## Performance Summary Table

| | Design metric | Performance | Specification |
|---|---|---|---|
| Input Matching | Worst case S11 in the specified band | -9.44dB | < −10dB |
| | Band over which S11 < −10dB | 1.91GHz-2.229GHz | 1.9GHz to 2.1GHz |
| | Band over which S11 < −15dB | 1.98GHz-2.065GHz | - |
| Voltage Gain | Minimum Gain in the specified band | 29.11dB | > 20dB |
| | Maximum Gain in the specified band | 32.34dB | > 20dB |
| | Gain flatness in specified band [Max-Min Gain] | 3.2dB | < 3dB |
| | 3dB Bandwidth | 211.40MHz | > 200M Hz |
| | Load Capacitance [Differential] | 1pF (diff) no extra cap | 1p F |
| Noise Figure | Maximum Noise Figure in the specified band | 1.1768dB | < 1.5dB |
| | Minimum Noise Figure in the specified band | 1.17216dB | - |
| | Band over which N F < 1.5dB | 730MHz - 2.76GHz | 1.9GHz to 2.1GHz |
| Linearity | IIP3 Tones used | 2GHz, 2.001GHz | - |
| | Input power used for extrapolation | -50.1215dBm | - |
| | Power of Fundamental Tone at output (at chosen input power) | -30.4888dBm | - |
| | Power of IM3 Tone at output (at chosen input power) | -127.337dBm | - |
| | Extrapolated IIP3 | -3.824dBm | > −10dBm |
| Power | LNA DC power consumption [Excluding Bias] | 2.738mW | Minimize |
| | Bias circuit power consumption | 1.356mW | Minimize |
| Other | Sum of all on-chip inductances | 7.58nH | - |
| | Sum of all off-chip inductances | 37.90nH | - |
| | Sum of all resistances [Including bias] | 21.3398K | - |
| | Sum of all capacitances [Including AC coupling, excluding load] | 200uF | - |
| | Simulator Used | Eldo | - |

# LNA Project

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## Introduction:

This project is about making a single ended to differential output Common-Source LNA (Low noise amplifier) using inductive impedance at the source and a cascode transistor. We have to tune various component values like Mosfet widths, resistors, inductors and capacitors in order to optimize and achieve specifications close to what is needed. We implement a single ended to differential output CS-LNA in order to facilitate differential input to the mixer.

## CIRCUIT SCHEMATIC:

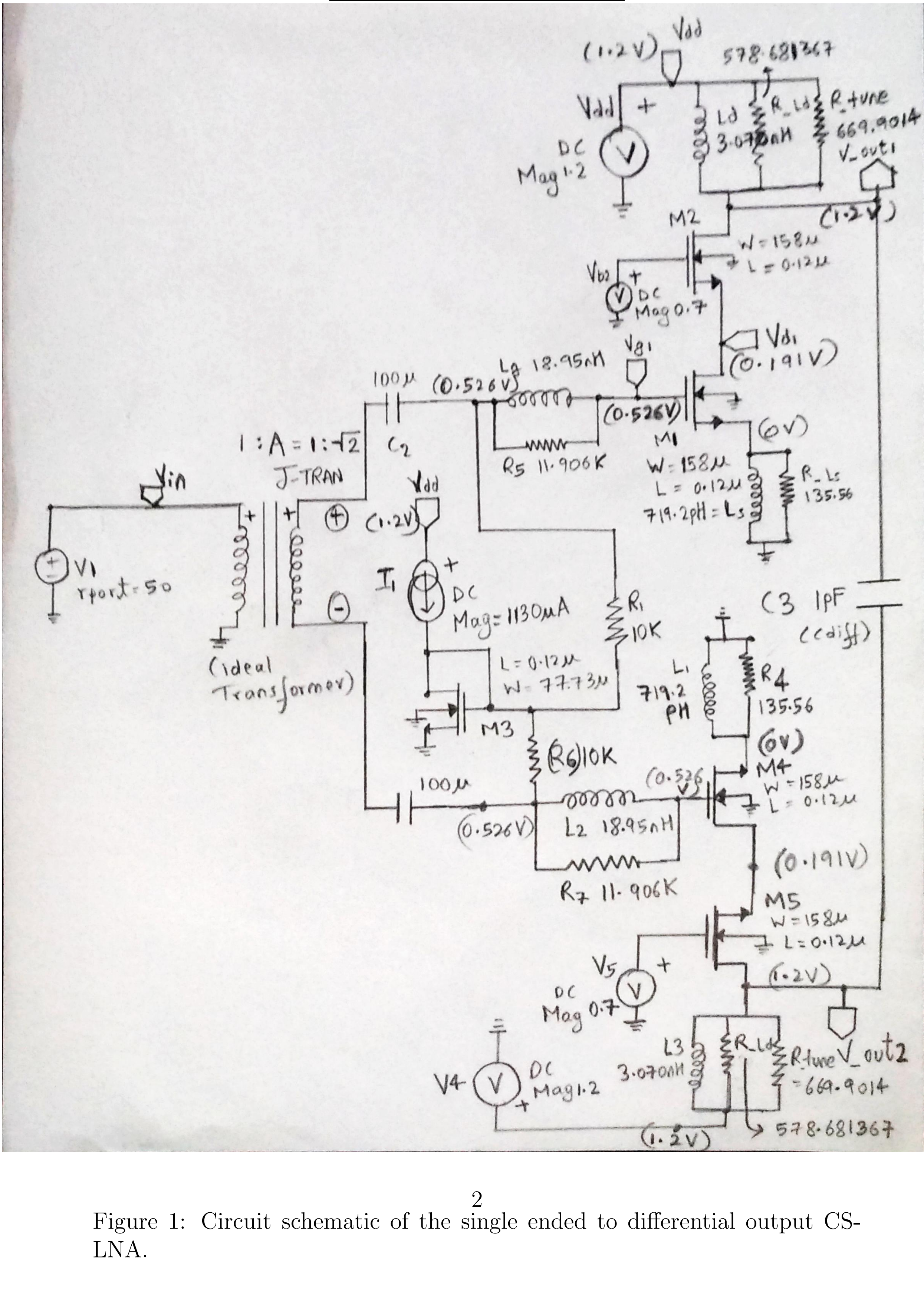




Figure 1: Circuit schematic of the single ended to differential output CS-LNA.

## Specifications of the Mosfet M1 used:

Before going into the performance analysis the following specs of MOSFETs M1 and M2 may be useful later on:
-gm1 = 28.493mS
-VTH1 = 0.422V
-VTH2 = 0.450V
-L1=L2 = 0.12u
-W1=W2 = 158u
-Cgs M1 = 235fF
-I1 = I2 = 1.457mA

## Performance and Graphs:

### Voltage Gain and S11:

We start with setting the Q of the voltage gain to be approximately 10 according to the specification ( center frequency 2GHz, with a 3dB BW of atleast 200MHz). As shown in the hand calculations for voltage gain in the appendix, we notice that the Qdrain is very high (around 15) so, we use a very low Qin and derive Cgs1 (for M1) from this. We get a ballpark value of around 200fF. Now, we still increase Cgs1 in order to lower Qin and also add an Rtune (arbitrarily chosen, but close enough to Rpar-Ld) at the output drain in order to make the response broadband. Also, the drain inductor (Ld) value is calculated by using the resonant freq. relation with Ld and Cload (here 2pF in single ended). As for Ls and Lg, we also need the input matching conditions. Initially, just from the wT*Ls = Rs relation, it turns out that the S11 graph had a big dip at 2Ghz, which is expected, but it wasn't lower than -10dB over the whole band. We had to make it broadband and decrease Qin. This leads us to changing the width. However, width being a fundamental parameter would affect a lot of things. So, the Lg, Ld and Ls was changed in such a way as to increase wo (input or output operating frequency) and hence decrease Qin. Additionally, Ls differed from the value calculated for the input match by about 0.3nH which was fine and expected since S11 had to be spread across the band and not have a sharp dip at 2GHz only. What was also observed was that when we try to bring S11 close to the specified band, the voltage gain center frequency shifts. So, we had to optimize such that if the S11 center frequency was low( with the theoretically calculated Lg of around 26nH), then we had to decrease Lg just enough so that the center frequency doesn't go past 2GHz as well.

After setting all these parameters, we obtain the following S11 and gain specifications:
Voltage Gain:
-Min. gain in specified band: 29.11dB
-Max. gain in specified band: 32.34dB
-Gain flatness in specified band: 3.2dB
-3dB bandwidth: 211.40MHz
-Load capacitance: 1pF differential. No extra cap. was added.
The voltage gain graph is as shown in fig.2.
Input matching:
-Worst case S11 in the band: -9.44dB
-Band over which S11 is<-10dB : 1.91GHz to 2.229GHz
-Band over which S11 < -15dB: 1.98GHz to 2.065GHz
The S11 coefficient graph is as shown in fig.3.

## Noise figure:

Now that we set out parameters, we just check for noise figure and see if it's satisfying the specifications. We see that via simulation, the noise figure is very low (1.17 dB) across the whole band and satisfies the specification of 1.5dB. This is probably because even though the Cgs1 is high, the gm1 is also around 28-30 mS which is pretty high implying wT is high. This is allowed from a very low value of Ls as well (from wT*Ls = Rs) ensuring that the noise figure is low. The wT term is finally proportional to $\sqrt{(Ibias/W)}$ where W is width of M1 and Ibias is bias current in M1. Hence, we also ensure that the bias current ( around 1.45mA seen later) is high enough. The Rd (Rtune parallel R-par-Ld) as well seen at the output drain is adjusted such that it's value isn't too low.
Two theoretical expressions for noise figure are discussed in the hand calculations in the appendix. The first one gives us an NF of around 0.092dB which is very low and not surprising because the simulation itself gives a value of around 1.17dB taking into account of parasitics, non exact input match etc. and the theoretical expression is calculated in the very ideal case.
Another approximate expression says that the NFmin is around 1.24dB which is different from the simulation results as expected because it's an expression approximating to only 2 parameters. Nevertheless, we see that it's somewhat close to the simulation value.
The noise figure graph is as shown in fig. 4.
Noise Figure Performance:
-Max. NF in given band: 1.17680dB

-Min. NF in given band: 1.17216dB
-Band over which NF < 1.5dB: 730MHz to 2.76GHz

## Linearity:

The two tone test was done for the differential output CS-LNA using two tones at 2GHz and 2.001GHz with phase +90 and -90 deg. The simulation was run for 15 harmonics of each tone. The amplitude 'A' of the Fourier voltage source of the two tones was swept from -300dBm to -5dBm with an increment of 1dBm. The fundamental output power (@ fund1 = 2GHz) and the 3rd intermodulation output power (@ 2*f1 -f2) was plotted with respect to fundamental input power (@ f1 = 2GHz). The linear regions were found by taking the derivative of output power (at frequencies f1 and 2*f1-f2) with respect to Pin(@fund1). These were also plotted with respect to 'A'. It's seen that there were quite linear regions at a Pin of around -50.12dBm (A = -50dBm) showing a 3dB/dB slope for the 3rd IM term and a 1dB/dB slope for the fund. output term as seen in fig. 5. So, the Pin(fund.) of -50.12dBm is used for extrapolation.
Now, we export the Pout(fund1) and the 3rd IM output power ( 2*f1 -f2) to Matlab and plot both of them with respect to Pin(fund.) as opposed to Eldo's plot w.r.t sweep parameter 'A'. This plot is shown in fig.6. We see that upon extrapolation the intersection lies at (-3.82dBm, 15.79dBm) implying the IIP3 found out is -3.82dBm from extrapolation.
This is a good value of iip3 satisfying the specification over the limit because, the current through the current mirror bias was initially 1000uA and was increased to 1130uA (and kept as such for volt. gain, NF and S11) . This implies the VGS1- VT1 increased hence increasing linearity. Although small changes in VGS are made, it is observed that the iip3 goes up by a significant amount. So, although the bias current went up to around 1.4mA in mosfets M1 and M2, it resulted in a big change in IIP3. Changing the current now back to a lower value changes VGS1, gm1 and esp. Cgs1 and many other parameters affecting the voltage gain, center frequency etc. Additionally, it's seen that IIP3 in the single ended and differential case gave different values.
<u>IIP3 Performance:</u>
Input power for extrapolation: -50.1215dBm
Output power of Fund. Tone: -30.4888dBm
Output power of 3rd IM tone: -127.337dBm
Extrapolated IIP3: -3.824dBm

## Power and bias points:

Finally, as for the power consumed and bias points, this minimum power specification was infact thought about at first when choosing the Vgs1. Its already seen in the Mosfets M1 and M2 specifications, that the threshhold voltage of M1 was around 0.42V. Hence, while making the single ended circuit we didn't choose a very high VGS and chose one around 0.52V (just above threshold) initially and then had to be increased to around 0.525V (for iip3 considerations). This corresponded to a current of 1130uA in the current mirror bias which is verified in the hand calculations as well. The M1 bias current controlled by the current mirror bias current was the only parameter which could be tuned such that the power consumption can change. We could have reduced the wdith of M3( current mirror MOSFET) and also reduce it's bias current to keep same VGS, but we needed a resolution in VGS of 0.005V ( 0.525V - 0.52V) and ofcourse we needed considerable current for that.

The bias point VD1 is 0.191V satisfying VD1>(VG1 -VT1) ( 0.104V). Hence, M1 is in saturation. The bias voltage VG2 for M2 was chosen such that VGS2 was also almost same as that of VGS1. It turned out to be 0.509V which is why the threshold voltages were also not very different and ac currents through both MOSFETS were verified to be almost the same. VD2 is obviously 1.2 V giving good headroom for output voltage swing. All the bias points of the top and lower halves of the differential circuit are ofcourse the same.

Power consumption( differential ckt.):
Power consumption excluding bias: 2.7375mW
Power Consumption by Current mirror bias: 1.356mW
Total DC Power consumed: 4.0935mW
This is verified in fig. 7 and 8.

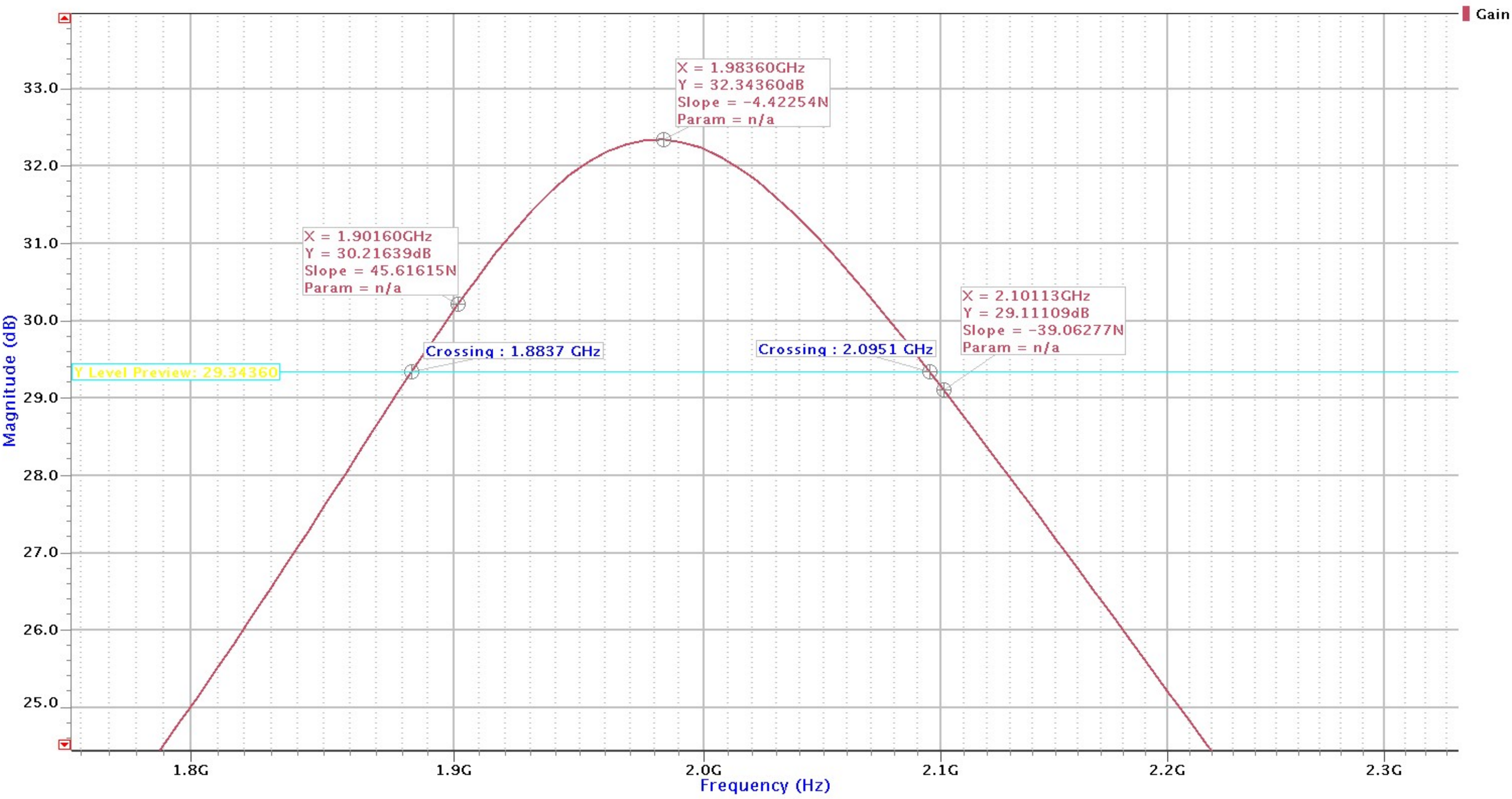


Figure 2: Differential output to single ended i/p Voltage gain for the CS-LNA.

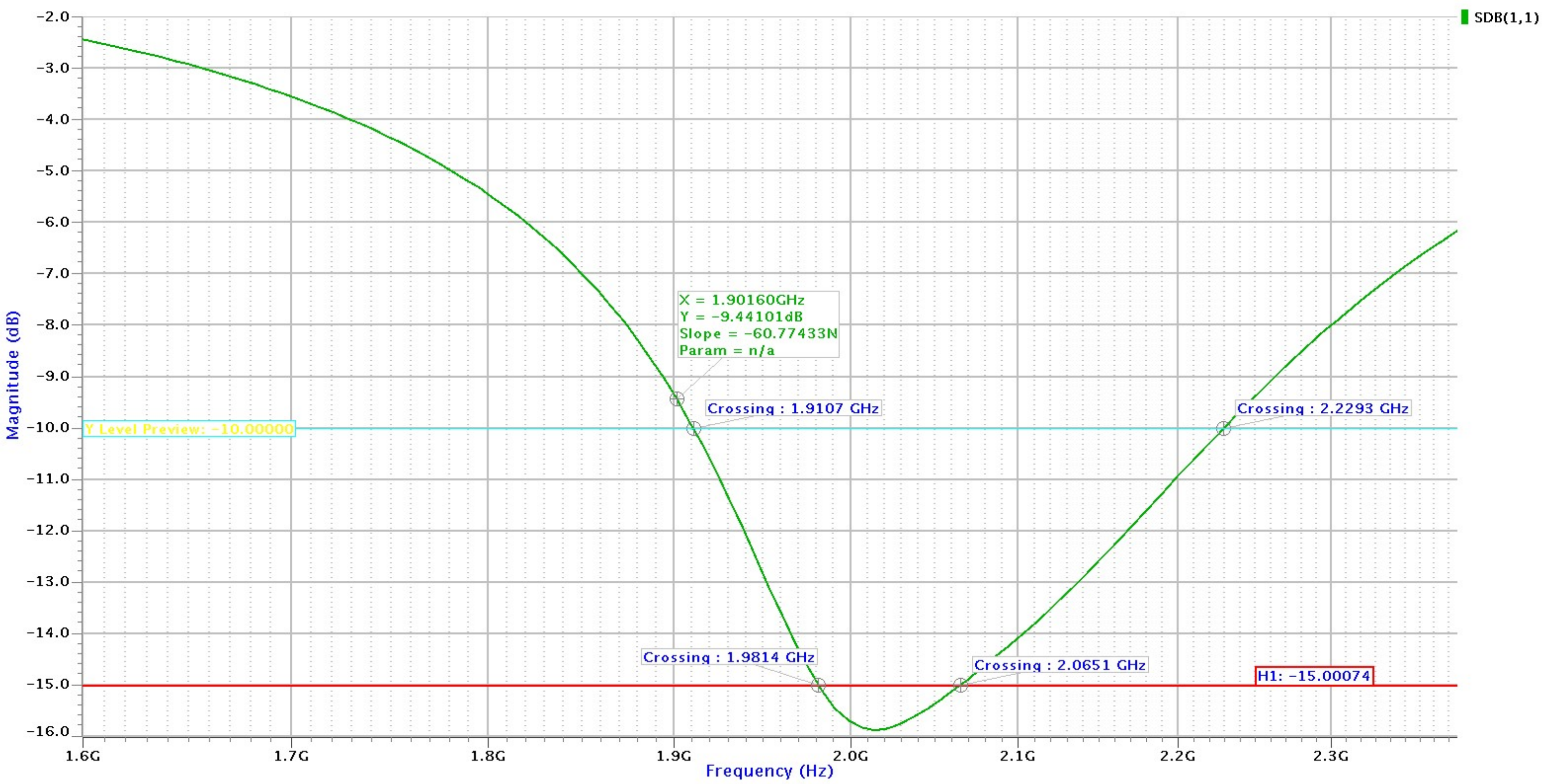


Figure 3: S11 coefficient for differential output single ended i/p CS-LNA.

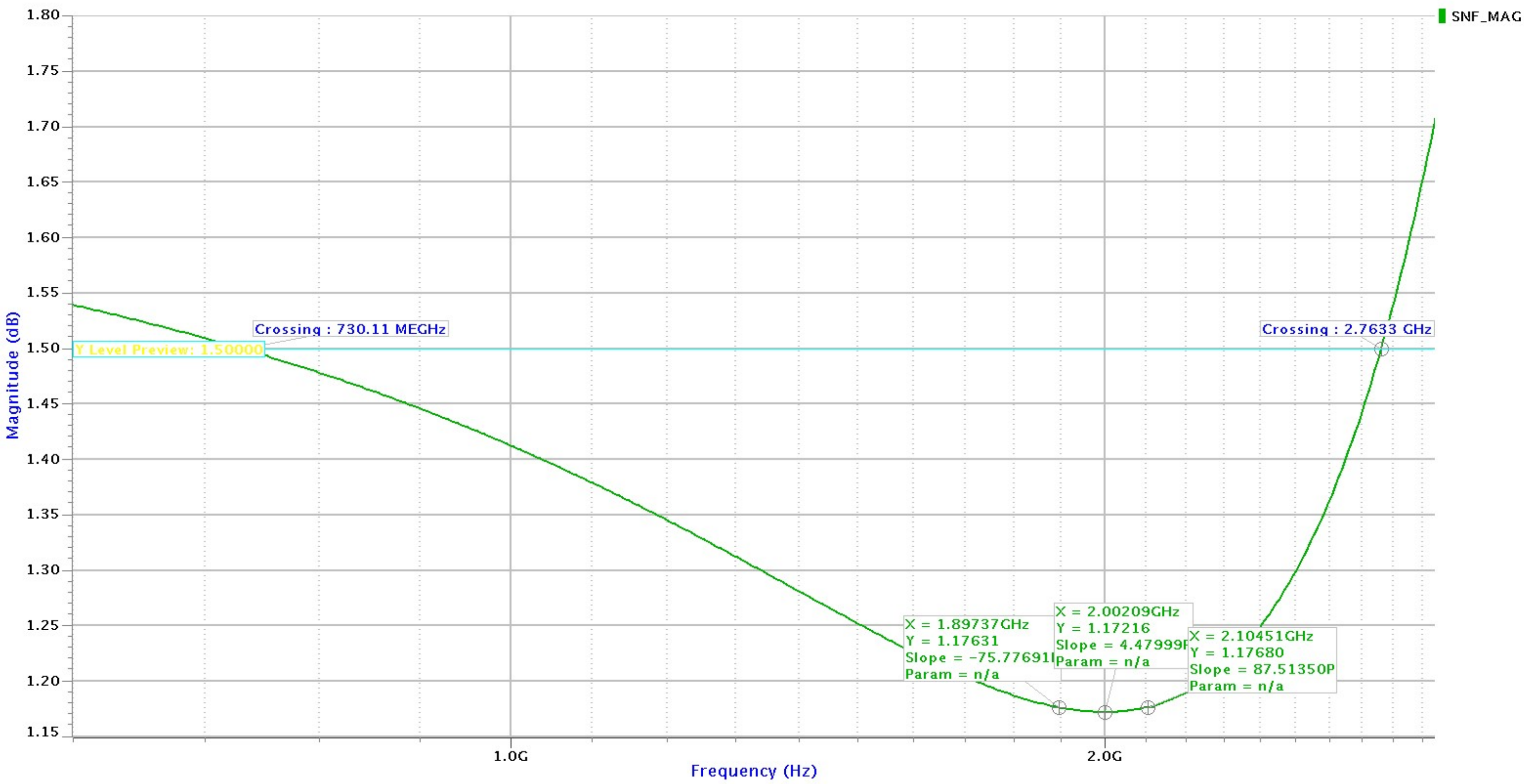


Figure 4: Spot Noise Factor (SNF) or Noise Figure for differential output single ended i/p CS-LNA.

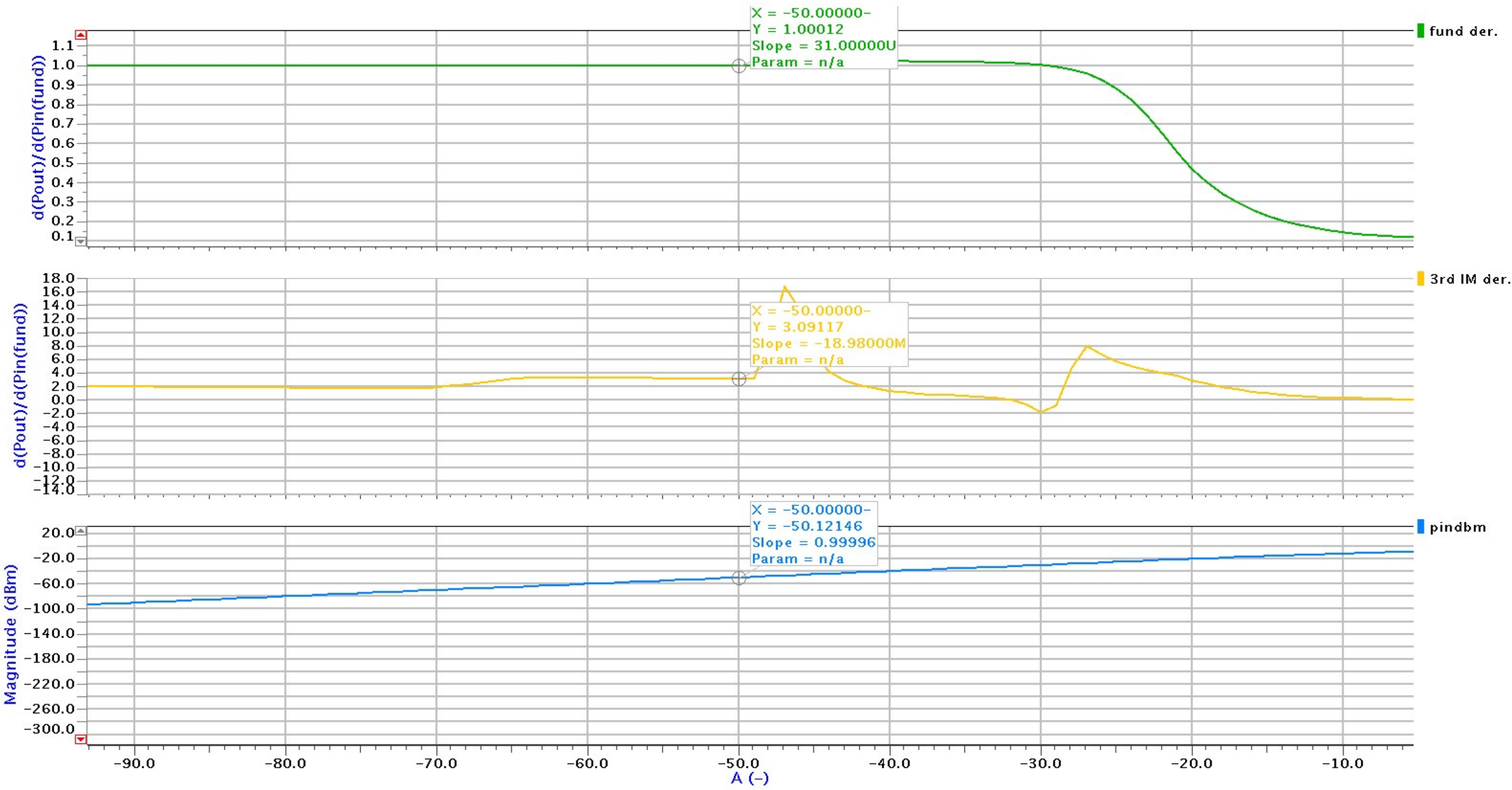


Figure 5: Plot of the derivatives of output power-3rd intermodulation and the fundamental with respect to input power (@ fund. frequency f1) vs. the sweep parameter 'A'. Flat 1dB/dB and 3dB/dB slope regions were observed for 'A' values around -65dBm to -50dBm. The third plot shows the fund. input power( -50.12dBm) hence used for extrapolation.

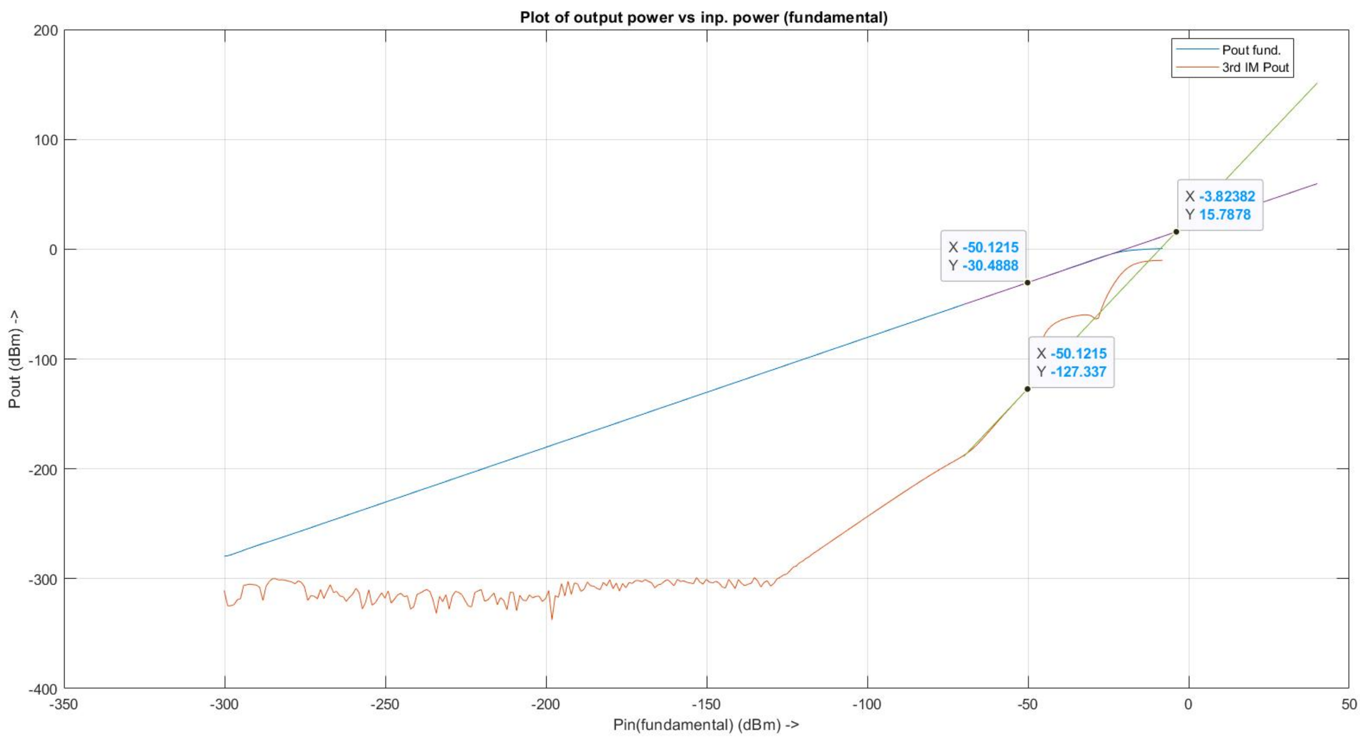


Figure 6: Final Plot of Output Power IM3 and fundamental vs Pin(fund.) with the extrapolation.

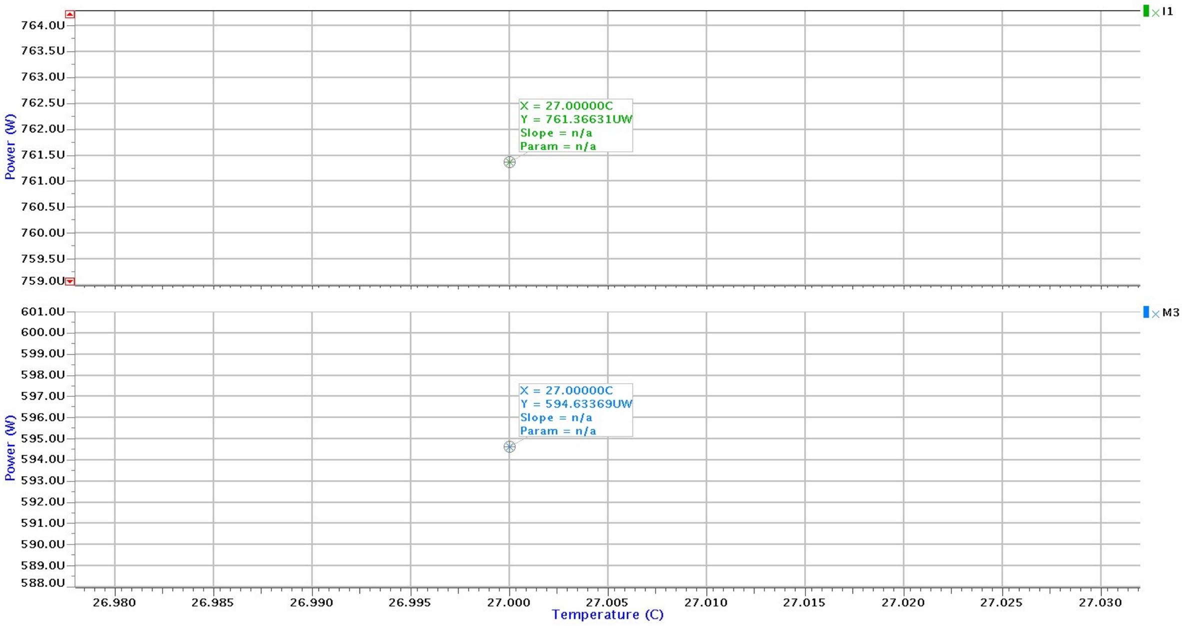


Figure 7: Power dissipation in M3 and I1 of CM bias.

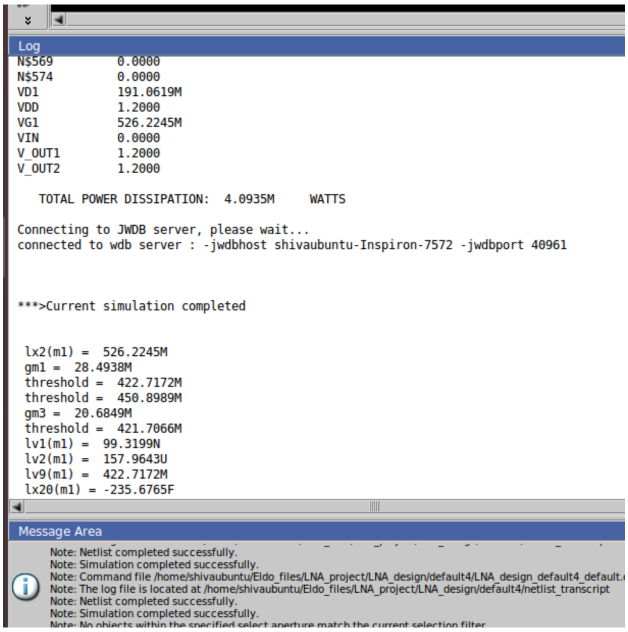


Figure 8: Total DC power dissipation

**Appendix:**

Voltage gain Calculations :-

At the drain tank, we know in a single ended case, the cap load is 2 pF.

$$\therefore \quad f_{opt} = 2\,GHz = \frac{1}{2\pi\sqrt{L_d \times (2pF)}}$$

$$\Rightarrow \boxed{L_d \simeq 3.166\,nH}$$

Corresponding to this the Rpar turns out to be 596.9654 Ω from the drain inductor having a Q of 15

$\Rightarrow Q_{Drain} = 15$ as well which is too high as :-

$$Q_{from\ volt\ gain\ req.} = \frac{f_{opt}}{\Delta f} = \frac{2\times10^9}{200\times10^6} = 10$$

So, we make the gate Q small enough.

We ballpark the $Q_{gate}$ to be around 4

$$\therefore \quad Q_{gate} = \frac{1}{2R_s\,\omega C_{gs}} \approx 4 \quad (R_s = 50\,\Omega,\ \omega = 2\pi \times 2\,GHz)$$

$$(M1). \Rightarrow C_{gs_1} \simeq 198.94\,fF.$$

Obviously upon simulation, these values didn't give the exact gain spec, infact it was quite narrow band, therefore the Cgs was increased to ≃ 235.67 fF for W of 158 μ to decrease $Q_{gate}$, and I added an R tune @ o/p of value small enough ≃ 669.901 Ω to reduce $Q_{drain}$ as well.

This enabled the design to meet the gain flatness as well.

Now that we know $C_{gs_1} \approx 235\,fF$ the $(L_s + L_g)$ value can be calulated

$$(L_s + L_g)(C_{gs_1}) = 1/\omega^2$$

$$L_s + L_g = \frac{1}{C_{gs_1} \times (2\pi f_{opt})^2}$$

Condn 1) $\boxed{L_s + L_g \approx 26.95\,nH.}$

We still need the i/p match cond'n to fix $L_s$. (Note that even these values aren't final, some fine tuning is done after this)

## $S_{11}$ Calculations:-

To get a good i/p match

$$\omega_T L_s = R_s = 50\,\Omega$$

$$\omega_T = \frac{g_{m_1}}{C_{gs_1}} \qquad g_{m_1} \approx 28.49\,mS$$ (measured)

$$C_{gs} \approx 235\,fF$$

$\boxed{L_s}$ turns out to be $\boxed{412.37\,pH}$

$\Rightarrow$ From condn 1 $\quad L_g \approx 26.54\,nH$

Now, the spec. is we need $S_{11} < -10\,dB$ over entire band so, these values were also tuned to do this. ($L_s$, $L_g$, $L_d$). It was seen that the $S_{11}$ dies sharply @ 2GHz, but was very narrowband

So, in order to spread the $S_{11}$ curve over the whole band, $Q_{in}$ was reduced. This meant we need to

$$Q_{in\,gate} = \frac{1}{2R_s\,\omega_0\,C_{gs}}$$

~~reduce~~ increase $\omega_0$, since we already fixed width for $C_{gs}$. So finally we designed the $L_g$, $L_s$ such that i/p series RLC operated @ $\approx 2.34$GHz., The o/p parallel RLC $f_{opt}$ was only slightly changed to 2.03 GHz

So, $$(L_s + L_g) = \frac{1}{C_{gs1} \times (2\pi \times \underbrace{f_{opt}}_{2.34\text{GHz}})^2}$$

$L_s + L_g \approx 19.67$ nH.

We chose an $\boxed{L_g \approx 18.95\text{nH} \;\&\; L_s \approx 719.2\text{pH}}$ as opposed to the $L_s$ found earlier of 412.37pH because, it was seen that decreasing $L_g$ shifted the $S_{11}$ curve more to the specified 200Meg band around 2GHz. and so, $L_s + L_g$ = const, $L_s$ went up. ~~by 31~~ to 719.2pH

@ Drain tank $$f_{opt} = \frac{1}{2\pi\sqrt{L_d\,(C_{diff})}}$$

So $$f_{opt} = \frac{1}{2\pi\sqrt{L_d\,C_{load}}} \quad C_{load} \to 2\text{pF}$$

$\therefore$ $$2.03\text{GHz} = \frac{1}{2\pi\sqrt{L_d \times 2\times10^{-12}\text{F}}}$$

$\boxed{L_d \approx 3.07\text{nH}}$.

Finally, the magnitude of peak gain theoretically found was :-

$$\frac{v_o}{v_{in}} = -2Q_{in}\, g_{m_1} R_d$$

$$\left|\frac{v_o}{v_{in}}\right| = \frac{\cancel{2}\, g_{m_1} \cdot (R_{par} \| R_{tune})}{(\cancel{2}R_s\, \omega\, C_{gs})}$$

$$= \frac{(28.49\,mS)(R_{par}\|R_{tune})}{50\,\Omega\;\omega_{opt}\;235\,fF}$$

$R_{par}$ for $L_d = 3.070\,nH$

$Q_{Ld} = 15$, $R_{Ld} = 578.68\,\Omega$

$R_{tune} = 669.901\,\Omega$

(as $g_{m_1}$, $C_{gs}$, $\omega$ are known)

$$20\log\left|\frac{v_o}{v_{in}}\right| = 35.37\,dB$$

~~close to the~~

This is in single ended wrt vin., In the balun diff. o/p case we get

$$\frac{V_{odiff}(@\,o/p)}{V_{in}(\text{to balun})} = \frac{v_{+o} - v_{-o}}{v_{in}}$$

$$= A_{\text{single ended wrt } v_{in}} \times \sqrt{2}$$

So Net gain (theoretical)

$$= 35.37 + 3.01\,dB$$

$\boxed{\text{Gain}_{net}(\text{theo}) = 38.37\,dB}$ — which is close to whats found as $\boxed{\text{peak gain of } 32.37\,dB}$ in the simulation (differences arise due to inexact i/p match etc.) ($S_{11}$ isn't exactly at dip @ 2GHz, and it's spread, therefore $R_{in}$ maybe close to $50\,\Omega$ but not exact)

## Noise figure calculations :-

NF for singleended LNA (C.S.) has the expression:-

$$NF \text{ or } F = 1 + \left(\frac{\omega_0}{\omega_T}\right)^2 R_s \gamma g_m + \left(\frac{\omega_0}{\omega_T}\right)^2 \frac{R_s \times 4}{R_d}$$

$$\omega_T = \frac{g_m}{C_{gs}} = \frac{28.493 \times 10^{-3} S}{235.67 fF} = 1.20902 \times 10^{11} S/F$$

$\cancel{F}$ $\gamma = 2/3$ (assuming) $g_m = 28.49\ mS$

$R_s = 50\ \Omega$ $\omega_0 = 2\pi \times 2 \times 10^9\ Hz$

$R_d = R_{tune} \| R_{par\_Ld} = 310.48\ \Omega$

We get $F \approx 1.02134778$

$$\boxed{NF = 91.74 \times 10^{-3}\ dB}$$

Using another very approximate relation

$$NF_{min} = 1 + 2.3\left(\frac{\omega}{\omega_T}\right)$$

$\boxed{NF_{min} \approx 1.24\ dB}$ → This being an approximate relation may deviate from simulation results.

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## Bias point calculations & Power :-

→ Current through $M_1$ = 1.46mA (simulation). $L_{eff}$ = 99nm $W_{eff}$ = 158 μ

$g_{m1}$ (simulation) = 28.49mS, $V_{GS1} = 0.525V$, $V_{TH1} = 0.422V$

$$g_{m1} = \mu_n C_{ox} \frac{W}{L} (V_{GS1} - V_{TH1})$$

$$I_1 = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS1} - V_{TH1})^2 = \frac{1}{2} g_{m1} (V_{GS1} - V_{TH1})$$

$= 1.47mA$ Hence it's close

→ Current in CM bias $M_3$: $L_{eff} \approx 99nm$ $W_{eff} = 77\mu m$

$$g_{m3} = \mu_n C_{ox} \frac{W}{L} (V_{GS1} - V_{TH}) \Rightarrow I_3 = \frac{1}{2} g_{m3} (V_{GS1} - V_{TH})$$

$I_{CMbias} = \frac{1}{2} g_{m_3} (V_{GS} - V_{TH})$

$V_{GS_1} = V_{GS_3} = 0.525V$

$g_{m_3} = 20.685 mS$

$V_{TH3} = 0.421V$

simulation

$\Rightarrow$ $\boxed{I_{CMbias} = 1.080 mA \text{ close to } 1130 \mu A}$

→ Power consumed :- Total power (simulation) = 4.0935 mW

Power by current mirror bias = 1.356 mW
(simulation) → from $P_{I_1} + P_{M_3} = (0.595 mW + 0.762 mW)$

This is easily verified by

$(V_{dd}) \times I_{CMbias} = P_{CMbias}$

$= 1.2V \times 1.13 mA = 1.36 mW$

Hence, verified.