RFIC

Assignment1

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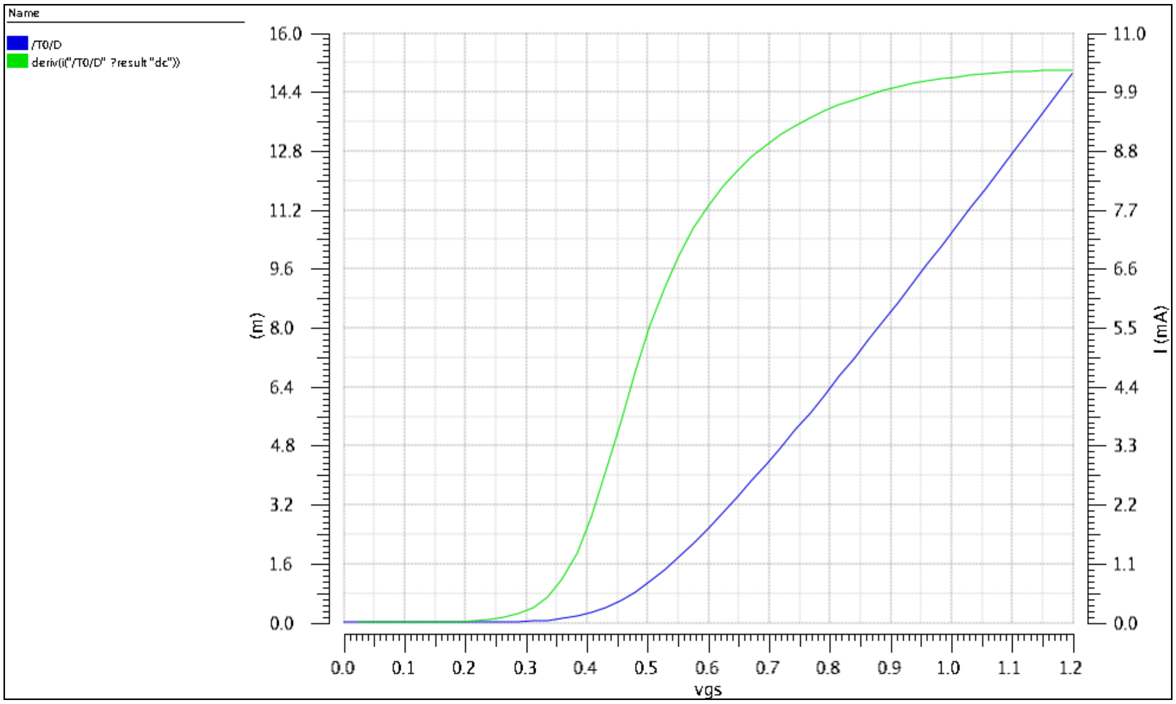
Table of Contents

Parameters	**Targeted specs**	**Achieved specs(ideal ind)**	**Achieved specs(real ind)**
Supply Voltage	1.2V	1.2V	1.2V
Center Frequency	7.295 GHz	7.295 GHz	7.295 GHz
Voltage gain	≥ 15 dB	19.536 dB	15.695 dB
Noise figure	≤ 2.3 dB	1.3264 dB	2.07
IIP3	≥ -15 dBm	-10.08 dBm	-7.72 dBm
1dB compression point	≥ -25 dBm	-24.9334 dBm	-22.934 dBm
S11	≤ -15 dB	-57.19 dB	-15.547 dB
$\|Z_{out}\|$	< 30Ω	20.8074	20.8316
Kf	> 1	23.71	54.41
B1f	> 0	0.826	0.852
Bias current	--	2.8 mA	2.8 mA
Buffer current	--	3.3 mA	3.3 mA

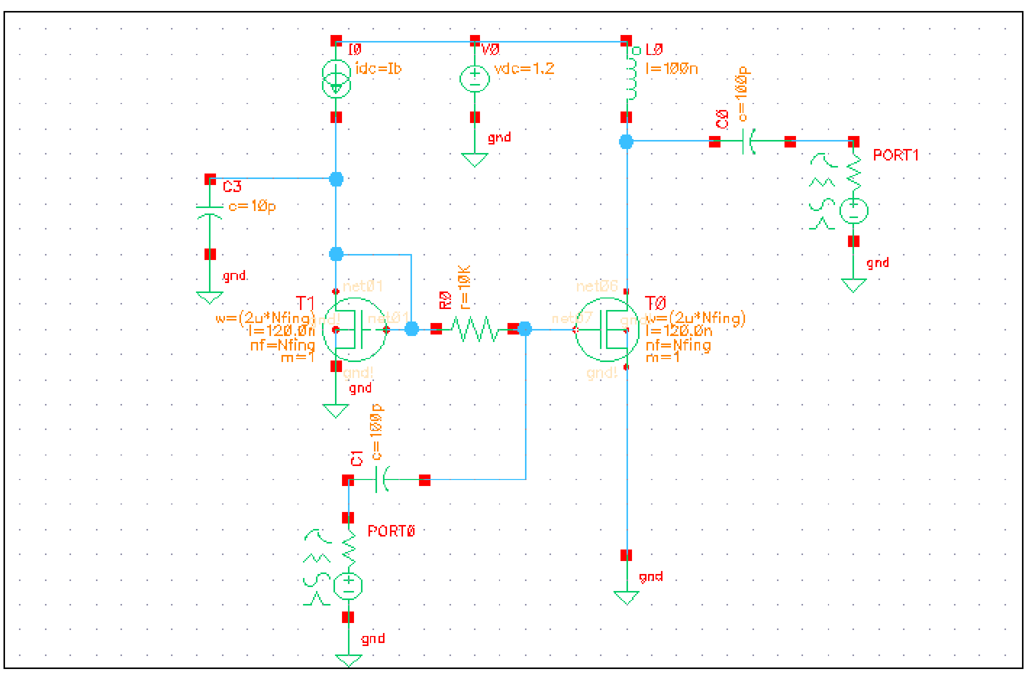
Chapter 1: Transistor characterization



From transistor characterization we can observe drain to source current and gm for given vgs when vds is fixed. This is for a transistor with W=20u and L=120n with 20 fingers.

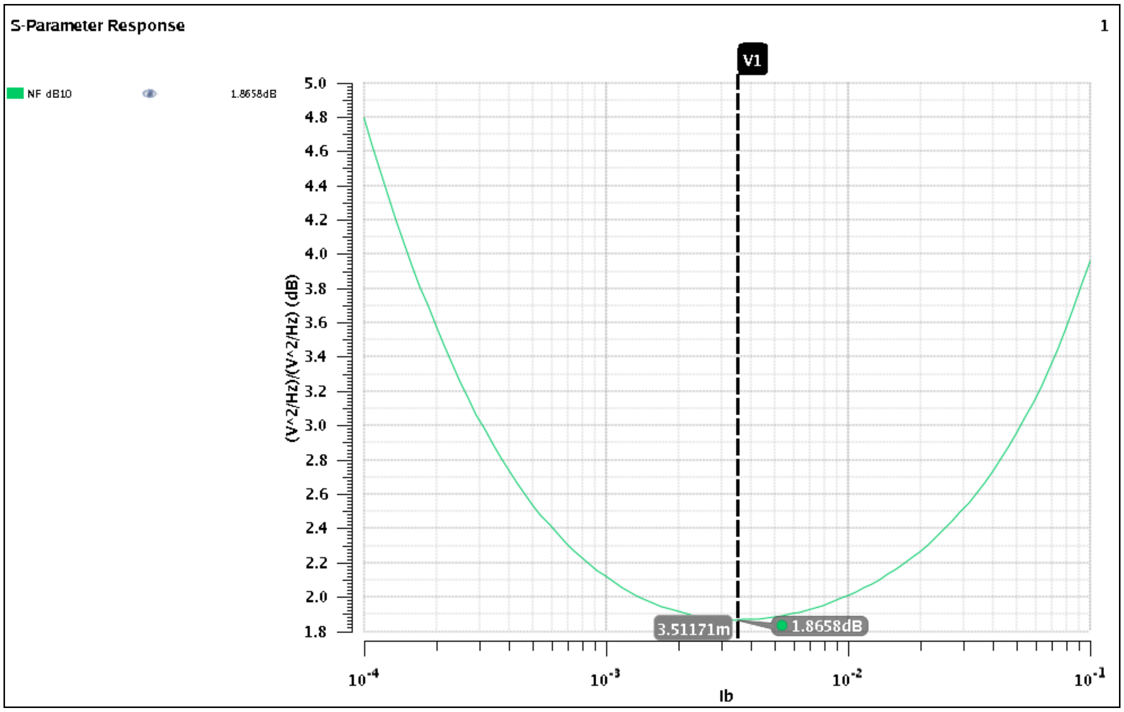
Chapter 2: Ft and Fmax analysis

Circuit

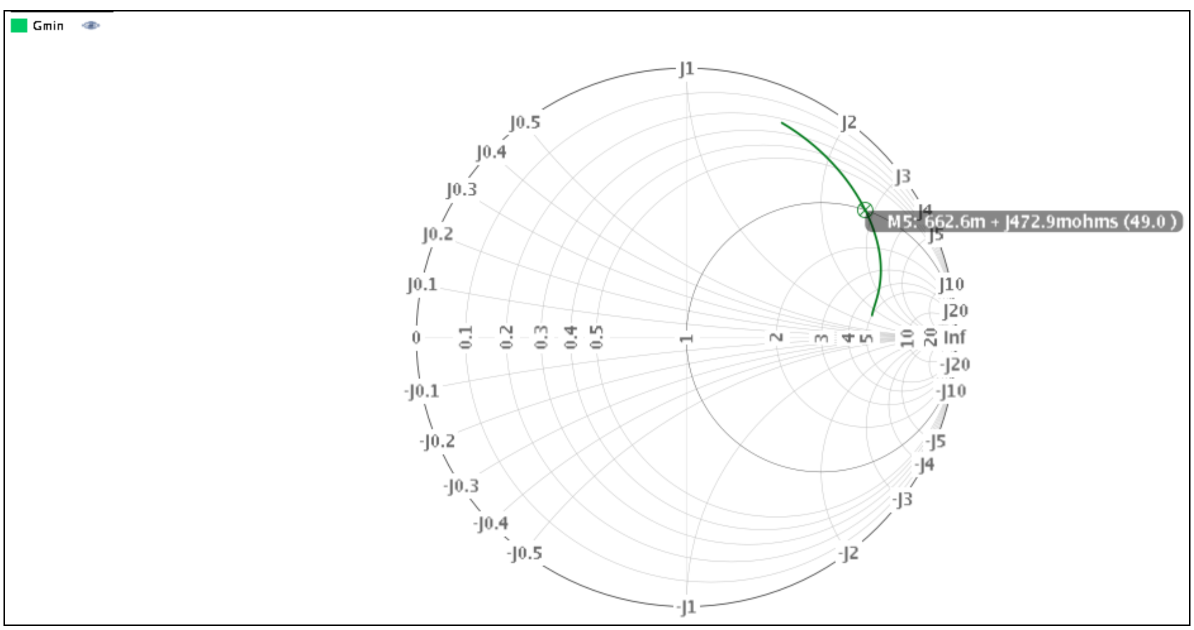


Chapter 3: Noise and input matching

Ibias vs noise figure

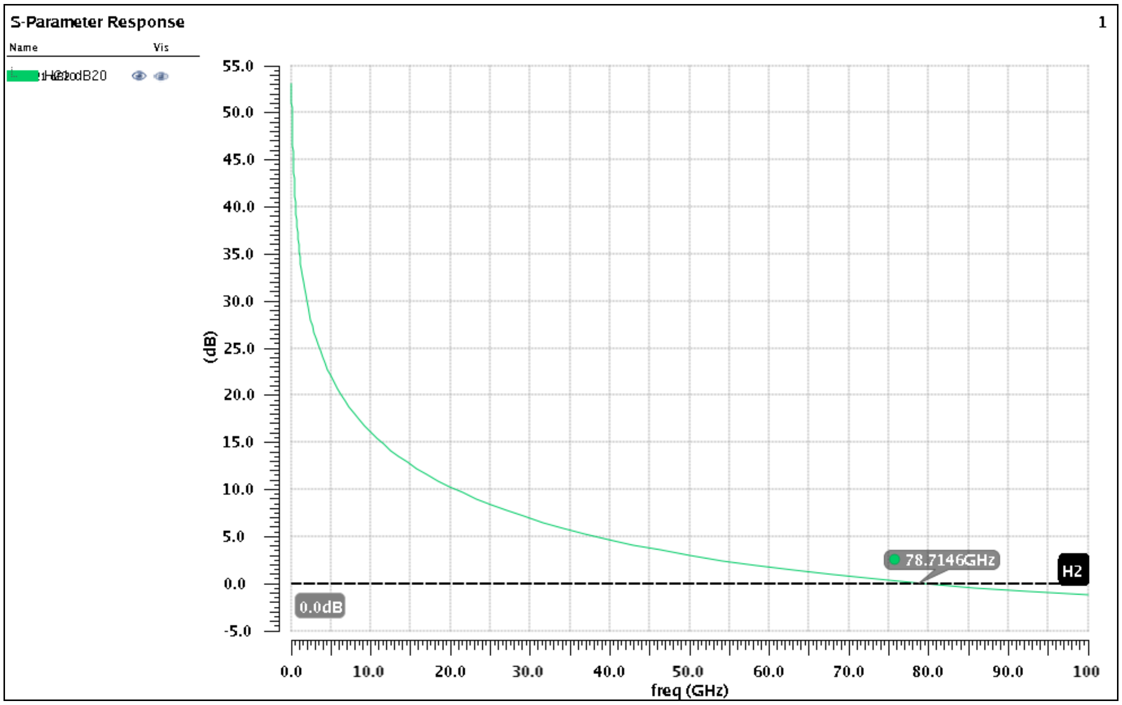


Gmin for different number of fingers

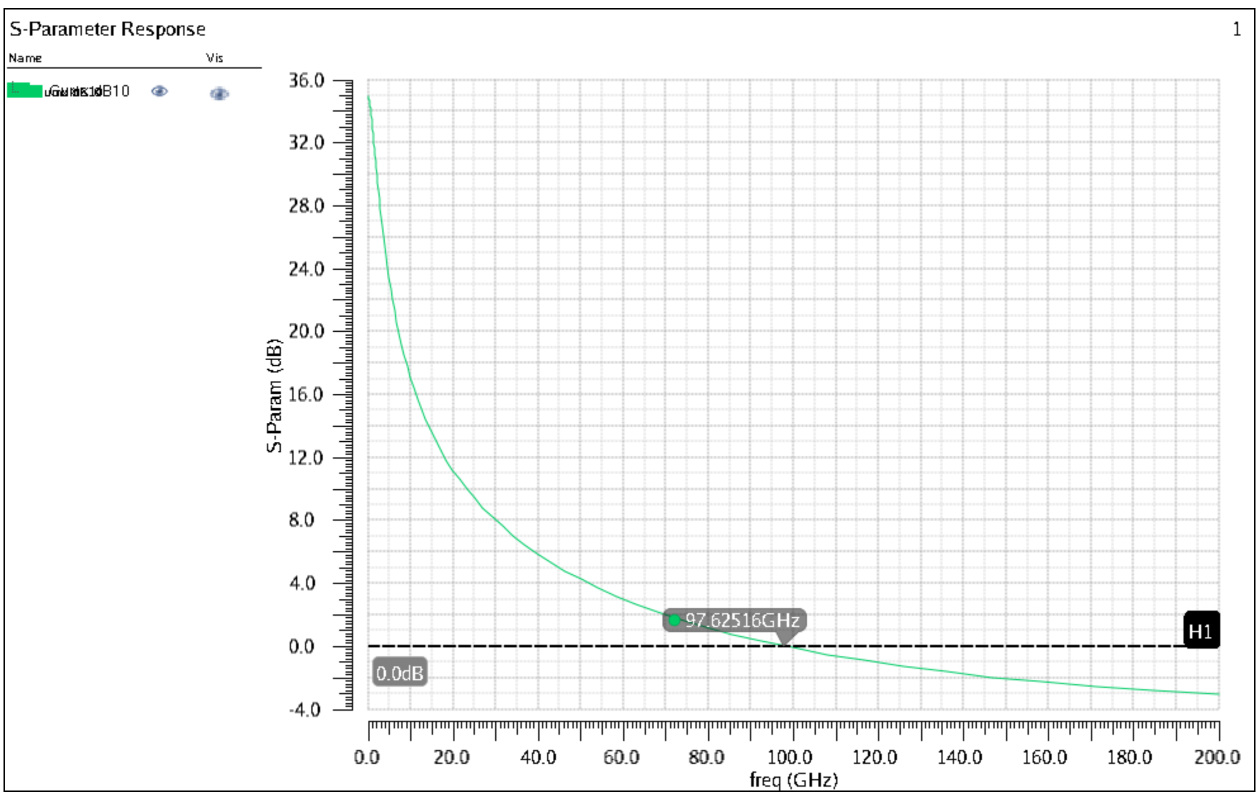


Current density $\frac{3.5117\ x\ 10^{-3}}{49\ x\ 2\ x\ 10^{-6}} = 0.035\ mA/\mu m$

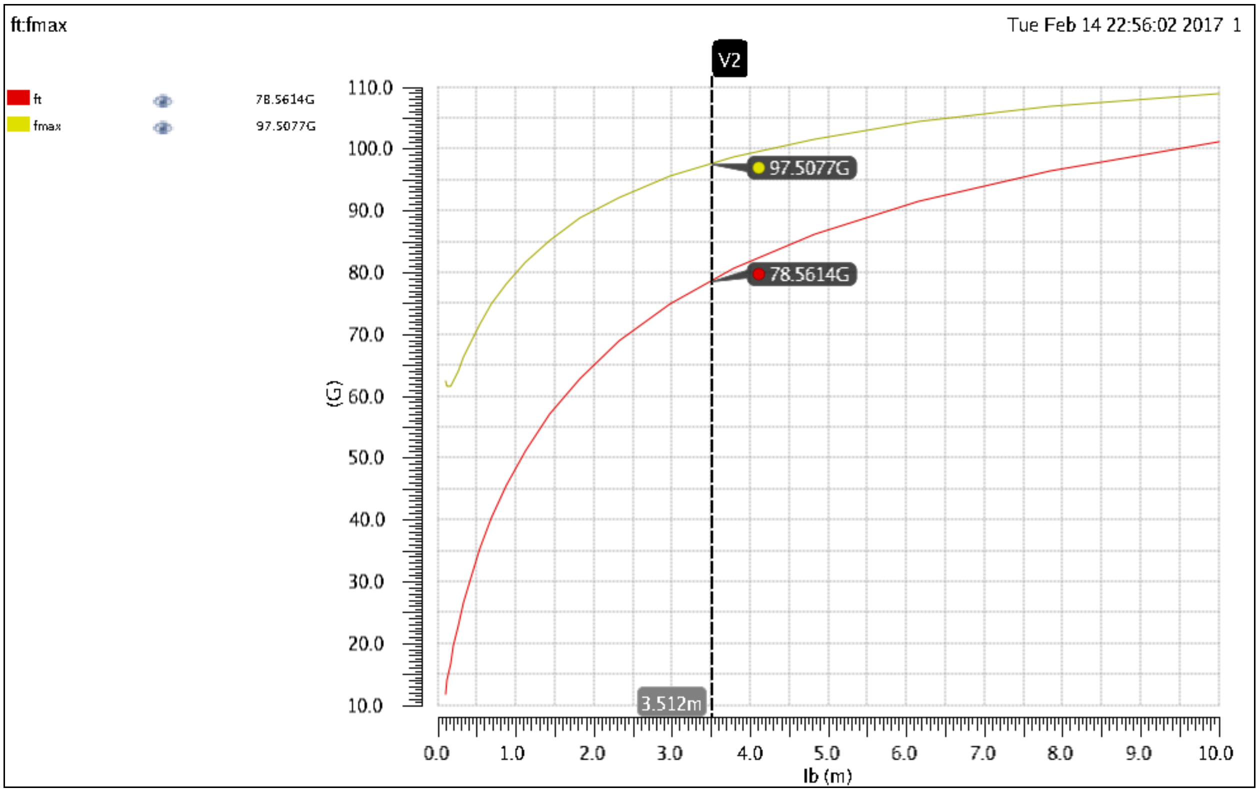
Calculating ft for this setup



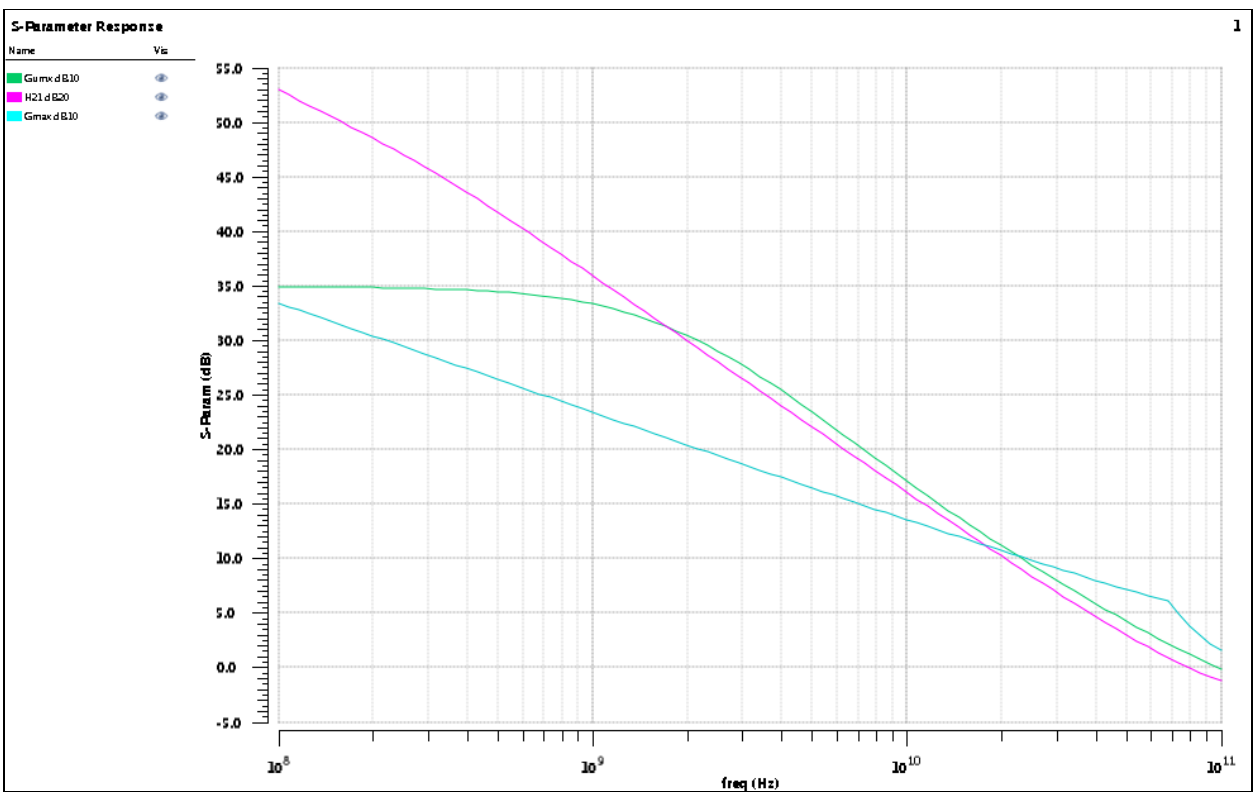
Fmax frequency when gumax is 0db



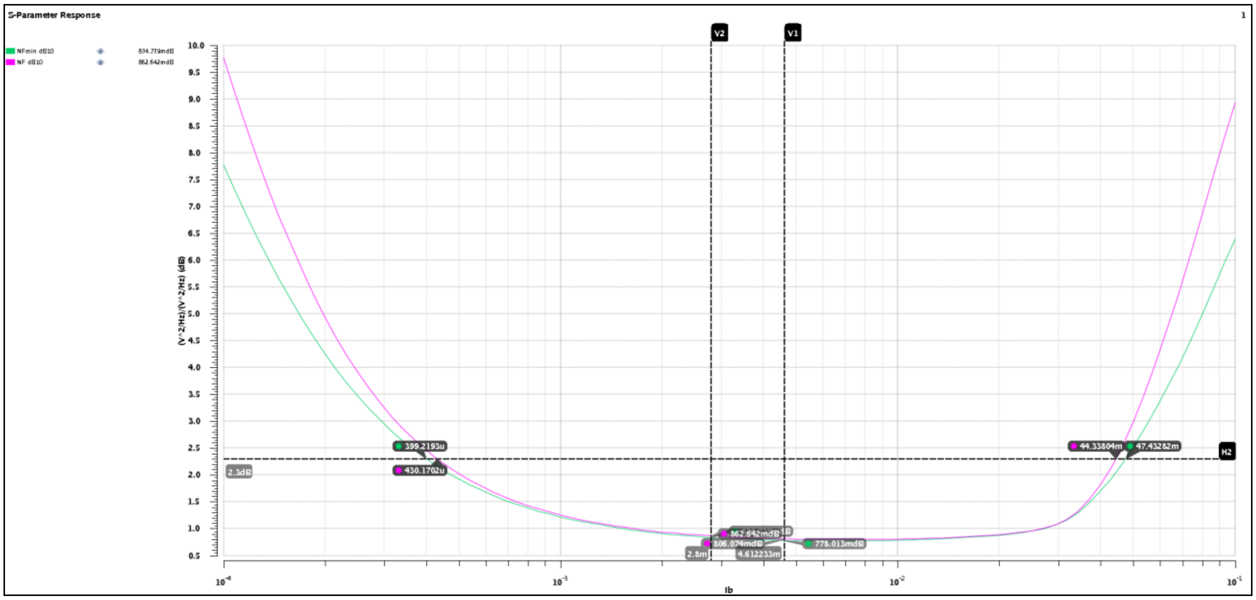
Now verifying that we are getting same ft and fmax for above current, using parametric analysis on current,



Now plotting H21, Gmax and Gumax for frequency range 100MHz to 100GHz



Changing transistor size after implementing cascode transistor



New current density $\frac{I}{A} = \frac{4.612}{49*2} = 0.047\ mA/\mu m$

As we can see from the figure that minimum current for which NF remains similar is about 2.8mA. For current below this noise figure will increase drastically. Hence, I have optimized current from the beginning of my assignment so that we do not have to worry about optimizing current anymore. I have performed number of simulation, which led me to the observation that, we can take current from 2.6mA to 2.8mA as optimized current. I have chosen to go for maximum current of this range because I wanted to leave enough margin for noise figure, as it is the main objective of the whole design.

For above current and current density I have calculated the transistor width to be around 60µm.

Width of transistor = $\frac{I}{J} = \frac{2.8}{0.047} \approx 60\mu m$

Thus, now onwards I Have chosen all transistor width to be 60µm. Therefore, I had to again find ft and fmax, which is respectively 85.92GHz and 105.4GHz.

Input matching

Since the LNA is first block in the receiver chain, the input must be matched to be driven by 50Ω. Input impedance of a LNA is given by equation below,

$$Z_{in} = \frac{-j}{\omega C_{gs}} + j\omega L_S + \frac{g_m L_S}{C_{gs}} + j\omega L_g$$

Note that in this equation we have not considered Miller effect as a dominating factor. This input impedance must be matched to 50Ω hence real part of the equation must be equal to 50Ω.

Hence,

$$\frac{g_m L_S}{C_{gs}} = R_S$$

Therefore

$$L_S = \frac{R_S}{\omega_T} = \frac{50}{2\pi x 78.71 x 10^9} = 101.1\ pH$$

Equating imaginary part of Zin we can get equation for Lg,

$$L_g = \frac{1}{C_{gs}\omega^2} - \frac{R_S C_{gs}}{g_m}$$

Where

$$C_{gs} = \frac{g_m}{\omega_T} = \frac{51.03x10^{-3}}{2\pi x 78.71x10^9} = 103.2fF$$

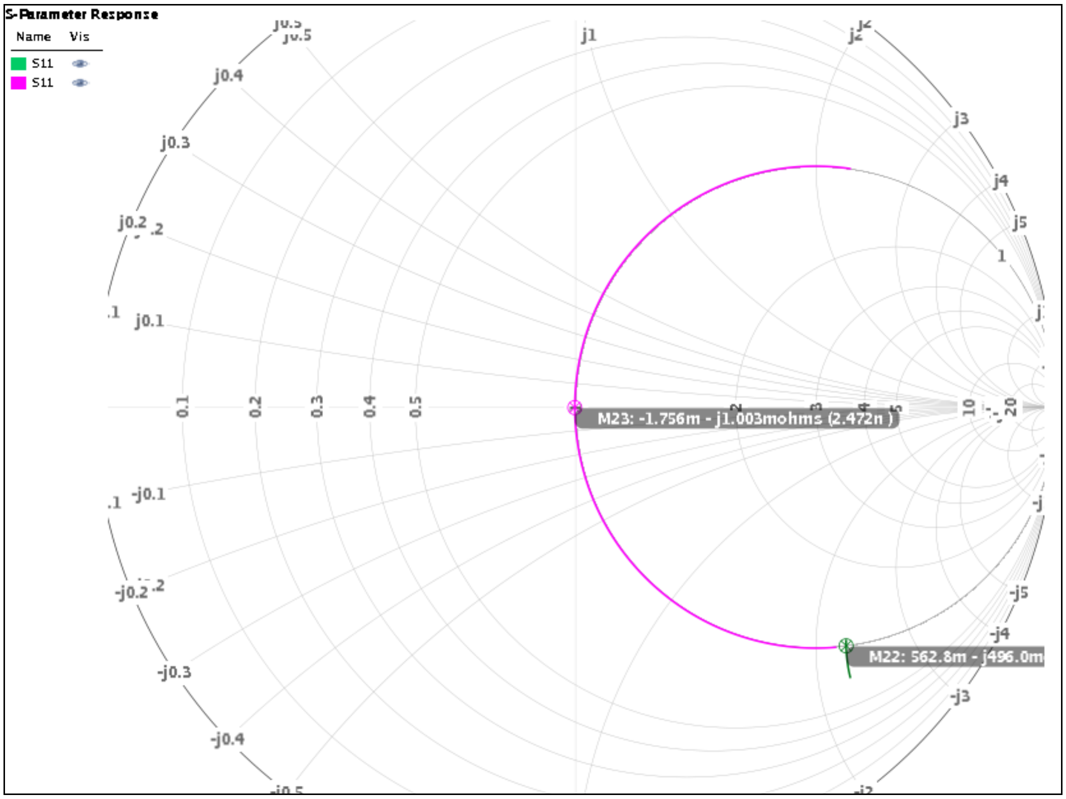
Thus,

$$L_S = \frac{1}{C_{gs}\omega^2} - \frac{R_S C_{gs}}{g_m} = \frac{1}{(2\pi\ x\ 7.295x10^9)^2 x 103.2x10^{-15}} - 0.1011x10^{-9}$$

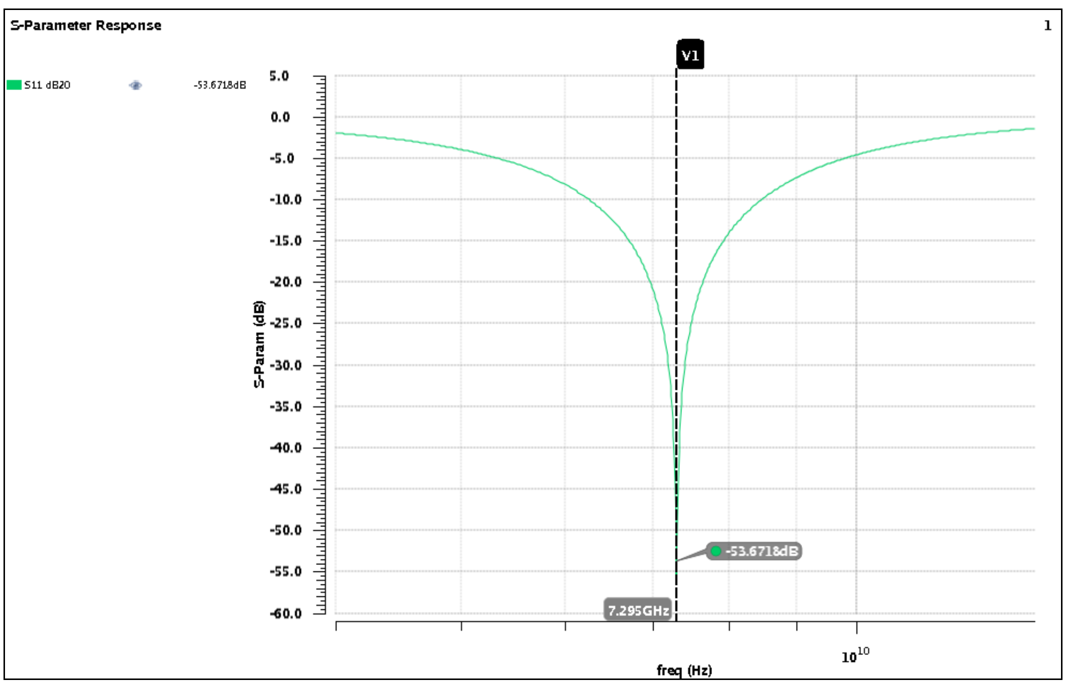
$$L_S = 4.51nH$$

Now as a part of simulation I have vary Ls from 100pH to 200pH and Lg from 0.1nH to 5nH.

Here we are getting Ls=182pH and Lg=2.472nH (without the buffer circuit)



S11 value after matching for simulated value



Chapter 4: Tank circuit

We need to implant the tank circuit to resonant at our desired frequency. Now, for calculation of the capacitor and inductor, we need to make assumption of one of the component. I assume the inductance value as the 1nH and find the capacitance,

$W = \frac{1}{\sqrt{LC}}$ $\sqrt{C} = \frac{1}{2\pi f\sqrt{L}}$

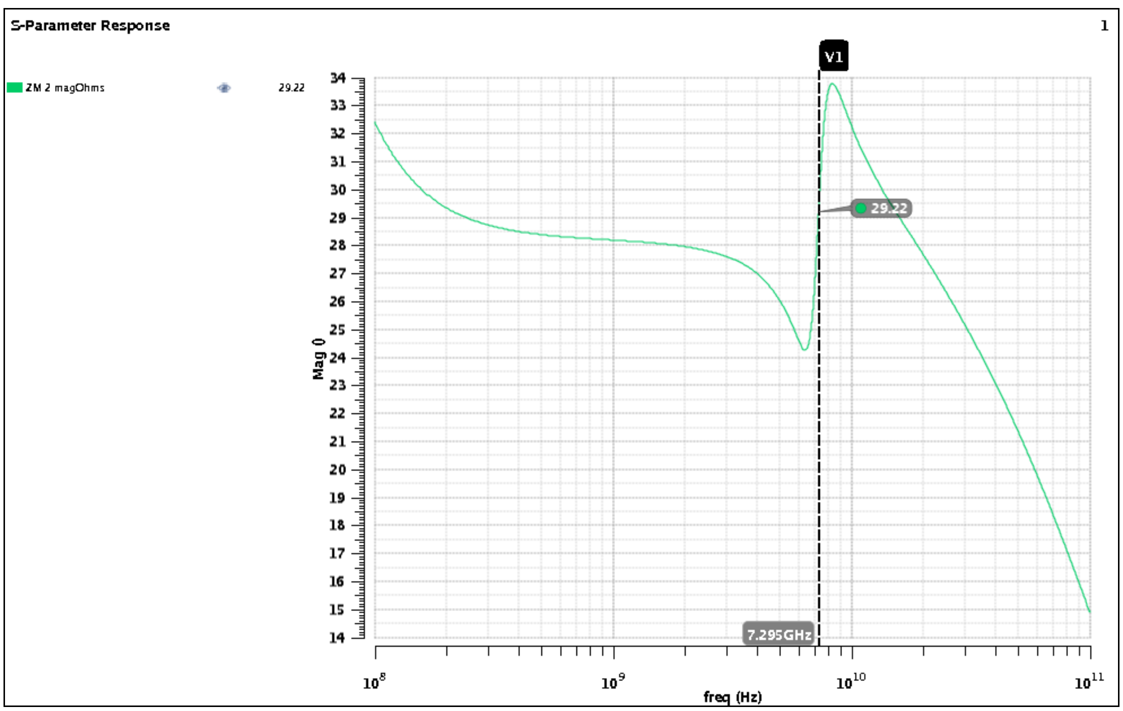
Now substituting f=7.295GHz and L= 1nH

$$C = \frac{1}{(2x3.14x7.295x10^9)^2\ x\ 1\ x\ 10^{-9}} = 475.98\ fF$$

I choose the capacitance value 350fF, because of the parasitic capacitance adds up and form the capacitance value near to that we just calculated. We add parallel the resistor. to adjust our gain.

Chapter 5: Output impedance

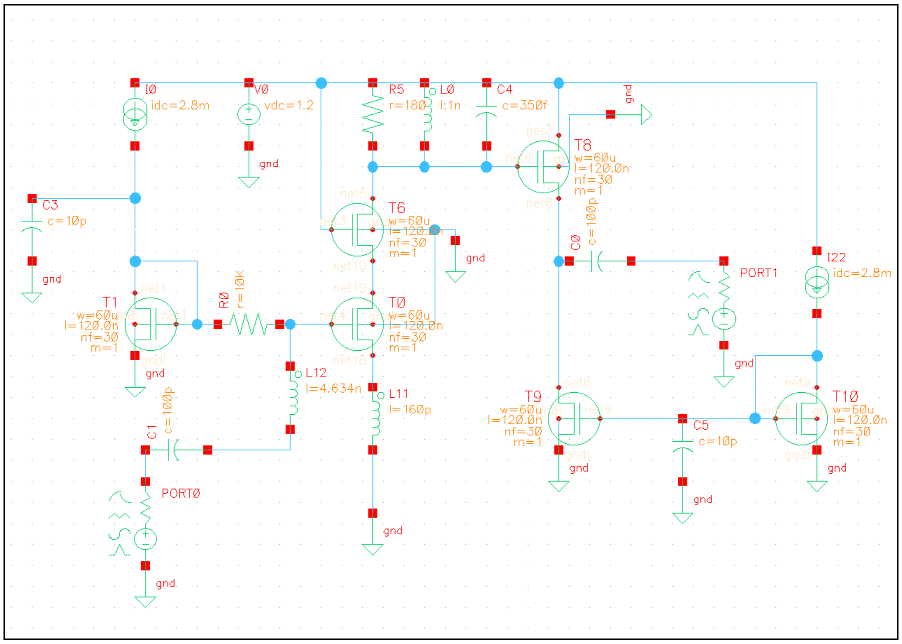
Here I have introduced buffer circuit with common drain configuration and found out |Zout| which is well matched to 30Ω. At first this value was almost 35Ω. I have adjusted tank capacitor to bring it to middle point. If I want to move the whole graph up or down I could have change current through the output branch as discussed in next topic. For this case I have choose my buffer current well so that |Zout| is less than 30Ω but not too low. For this case buffer current is same as bias current, which is equal to 2.8mA.



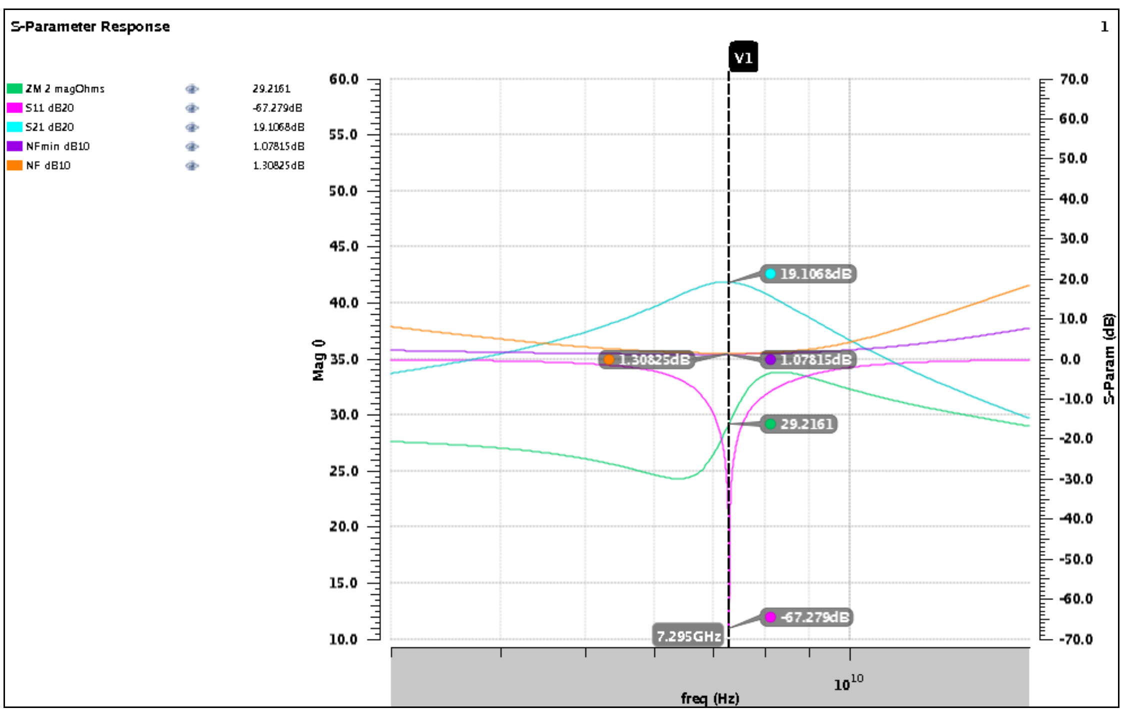
Chapter 6: All specs with ideal inductor

All spec with ideal inductor. Linearity has not considered at this point. The main intension behind putting all specs before and after linearity is that which parameter is affected.

Circuit



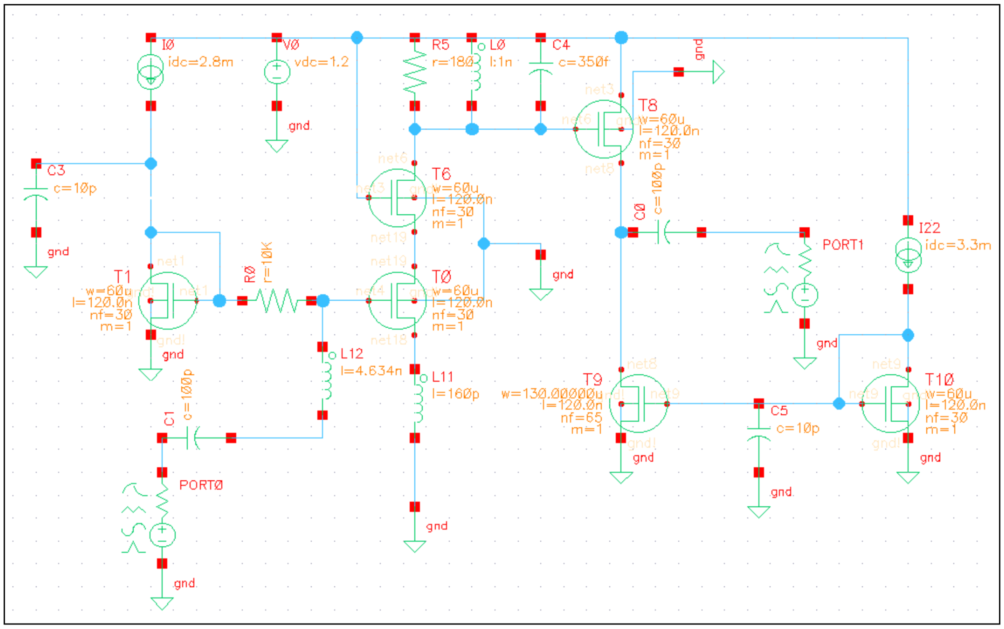
Specifications with ideal inductor and with satisfying linearity:



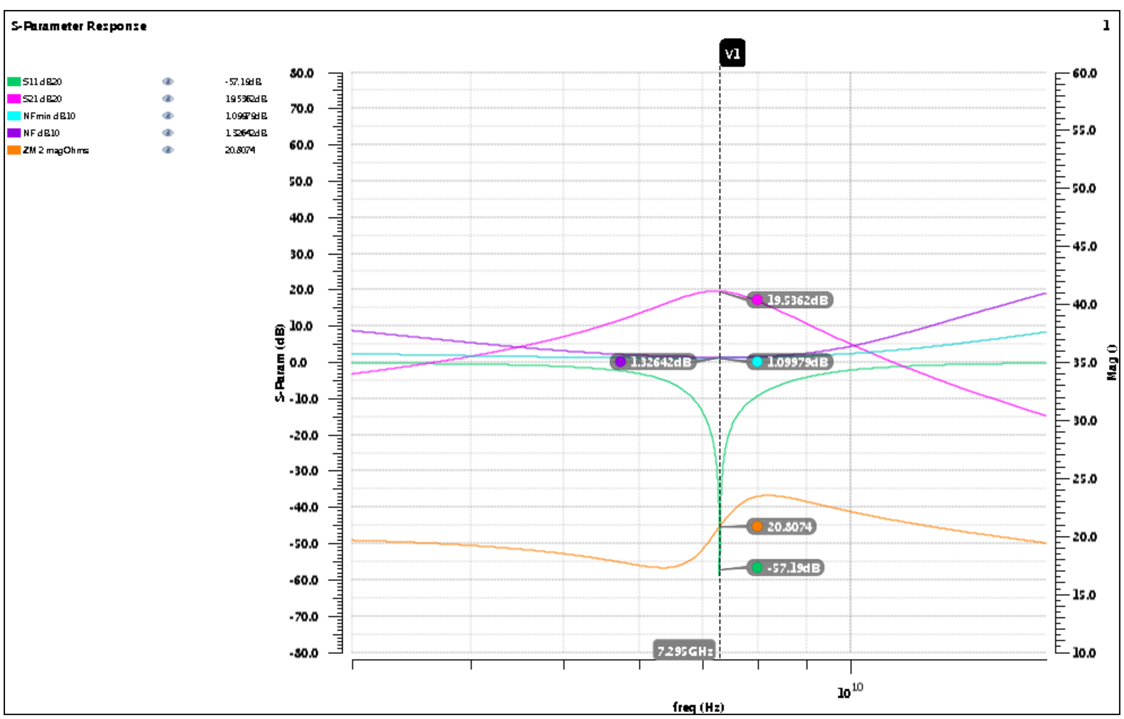
Now for linearity

Size of the transistor T9 is increased to 130nm and buffer current is increased to 3.3mA to meet linearity specs.

Circuit and simulation after all specs (including linearity) have been met. (With ideal inductors)



As we can see below that after increasing transistor width and buffer current we satisfy linearity specs and |Zout| is the parameter affect by this change all other parameter is almost similar.



Linearity

It is important as a linear system is less likely to have clipping at output. In an ideal system, the output is linearly related to the input. The third-order intercept point and 1—dB compression point is used to measure linearity of circuit.

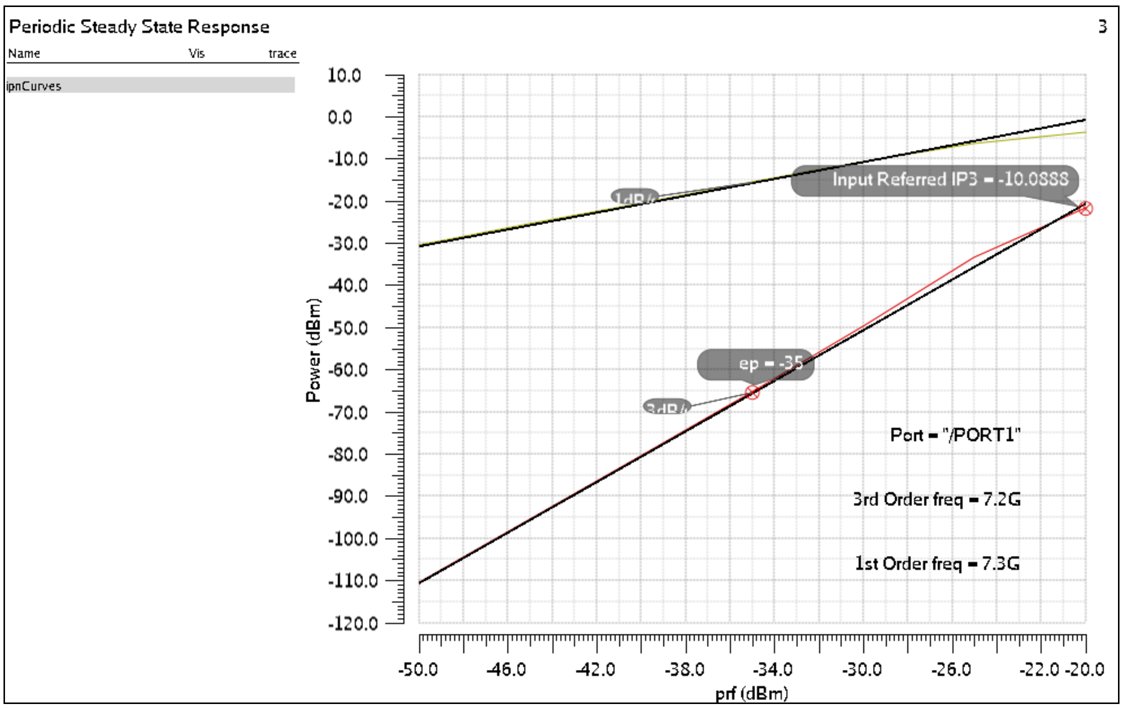
IM3 (third order inter modulation)

$$IIP3 = P_1 + \frac{1}{2}[P_1 - P_3] - G$$

From the power graph which is not shown here. P_1 = -15.55 dBm, P_3 = -65.37 dBm and G = 19.54 dB

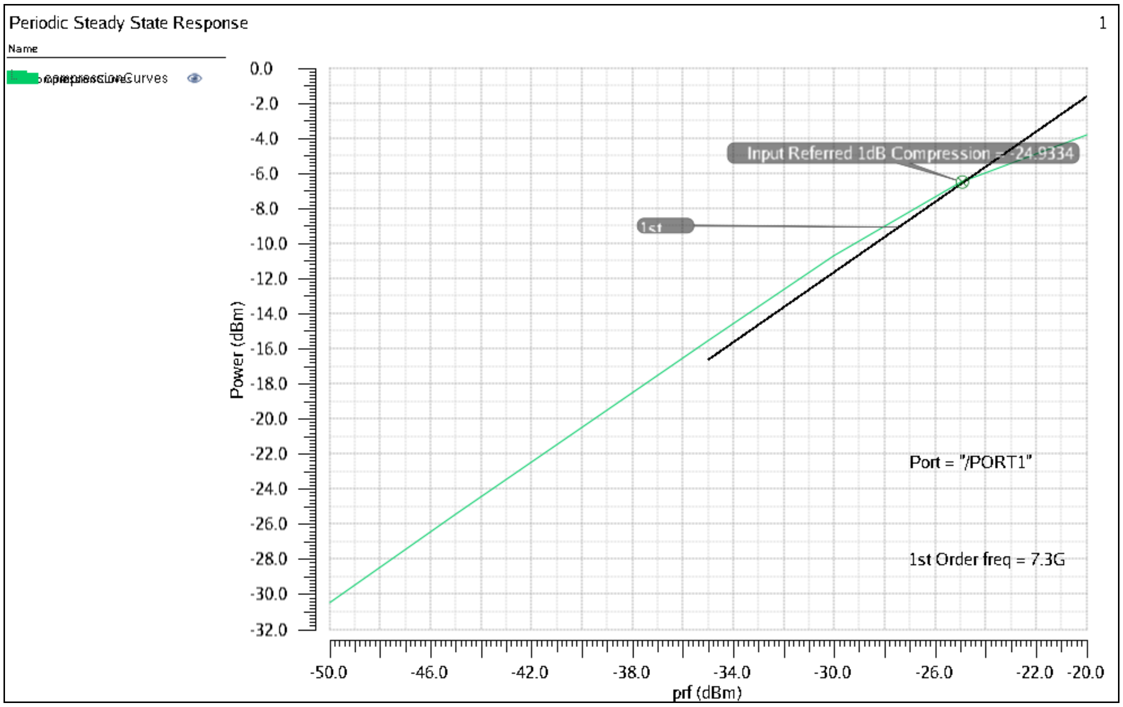
$$IIP3 = -15.55 + \frac{1}{2}[-15.55 + 65.37] - 19.64 = -10.28\, dBm$$

Here, the calculated value **-10.28 dBm** is very close to practical value **-10.088 dBm**.



1db compression point

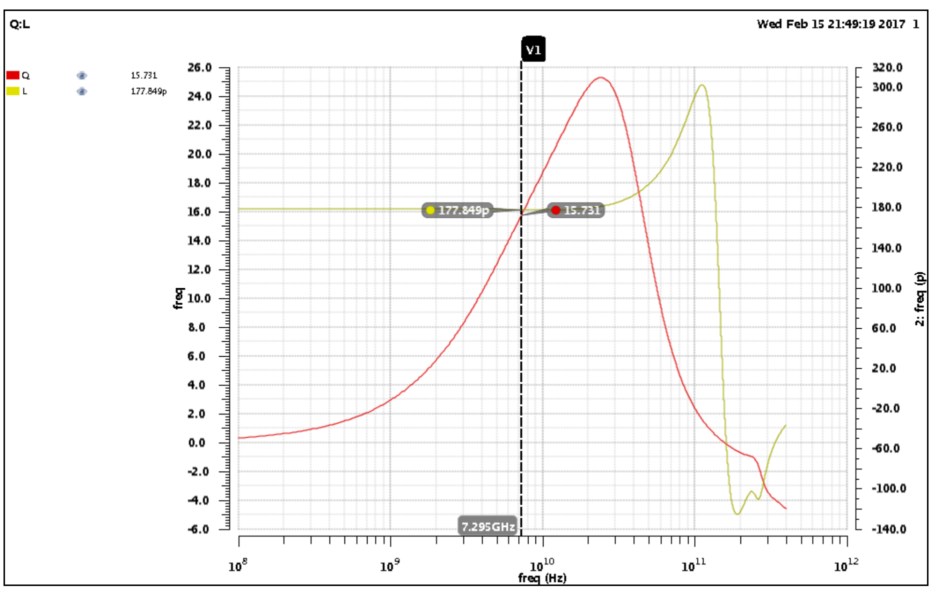
From above calculation we can say that 1db compression point of the system is at about -25 dBm for two tones and -20 dBm for one tone. The two tone value of the same is simulated in the figure below.



Chapter 7: All specs with real inductor

Inductor characterization

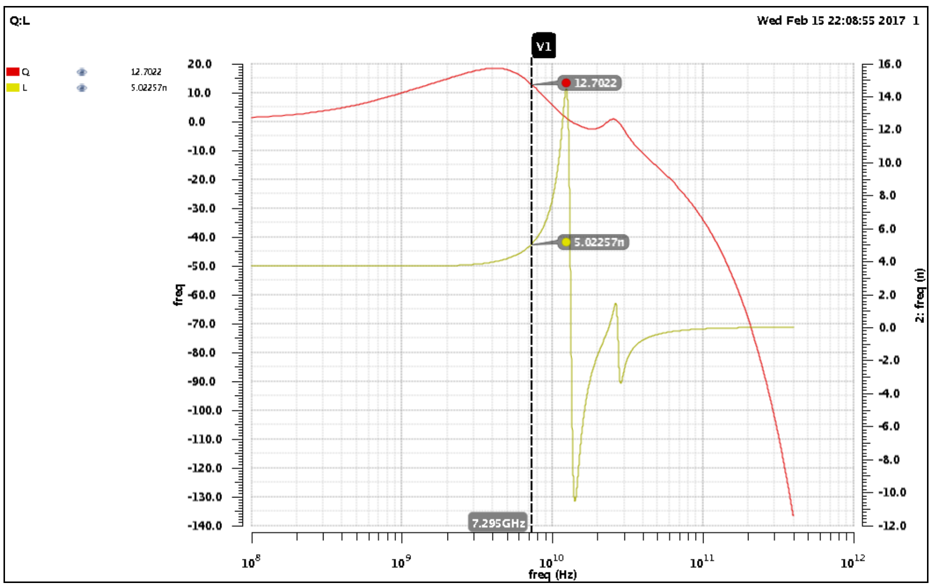
For Ls,



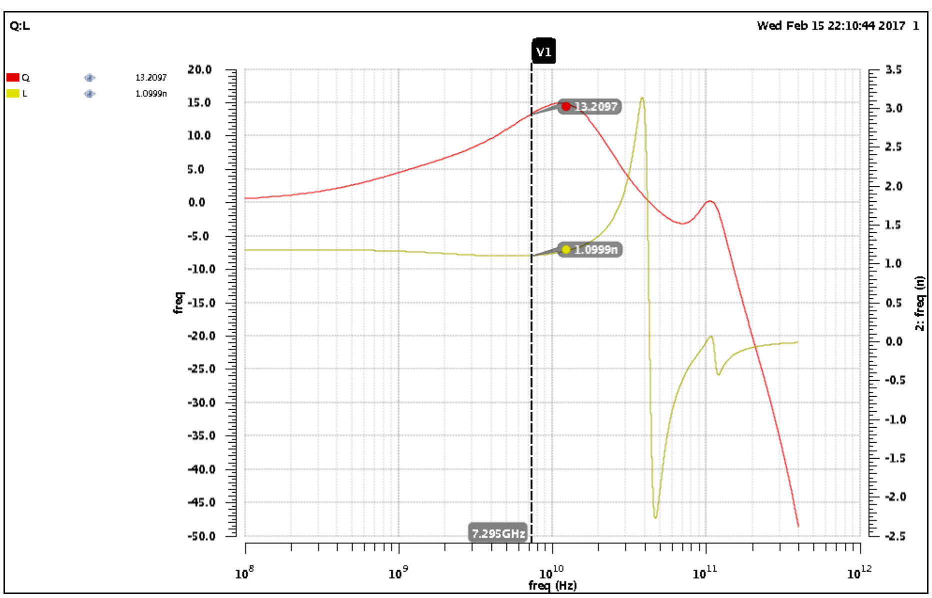
For Lg,

While setting up the value of Lg I have tried to bring the inductance close to linear region but after many parametric analyses by varying outer dimension and metal width of inductor, while changing number of turns for each simulation, I wasn't unable to find right inductance in linear region. After all those tries I have found out that for high inductance we need to increase the spacing between spiral loops, but to do that while going for high inductance we need larger outer dimension which is not allowed by library inductor.

Also, we can not take number of turns as variable because its maximum value changes with outer dimension and metal width. Hence, we cannot correctly upper bound its value.



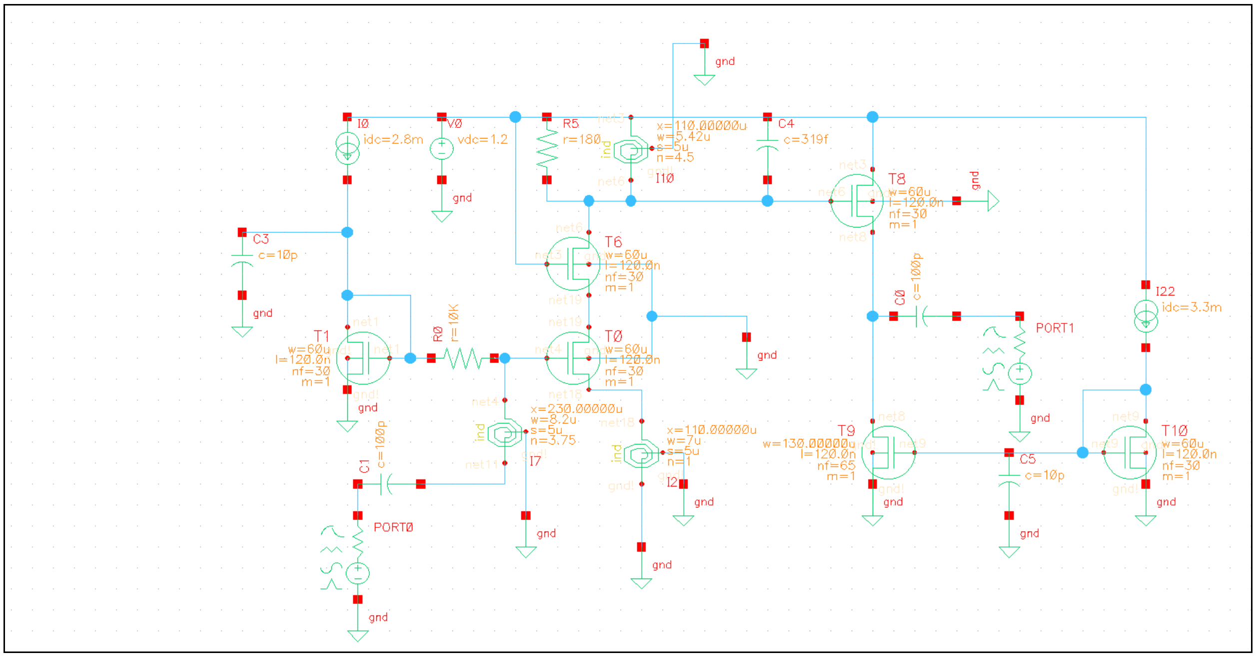
For Lt,



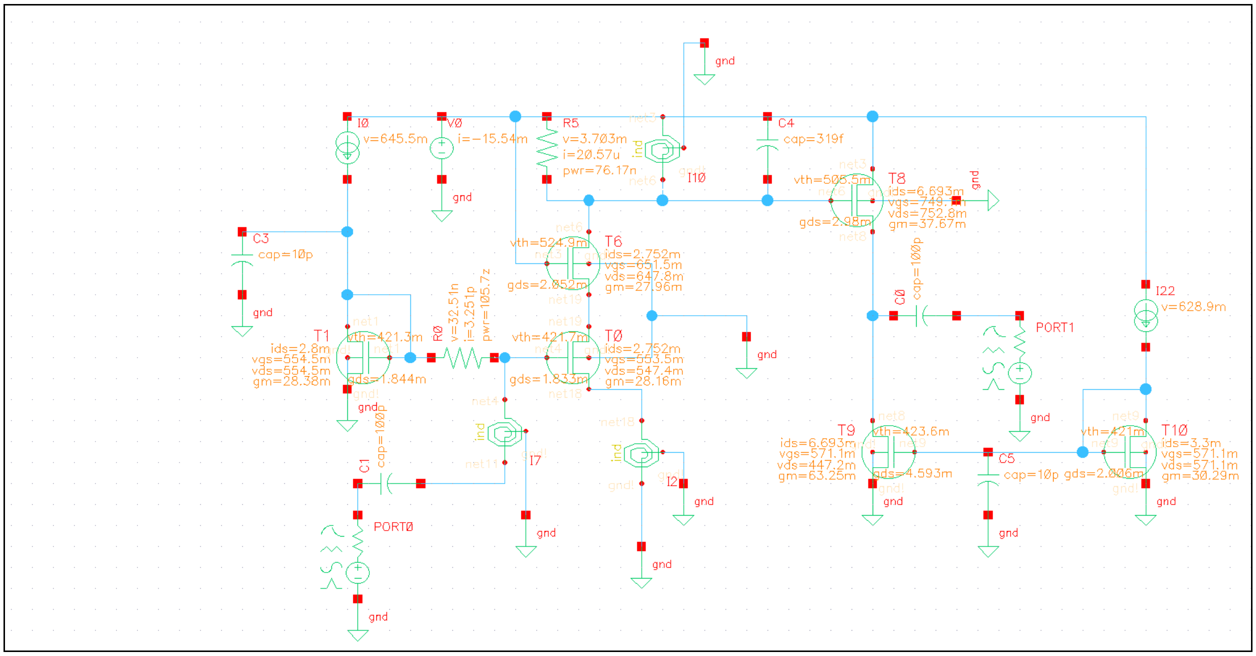
Circuit and simulation with real inductor

I have put above inductors in the circuit below and simulate all the outputs again.

Circuit



DC operating points for circuit



Equation of Gain is given by,

$$Av = \frac{R_L \omega_T}{R_S \omega_0} \frac{50}{r_0 + 50}$$

We need to find equivalent R_L at tank circuit. I have found R_P with practical value of Q of tank inductor,

$$Q = \frac{R_P}{\omega_0 L_T}$$

Hence,

$$R_P = 13.21 \; x \; 2 \; x \; 3.14 \; x \; 7.295 \; x \; 10^9 \; x \; 1.1 \; x \; 10^{-9} = 665.7\Omega$$

Now,

$$\mathrm{R}_L = \mathrm{R}_T \; || \; \mathrm{R}_P = \frac{665.7 \text{ x } 180}{665.7 + 180} = 141.68 \; \Omega$$

$$Av = \frac{R_L \omega_T}{R_S \omega_0} \frac{50}{r_0 + 50} = \frac{141.68 \; x \; 78.71 x 10^9}{50 \; x \; 7.295} \; x \; 0.5 = 15.28 \text{ , } \mathrm{Av}|_{dB} = 20 \log 15.28 = 23.68 \text{ dB}$$

This difference in calculated values and practical value is because of C_{gd} was ignored. Hence, we are getting significant error. To compensate the error, we can reduce ft by half of measured value.

$$Av = \frac{R_L \omega_T}{R_S \omega_0} \frac{50}{r_0 + 50} = \frac{141.68 \; x \; 39.35 x 10^9}{50 \; x \; 7.295} \; x \; 0.5 = 7.64 \text{ , } \mathrm{Av}|_{dB} = 20 \log 7.64 = \mathbf{17.66 \; dB}$$

Noise factor

$$F = 1 + \frac{r_g r_{LG}}{R_s} + \frac{\gamma}{g_m R_s} + \frac{\delta g_m R_S}{5} \left(\frac{\omega_0}{\omega_T} \right)^2$$

For Lg,

$$Q = \frac{\omega_0 L_g}{R_{LG}}$$

Hence,

$$R_{LG} = \frac{2 \; x \; 3.14 \; x \; 7.295 \; x \; 10^9 \; x \; 4.51 \; x \; 10^{-9}}{12.71} = 16.26$$

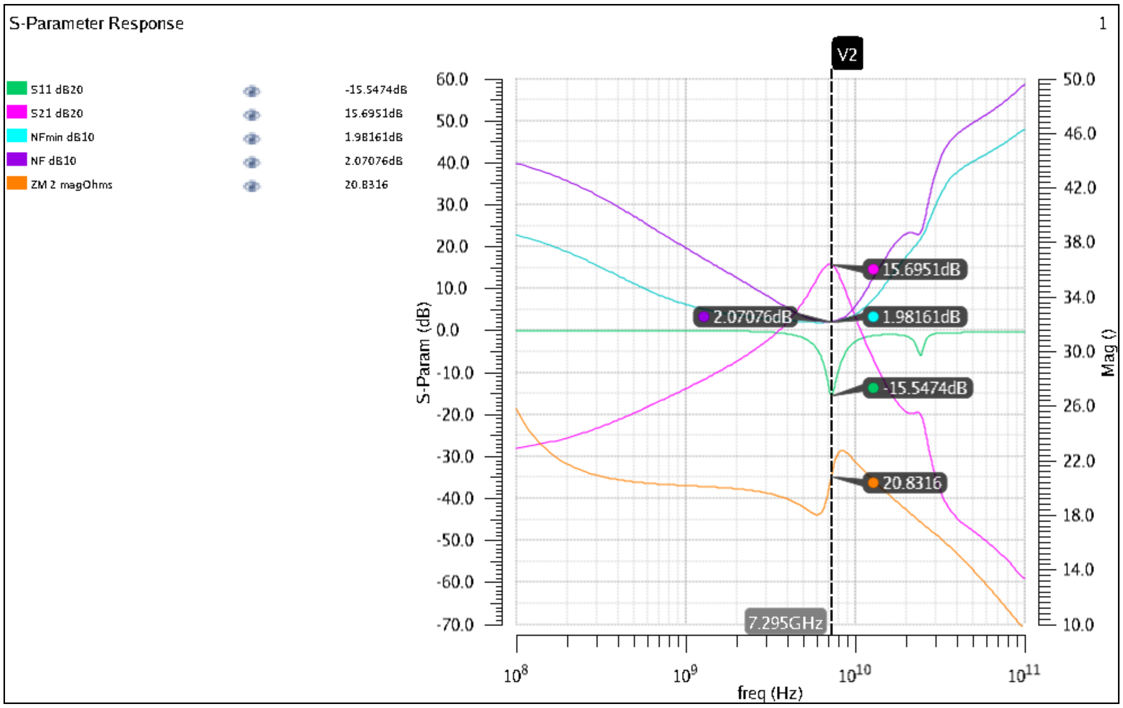
Putting this in the equation, with $\gamma = 0.67 \; and \; \delta = 1.33$

$$F = 1 + \frac{16.26}{50} + \frac{0.67}{51.03 x 10^{-3} x 50} + \frac{1.33 x 51.03 x 10^{-3} x 50}{5} \left(\frac{7.295}{78.71} \right)^2$$
$$= 1 + 0.3252 + 0.2625 + 0.00582 = 1.59$$

Now,

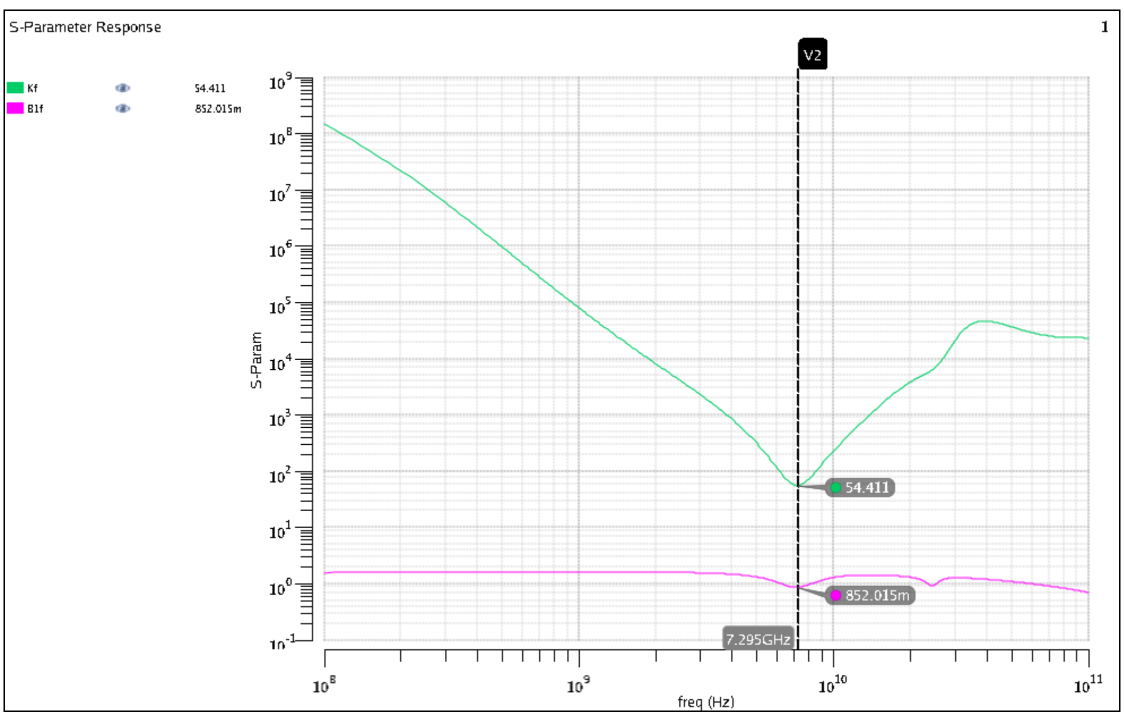
$$NF = 10 log F = 10 \log 1.59 = \mathbf{2.02 \; dB}$$

All the parameters shown in one graph,

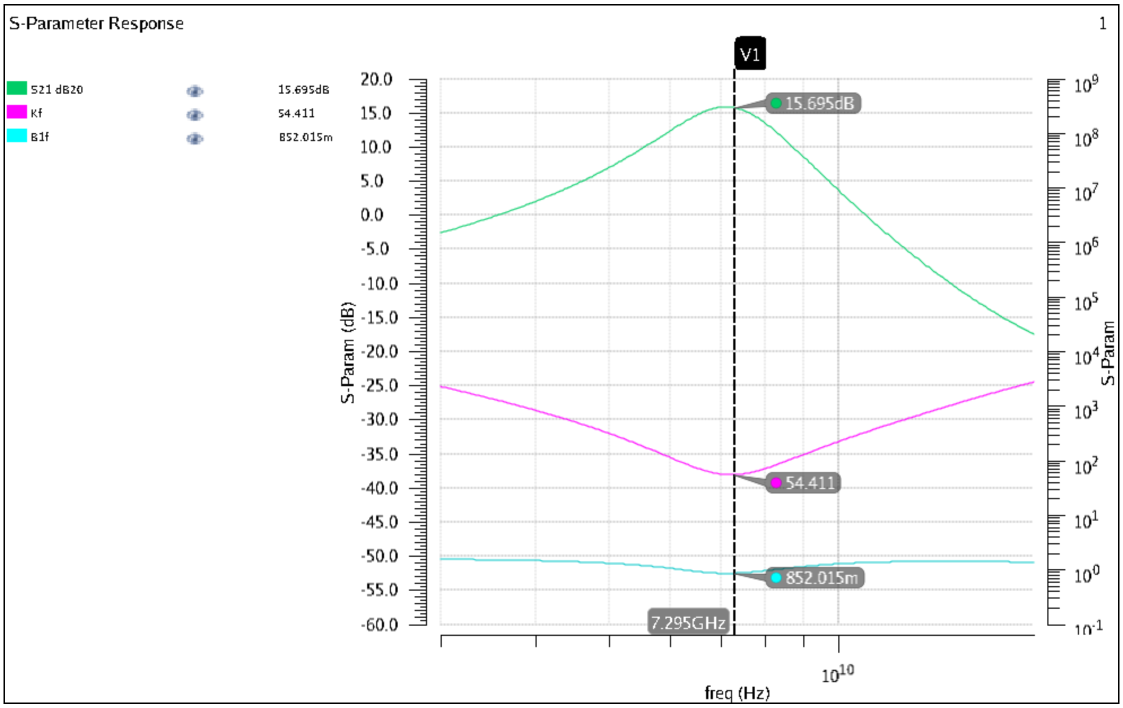


Stability

The plots for Kf and B1f are shown below. The value of Kf at our desired frequency is 54.411 which is greater than one for all the frequency and the value of B1f at our desired frequency is 852.015m which is greater than zero and hence the circuit is unconditionally stable.



Enlarge graph to show accuracy of the plots



Linearity

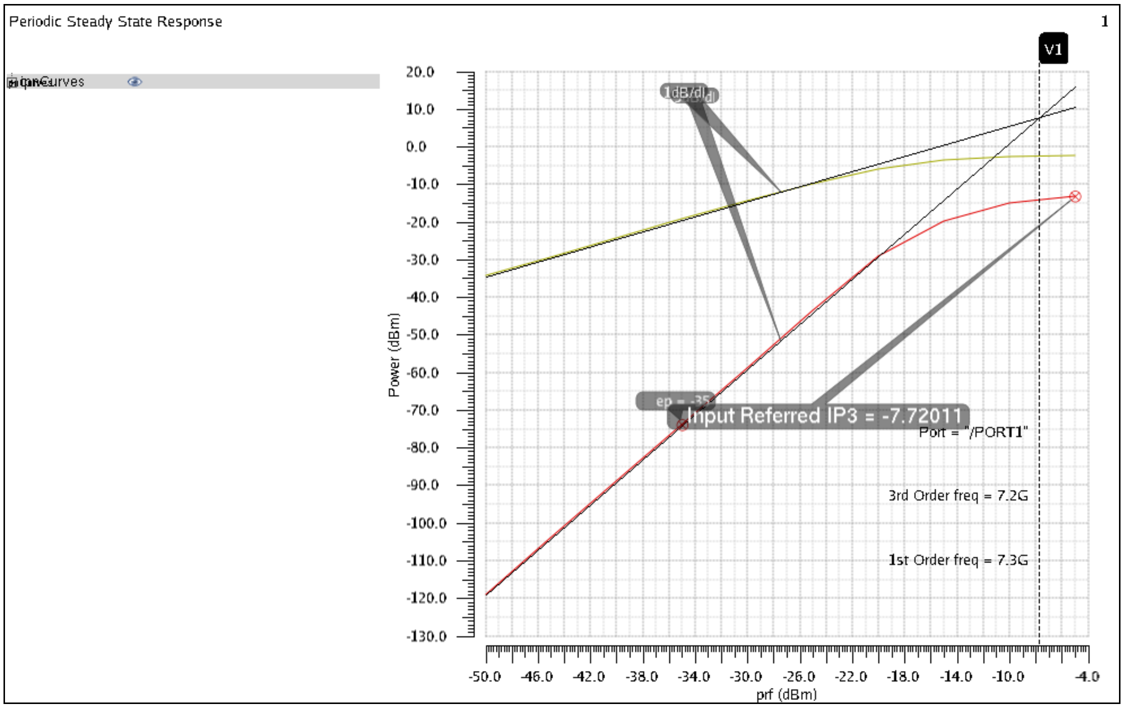
IM3 (third order inter modulation)

$$IIP3 = P_1 + \frac{1}{2}[P_1 - P_3] - G$$

From the power graph which is not shown here. P_1 = -19.36 dBm , P_3 = -73.92 dBm and G = 15.7dB

$$IIP3 = -19.36 + \frac{1}{2}[-19.36 + 73.92] - 15.7 = -7.78\ dBm$$

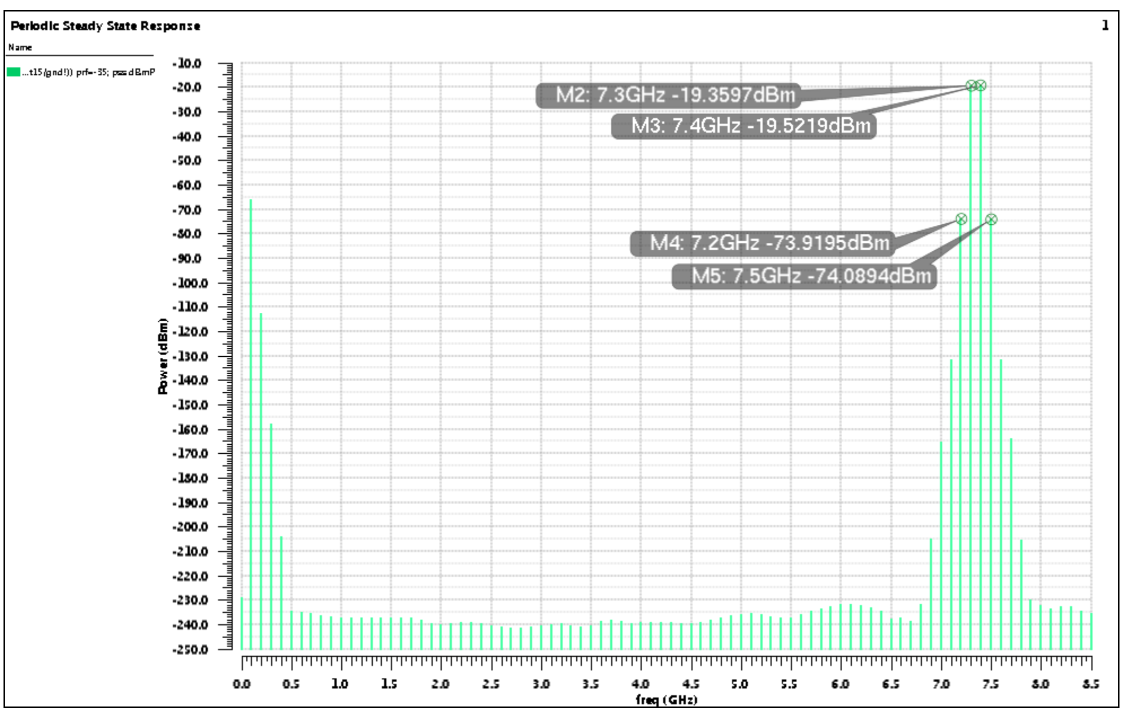
Here, the calculated value **-7.78 dBm** is very close to practical value **-7.72 dBm**.



1dB-Compression

From above calculation we can say that 1db compression point of the system is at about -22.78 dBm for two tones and -17.78 dBm for one tone. The two tone value of the same is simulated in the figure below.

Power



Noise summary

Device	Param	Noise Contribution	% Of Total
/PORT0	rn	7.42945e-18	61.72
/T0	id	7.96043e-19	6.61
/R5	rn	4.22371e-19	3.51
/R0	rn	4.20755e-19	3.50
I7.xstack.rsxoutp	rn	3.69587e-19	3.07
/T6	id	3.20569e-19	2.66
/T9	id	2.34532e-19	1.95
I7.xstack.rse1a	rn	1.7414e-19	1.45
/T8	id	1.60574e-19	1.33
I7.xstack.rsrf2	rn	1.38302e-19	1.15
I7.xstack.rsxinp	rn	1.33884e-19	1.11
I7.xstack.rsxins	rn	1.33884e-19	1.11
I7.xstack.rpr1a	rn	1.29752e-19	1.08
I7.xstack.rse2a	rn	1.07175e-19	0.89
I7.xstack.rprf2	rn	1.03049e-19	0.86
I7.xstack.rpr2a	rn	7.98564e-20	0.66
/PORT1	rn	6.92892e-20	0.58
/T0	rs	6.19483e-20	0.51
I7.xstack.rsxouts	rn	6.00785e-20	0.50
/T0	rbpb	5.57014e-20	0.46

Spot Noise Summary (in V^2/Hz) at 7.295G Hz Sorted By Noise Contributors
Total Summarized Noise = 1.20376e-17
No input referred noise available
The above noise summary info is for sp_noise data

Parameters	**Calculated values**	**Practical values**
Ls	101.1 pH	177.85 pH
Lg	4.51 nH	5.022 nH
S21	17.66 dB	15.69 dB
NF	2.02 dB	2.07 dB
IIP3	-7.78 dBm	-7.72 dBm
1 db compression point	-22.93 dBm	-22.78 dBm
Zout (1/gm)	19.59	20.83

Inductor properties

Parameter	**Lg**	**Ls**	**Lt**
Outer Dimension	230 µm	110 µm	110 µm
Metal width	8.2 µm	7 µm	5.42 µm
Number of turns	3.75	1	4.5
Q	12.71	15.73	13.21
L	5.022 nH	177.85 pH	1.1 nH

Design trade-off

During number of simulation I have encountered varies design trade off. One which is current and noise figure. If we wish to have excellent noise matching, then we should keep current density optimum. But for that we have to invest huge amount of power. Similar with gain too. We keep gain too high it will create problem with linearity at output. The tank circuit determine two things. First, at what frequency will the peak of voltage gain curve will occur. Second, the tank resistor will determine the value of the voltage gain peak along with current. Every time we change a parameter of the circuit it has became my practice to first check whether the peak voltage gain is for my frequency or not. If not, then change value of tank capacitor. By doing this I will disturb the input matching. Thus, I have to change Ls and Lg too. The challenge is not well your circuit works but how efficiently it works considering all specs have been met.

Conclusion

To conclude I would say, for LNA design we have to consider input matching, current density, properly tuned tank circuit, linearity and stability. As LNA is the first block receiver section it has to be build well in terms of noise figure. Also, it must be properly matched, so that weakest received signal can make it through the circuit. In addition, we cannot have non-linear distortion of this signal.

To pen down I would say, LNA is very crucial part of a receiver as it has to be capable of detecting small signal in the presence of large interference.

References

Radio Frequency Integrated Circuit Design 2nd edition by Calvin Plett and John Rogers.

A 2.4GHz Cascode CMOS Low Noise Amplifier by Gustavo Campos Martins.