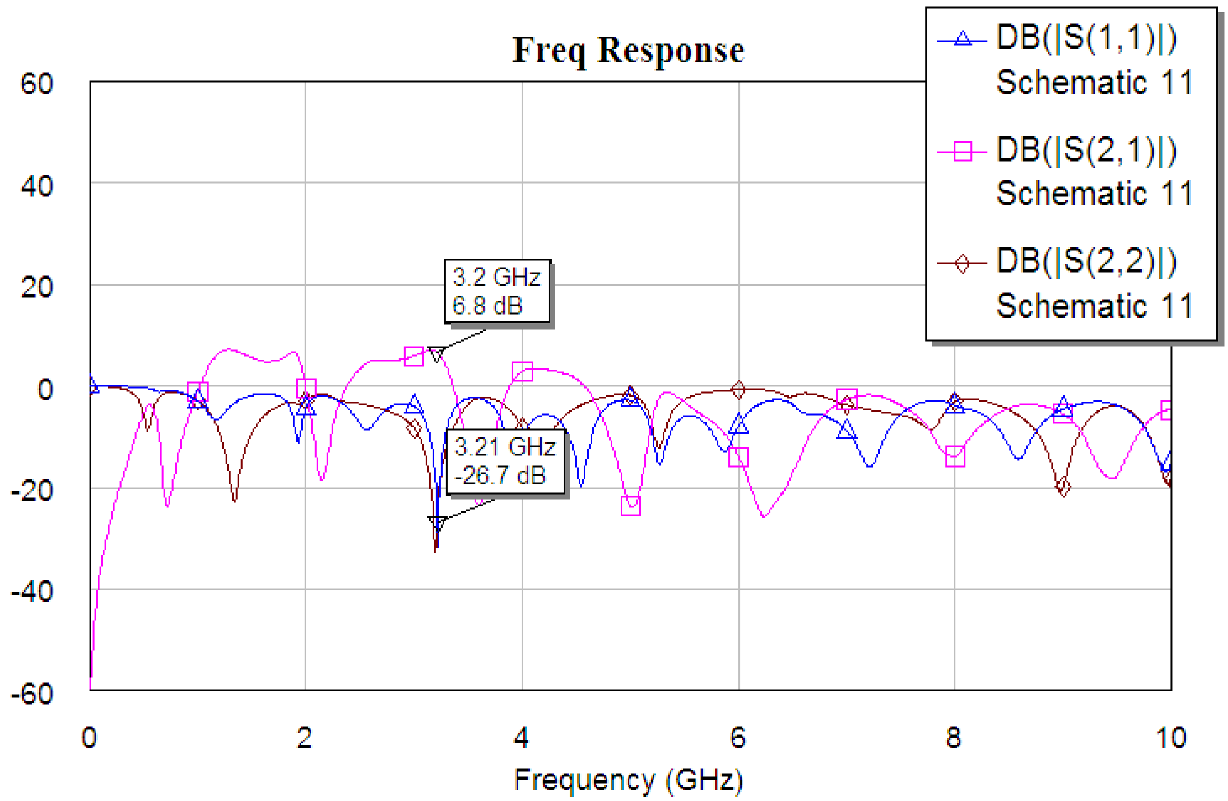
- After matching ZM1 and ZM2 the Smith chart will look like :



Adding the two matched networks to the above circuit.



The frequency Response



Results

We get;

6.8db gain at 3.2 GHz which is less than the gained obtained in lumped elements. The primary reason of having lesser gain here is that we have used CPW transmission line along with the resistance of ~87 ohm. The CPW we have used in distributed element has higher length and along with resistance in series, so less gain is obtained.

If we reduce the length of transmission line CPW or reduce resistance we will see that the gain will increase and we can have the gain equal to gain in lumped elements.

Analytical Calculations:

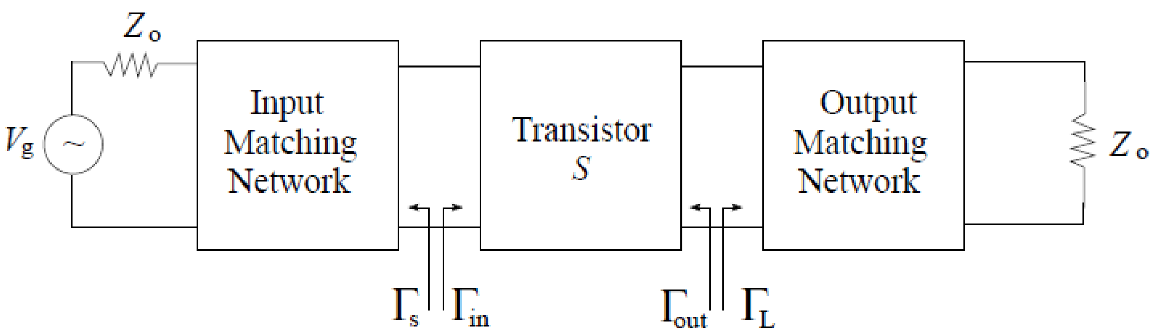
S_{11} = 0.60168-j0.72409 => |S11|=0.941

S_{21}= -2.7153+j2.5467 => $|S_{21}|$=3.722

S_{22}= 0.34582-j0.36091 => $|S_{22}|$=0.499

S_{12}=0.0534+j0.071187 => $|S_{12}|$=0.5387

Microwave Frequency Transistor Amplifier Design Equations



Stability Factor Analysis

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

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| = 0.4928$$

$$K = 0.1610$$

Therefore the system is unstable since K<1. We need to stabilize the system first.

Series Resistance Stabilization Method

Steps:

1. Convert Transistor S-parameters to Z-Parameters
2. Add series resistance to real part of Transistor Z_{22}
3. Convert composite Z-Parameters to S-Parameters
4. Check K
5. Design for Simultaneous Conjugate match

Converting Transistor S parameters to Z parameters

The equations to transform S-Parameters into Z-Parameters are given below:

$$Z_{11} = Z_0 \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$$

$$Z_{12} = Z_0 \frac{2S_{12}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$$

$$Z_{21} = Z_0 \frac{2S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$$

$$Z_{22} = Z_0 \frac{(1+S_{22})(1-S_{11})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$$

$$Zo = 50\Omega$$

$$Z_{11} = 31.3272 - j57.7113$$

$$Z_{12} = 11.6562 - j2.2899$$

$$Z_{21} = 148.66 - j2.2899$$

$$Z_{22} = 60.1466 - j5.8840$$

Adding Resistance to Drain Circuit

The stability factor, K, can be expressed in terms of Z-Parameters:

$$K = \frac{2\operatorname{Re}(Z_{11})\operatorname{Re}(Z_{22}) - \operatorname{Re}(Z_{12}Z_{21})}{\left|Z_{12}Z_{21}\right|}$$

This can be rearranged to give:

$$\operatorname{Re}(Z_{22}) = \frac{K\left|Z_{12}Z_{21}\right| + \operatorname{Re}(Z_{12}Z_{21})}{2\operatorname{Re}(Z_{11})}$$

$$\operatorname{Re}(Z_{22Tran} + Rd) = \frac{K\left|Z_{12}Z_{21}\right| + \operatorname{Re}(Z_{12}Z_{21})}{2\operatorname{Re}(Z_{11})}$$

$$Rd = \frac{K\left|Z_{12}Z_{21}\right| + \operatorname{Re}(Z_{12}Z_{21})}{2\operatorname{Re}(Z_{11})} - \operatorname{Re}(Z_{22Tran})$$

For example, using the calculated Z - Parameters, if we want K=1.05 then:

$$\mathrm{Re}(Z_{22}) = \frac{K\left|Z_{12}Z_{21}\right| + \mathrm{Re}(Z_{12}Z_{21})}{2\,\mathrm{Re}(Z_{11})} = 143.9005$$

Now subtract 60.1466 in the Z_{22} than we'll get

$$\mathrm{Re}(Z_{22}) = 143.9005 - 60.146 = 83.7539$$

Normalized Z by dividing 50 Ohms

We get:

$$Z_{11} = 0.6265 - j1.1542$$
$$Z_{12} = 0.2331 - j0.0458$$
$$Z_{21} = 2.9732 + j9.4823$$
$$Z_{22} = 2.8780 - j0.1177$$

Converting Composite Z parameters to S parameters

The equations for converting the composite Z-Parameters to S-Parameters are given below:

First divide the Z-Parameter matrix by Z_0.

$$S_{11} = \frac{(Z_{11}-1)(Z_{22}+1) - Z_{12}Z_{21}}{(Z_{11}+1)(Z_{22}+1) - Z_{12}Z_{21}} = 0.4258 - j0.7208$$

$$S_{12} = \frac{2Z_{12}}{(Z_{11}+1)(Z_{22}+1) - Z_{12}Z_{21}} = 0.0419 + j0.0378$$

$$S_{21} = \frac{2Z_{21}}{(Z_{11}+1)(Z_{22}+1) - Z_{12}Z_{21}} = -1.3803 + j1.9148$$

$$S_{22} = \frac{(Z_{11}+1)(Z_{22}-1) - Z_{12}Z_{21}}{(Z_{11}+1)(Z_{22}+1) - Z_{12}Z_{21}} = 0.5490 - j0.1451$$

Completing steps again:

$$|\Delta| = \left|S_{11}S_{22} - S_{12}S_{21}\right| = 0.5505$$

Check K

As a check we can Calculate K from the composite S-Parameters:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} = 1.0499$$

It can be seen that K is evaluated to be approximately 1.05 as above.

Design for Simultaneous Conjugate Match

The equations for simultaneous conjugate match are given below:

$$B_1 = 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 = 1.3937$$

$$C_1 = S_{11} - \Delta S_{22}^* = 0.3592 - j0.6808$$

$$\Gamma_S = \frac{B_1 \pm \sqrt{B_1^2 - 4|C_1|^2}}{2C_1} = 0.0468+j0.9989,\ 0.7981+j0.6025$$

$$B_2 = 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2 = 1.0733$$

$$C_2 = S_{22} - \Delta S_{11}^* = 0.2129-j0.4919$$

$$\Gamma_L = \frac{B_2 \pm \sqrt{B_2^2 - 4|C_2|^2}}{2C_2} = -0.4524+j1.2888,\ 1.2492+j0.5523$$

Voltage Standing Wave Ratio (VSWR)

The VSWR for the unmatched amplifier is calculated as follows:

$$VSWRin = \frac{1 + |S_{11}|}{1 - |S_{11}|} = 11.2805$$

$$VSWRout = \frac{1 + |S_{22}|}{1 - |S_{22}|} = 3.6284$$

Source and Load Stability Circles

$$C_1 = S_{11}^{\ *} - \Delta^* S_{22} = 0.2129 \text{ - j}0.4919$$

$$rs1 = \frac{C_1}{|S_{11}|^2 - |\Delta|^2} = 0.3772 + j0.4565$$

center of circle

$$ps1 = \left| \frac{S_{12}S_{21}}{|S_{11}|^2 - |\Delta|^2} \right| = 0.3348$$

radius of circle

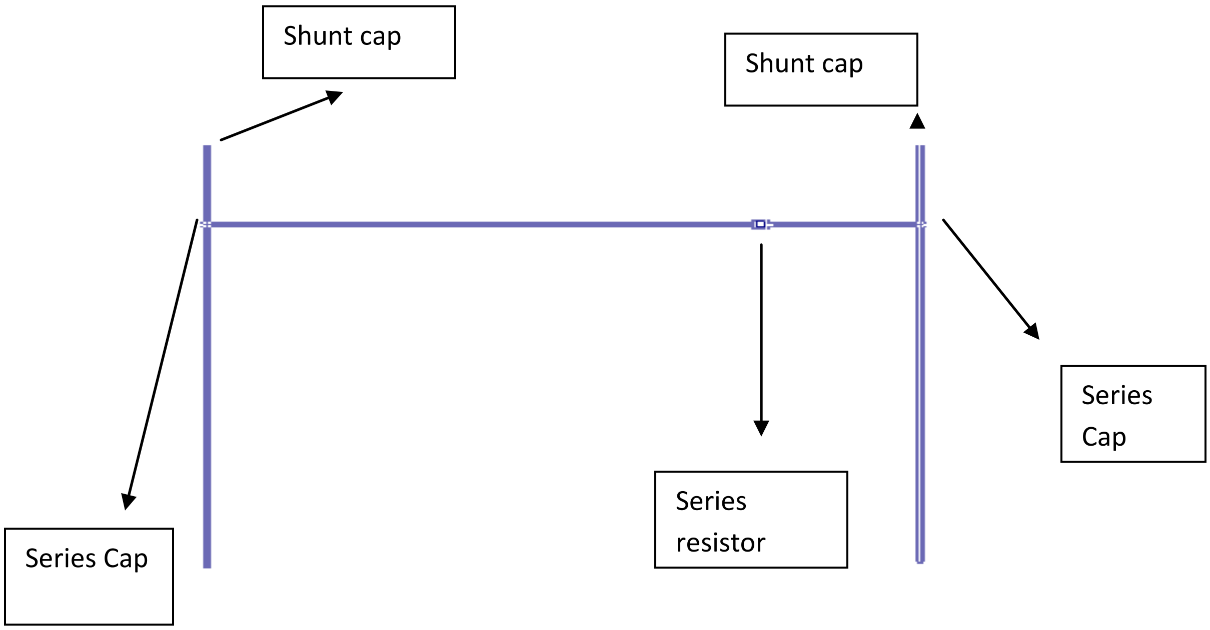
$$C_2 = S_{22}^{\ *} - \Delta^* S_{11} = 0.0886 + j0.1254$$

centre of load stability circle

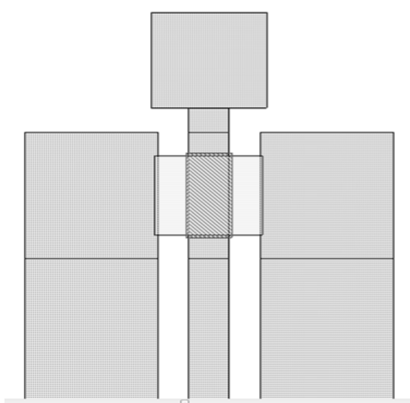
$$pl1 = \left| \frac{S_{12}S_{21}}{|S_{22}|^2 - |\Delta|^2} \right| = 6.8316$$

radius of load stability circle

Physical Layout



Shunt Capacitor



Calculations for Shunt Capacitors

$$c = \varepsilon \frac{(6.7)(Wcap)(Lcap)}{150nm}$$

$4.78*10^{-12} = 8.84 * 10^{-12} * (6.7)\ (60* 10^{-6})* Lcap / 150 * 10^{-9}$

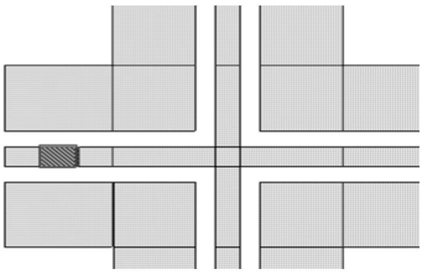
Lcap = 186 µm

$$c = \varepsilon \frac{(6.7)(Wcap)(Lcap)}{150nm}$$

$6.1*10^{-12}= 8.84*10^{-12}*(6.7)\ (60*10^{-6}) * Lcap / 150 * 10^{-9}$

Lcap = 240 µm

Series Capacitor



Calculations for Series Capacitors

$$c = \varepsilon \frac{(6.7)(Wcap)(Lcap)}{150nm}$$

$1.82 * 10^{-12} = 8.84 * 10^{-12} * 469 * 10^{-6} * Lcap / 150 * 10^{-9}$

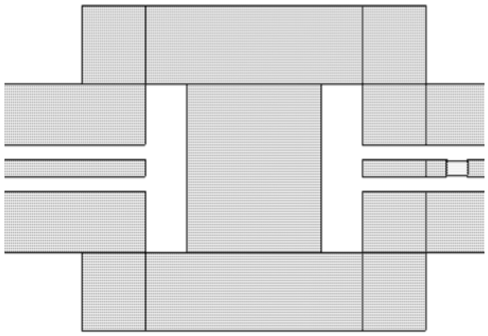
Lcap = 138 µm

$$c = \varepsilon \frac{(6.7)(Wcap)(Lcap)}{150nm}$$

$3.6 * 10^{-12} = 8.84 * 10^{-12} * 469 * 10^{-9} * Lcap / 150 * 10^{-9}$

Lcap = 130 µm

Series Resistor

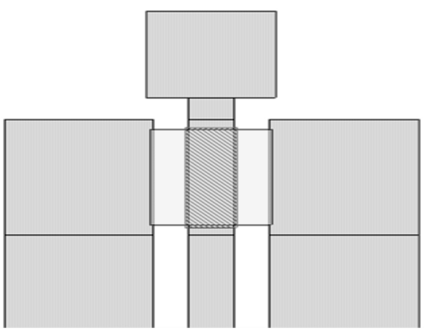


Calculations for Series Resistance

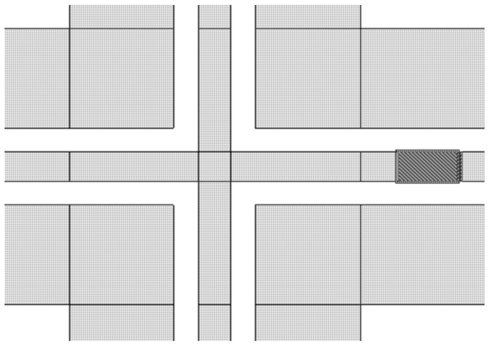
R= sheet resistance * L_{res} / W_{res}

87.53= 50*(Lres / 60)

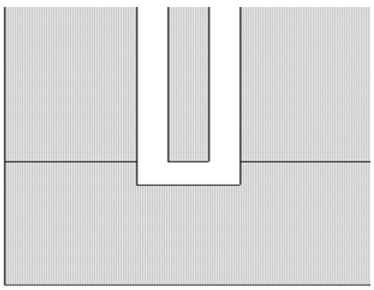
Lres = **105.036 µm**



Circuit for the cross junction for CPW dimensions 70/70/70



CPWEG - Coplanar Open, with Ground Connected (Closed Form)



From AWR Help

This circuit component models a gap termination of a strip of coplanar waveguide. Model doesn't account for substrate thickness or presence of metallic cover or backing ground. The parameters W (strip width), S_1 (S_1 - spacing between strip and the left/right ground halfplane) and G (gap length) are dimensions entered in the default length units. The parameter CPSUB specifies the substrate element, which defines additional cross sectional parameters of the transmission line. If blank, a default is used. Some parameters CPSUB, that are Hcover, Cover, and Gnd, are not used by this component. Conductor thickness is assumed zero.

The component doesn't account for losses in metal and in substrate dielectric. Dispersion is not include.

Conclusions

At 3.2 Ghz we get a higher gain with a Lumped element design than a Distributed element design. The reason of achieving higher gain in lumped elements as compare to distributed element is that, in lumped elements we have achieved a higher gain by only adding a resistance of ~87 ohms, but in distributed, lesser gain is achieved because of higher transmission and series resistance of ~87 ohms. The result concluded is that if we reduce the length of transmission line and resistance we will achieve a higher gain.

Lumped Element

Lumped element is easy to design but difficult in fabrication also difficult in designing the elements like inductor etc. But the main advantage is that the design of the lumped circuit is small in size as compared to the distributed.

Distributed Element

Distributed element is easy to tuned and easy in fabrication but it'll increase the resistance and therefore in the end resulting in a lower gain.

Analytical Method

Analytically, we had results very closer to the ones we achieved in the AWR using lumped element design.

References

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