Lab 3

Cascode Amplifier

Part 1: Sizing Chart

Required Spec:

$A_v = g_m r_o$	50
g_m/I_D	$10\ S/A$
Supply (V_{DD})	$1.8\ V$
Quiescent (DC) output voltage	$V_{DD}/2 = 0.9\ V$
Bias Current	20 uA

Analytic Calculations:

$$|A_v| \approx g_m ro = \frac{2I_D}{V_{ov}} \times \frac{V_A}{I_D} = \frac{2V_A}{V_{ov}}$$

$$In\ Simulation\ V_{ov} \neq \frac{2I_D}{gm}\ all\ the\ time, \qquad Instead\ use\ V^* = \frac{2I_D}{gm}$$

$$|A_v| = \frac{2V_A}{V^*}$$

$$gm = \frac{2I_D}{Vov} \rightarrow \frac{gm}{I_D} = \frac{2}{Vov}$$

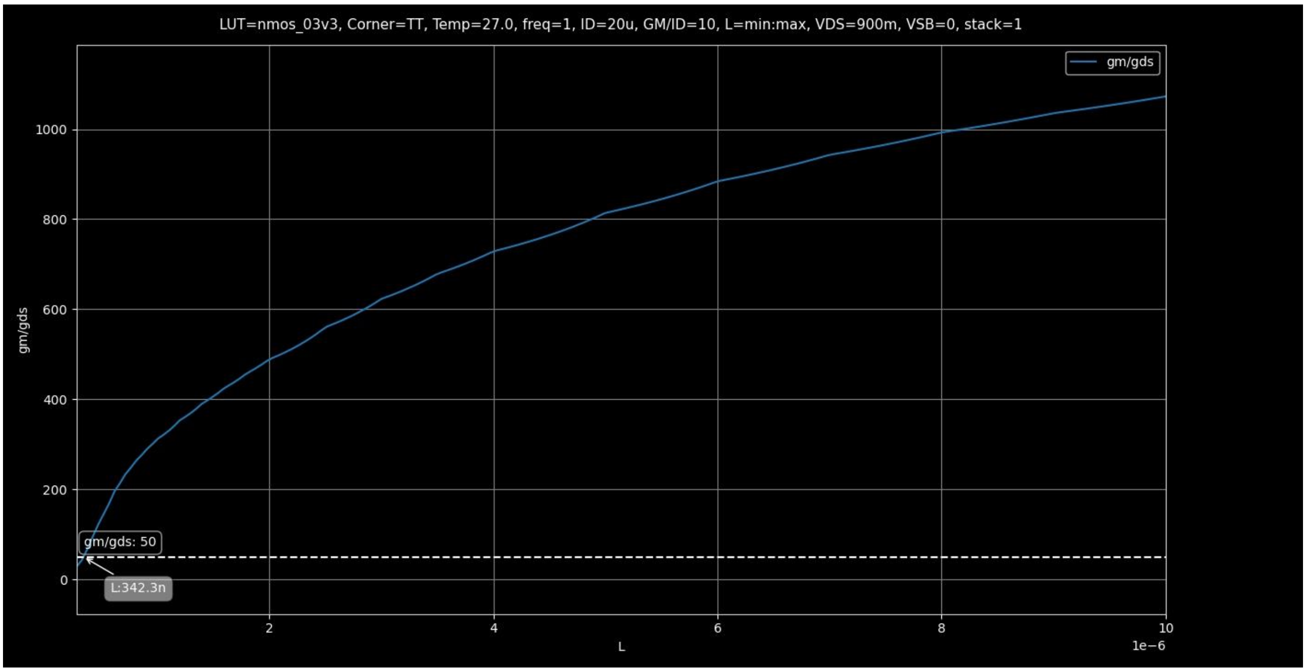

Figure 1 gm/gds vs L

$$L = 342.3nm \rightarrow L \approx 350nm\ to\ account\ for\ gain\ drops\ in\ simulation.$$

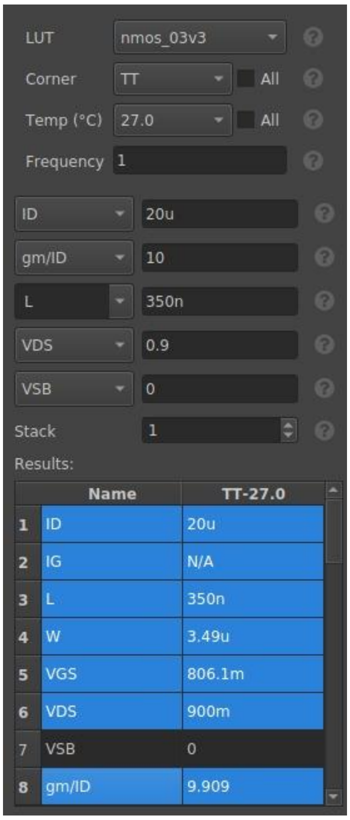

Figure 2 Remaining Parameters @ L = 350nm

6) W using SA: $W = 3.5\mu m$

7)

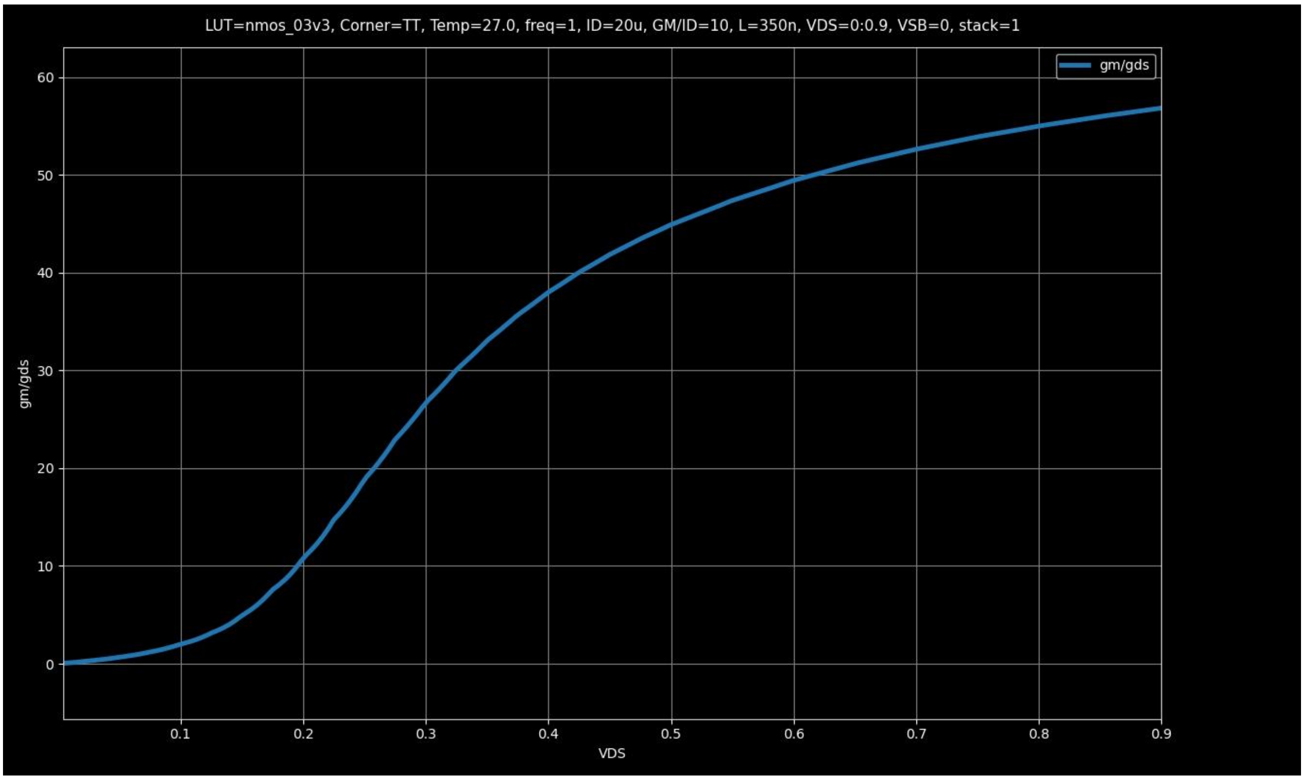

Figure 3 gm/gds vs VDS Graph

8) gm/gds will be slightly lower approximately equal to 41.83

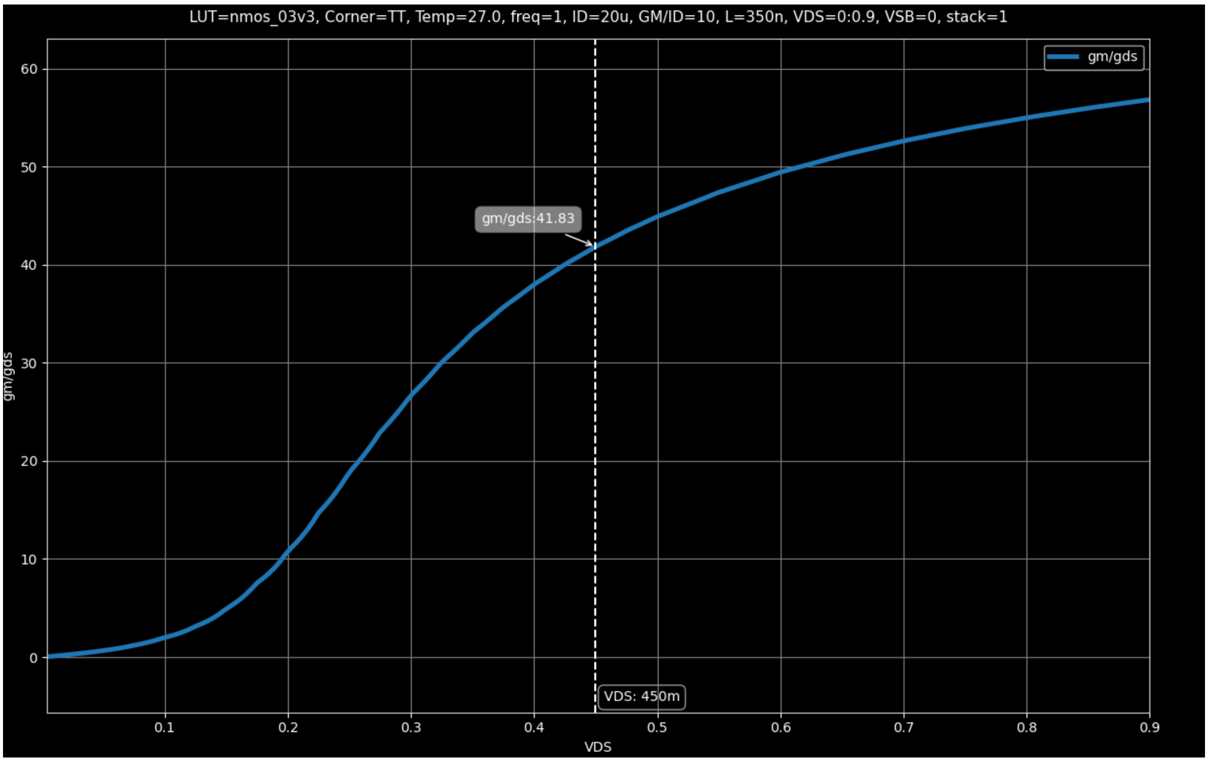

Figure 4 Expected gm/gds

Part 2: Cascode for Gain

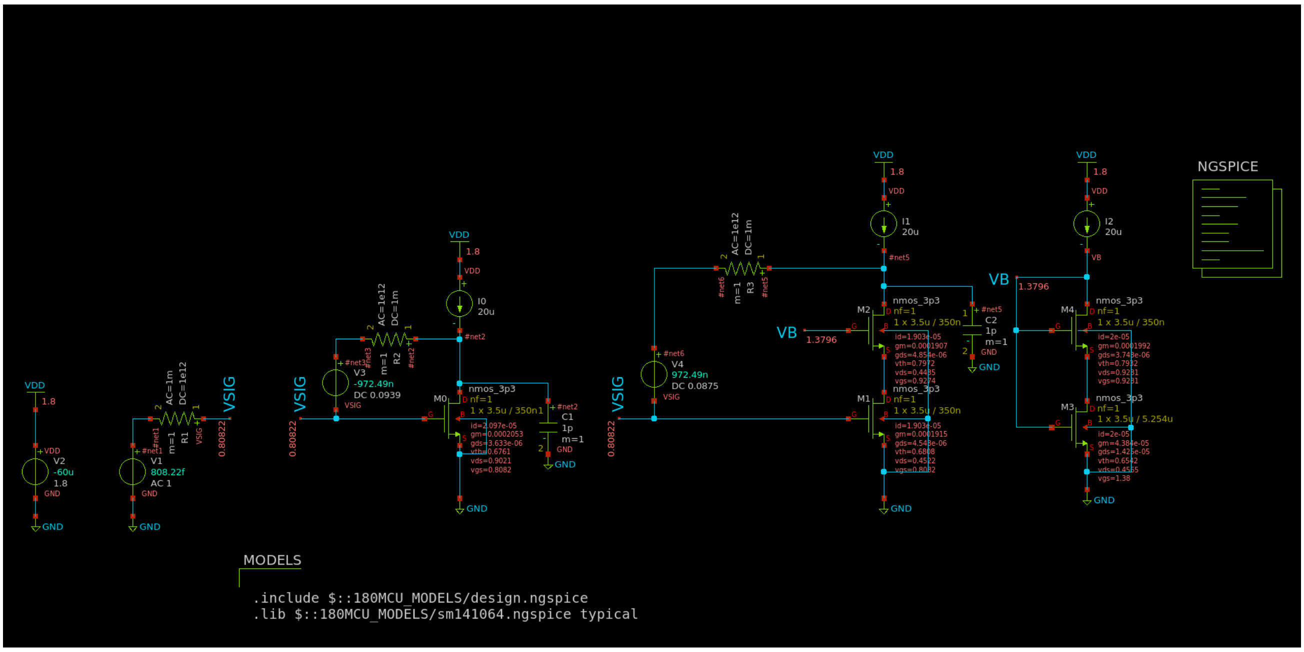

Figure 5 Testbench Schematic

$$V_3 \approx V_4 \approx 0.1mV$$

Finding VG0 and VGS1 for V3 and V4 (ADT):

$$VGS_0 = 806.1mV \quad VGS_1 = 812.5m$$

$$V_{Bias} = VDC - VGS \quad \rightarrow \quad V_3 = 900m - 806.1m = \mathbf{93.9mV}, V_4 = 900m - 812.5m = \mathbf{87.5mV}$$

Calculating VB:

$$V_B = VGS_2 + VDS_1$$

We can get VGS2 using ADT by putting VDS = 0.45 and accounting for body effect so VSB = 0.45 and inputting the dimensions calculated previously.

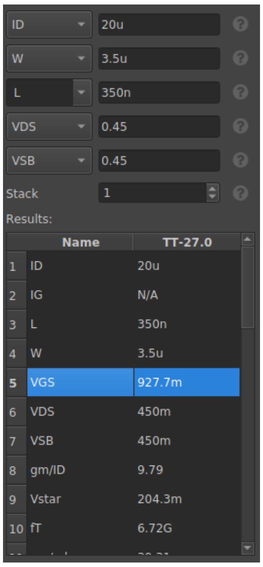

Figure 6 VGS2 using ADT

$$V_B = 927.7m + 450m = 1.377V$$

Getting L of M3:

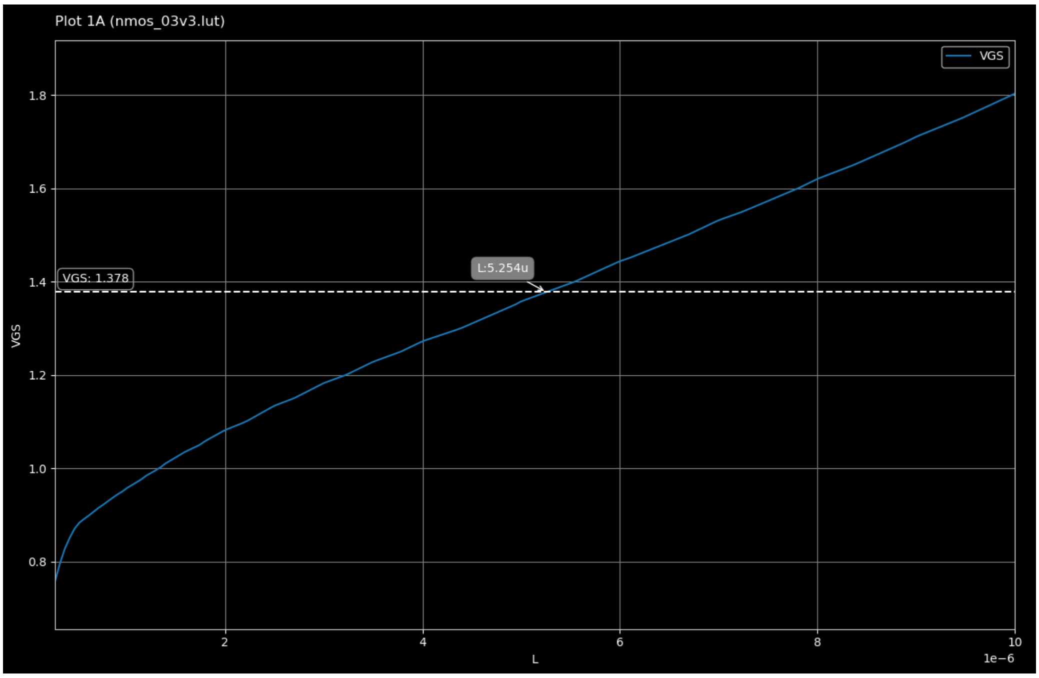

Figure 7 VGS vs L (ADT) for M3

$$L_{required} = 5.254\mu m$$

DC Operating Point:

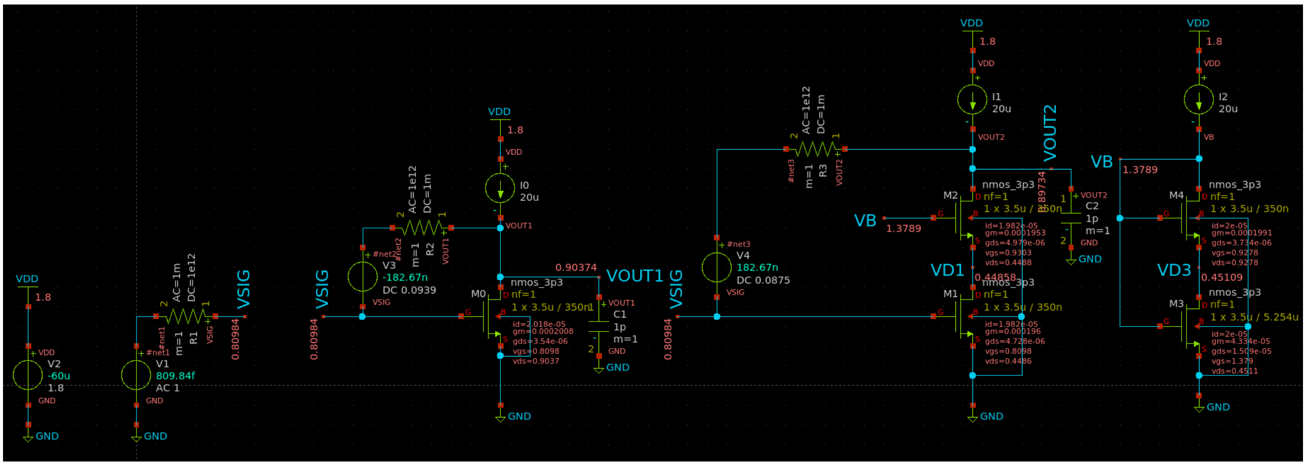

Figure 8 DC Voltages Annotated on Schematic

9) OP parameters for M0 to M4

To get these quickly I exported the results to a CSV and displayed the results here as follows:

	M0	M1	M2	M3	M4
cdb	-3.11E-16	-3.09E-16	-2.39E-16	-9.57E-15	-2.36E-16
cgd	1.65E-17	1.16E-17	1.49E-17	-5.63E-15	2.13E-17
cgs	-2.60E-15	-2.56E-15	-2.62E-15	-5.18E-14	-2.63E-15
csb	-4.66E-16	-4.61E-16	-3.56E-16	-1.25E-14	-3.54E-16
gds	3.72E-06	4.36E-06	4.82E-06	1.33E-05	3.76E-06
gm	2.09E-04	1.88E-04	1.87E-04	4.45E-05	1.99E-04
gmbs	5.99E-05	5.40E-05	4.13E-05	1.73E-05	4.38E-05
id	2.16E-05	1.84E-05	1.84E-05	2.00E-05	2.00E-05
vds	8.96E-01	4.60E-01	4.30E-01	4.63E-01	9.16E-01
vdsat	1.67E-01	1.60E-01	1.64E-01	5.59E-01	1.66E-01
vgs	8.02E-01	8.02E-01	9.19E-01	1.38E+00	9.16E-01
vth	6.67E-01	6.79E-01	7.92E-01	6.55E-01	7.86E-01

- **Check that all transistors operate in saturation.**

All Operate in saturation except for M3 operates in triode, The cascode configuration is meant to increase the length of the equivalent transistor that we can get from the series connection of the transistors, as the voltage of the middle point is too low for M3 to operate in saturation especially when M4 pulls it down to operate in saturation.

- **Do all transistors have the same vth? Why?**

M0, M1 and M3 have similar Vth as they are not affected much by body effect but M2 and M4 being cascode devices have a higher Vth than the others due to body effect.

- **What is the relation (≪, <, =, >, ≫) between gm and gds?**

gm >> (Much Greater Than) gds, except for M3 it's only greater than (>)

- **What is the relation (≪, <, =, >, ≫) between gm and gmb?**

gm > (Greater Than) gmb

- **What is the relation (≪, <, =, >, ≫) between cgs and cgd?**

Cgs >> (Much Greater Than) Cgd except for M3 the ratio is about 9.2 so only almost much greater than it

- **What is the relation (≪, <, =, >, ≫) between csb and cdb?**

Csb > (Greater Than) cdb

AC Analysis:

Outputs:

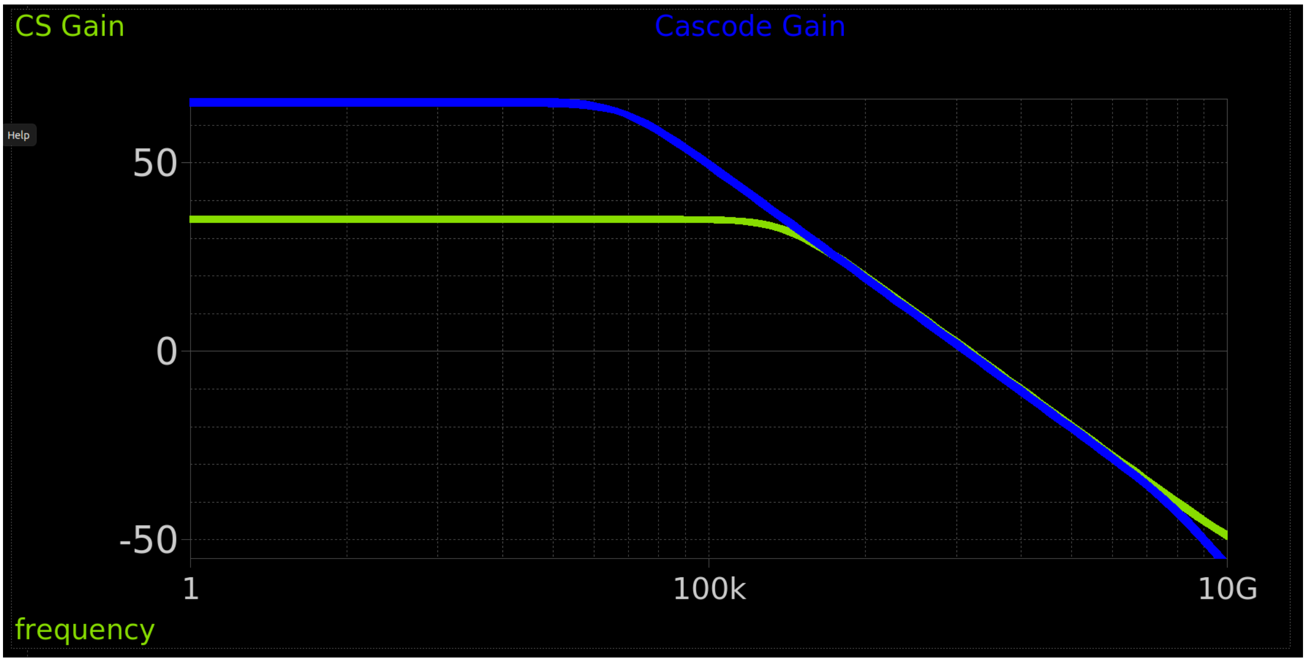

Figure 9 Bode Plots of both CS and Cascode Amplifiers

All Results:

	CS	Cascode
Gain (dB)	35.14	65.56
Gain	57.2	1.9 K
BW	523.3 KHz	16.98 KHz
GBW	29.936 MHz	32.338 MHz
UGF	30.134 MHz	32.371 MHz

Hand Analysis:

CS Amplifier:

$$DC\ Gain = |A_v| = gm * ro = \frac{gm}{gds} = \frac{209\mu}{3.72\mu} \approx \mathbf{56.182}$$

$$Gain\ in\ dB = 20Log(A_v) = 20Log(56.182) \approx \mathbf{35dB}$$

$Bandwidth\ (Neglecting\ transistor\ Capacitances\ and\ current\ source\ resistance):$

$$F_P = \frac{1}{\tau * 2\pi} = \frac{1}{2\pi * ro * C_L} = \frac{gds}{2\pi * C_L} = \frac{3.72\mu}{2\pi * 1p} = \mathbf{592.05\ KHz}$$

$$GBW = Gain * BW = 56.182 * 592.05\ K = \mathbf{33.263MHz}$$

$$Since\ this\ is\ a\ Single\ Pole\ System: \quad UGF = GBW = \mathbf{33.263MHz}$$

Cascode Amplifier:

$$R_{out} \approx ro_2(gm_2 + gmb_2)ro_1 = \frac{gm_2 + gmb_2}{gds_1 * gds_2} = \frac{187\mu + 41.3\mu}{4.36\mu * 4.82\mu} = \mathbf{10.86M\Omega}$$

$$DC\ Gain = |A_v| = Gm * R_{out} = gm_1 * R_{out} = 188\mu * 10.86M \approx \mathbf{2K}$$

$$Gain\ in\ dB = 20Log(A_v) = 20Log(2K) = \mathbf{66.2\ dB}$$

$Bandwidth\ (Neglecting\ transistor\ Capacitances\ and\ current\ source\ resistance):$

$$F_P = \frac{1}{\tau * 2\pi} = \frac{1}{2\pi * R_{out} * C_L} = \frac{1}{2\pi * 1p * 10.86M} = \mathbf{14.65\ KHz}$$

$$GBW = Gain * BW = 7K * 2.78K = \mathbf{29.31\ MHz}$$

$$Since\ this\ is\ a\ Single\ Pole\ System: \quad UGF = GBW = \mathbf{29.31MHz}$$

Comparison of Results:

	CS		Cascode	
	Simulation	Analytic	Simulation	Analytic
Gain (dB)	35.14	35	65.56	66.2
Gain	57.2	56.182	1.9 K	2 K
BW	523.3 KHz	592.05 KHz	16.98 KHz	14.65 KHz
GBW	29.936 MHz	33.263 MHz	32.338 MHz	29.31 MHz
UGF	30.134 MHz	33.263MHz	32.371 MHz	29.31 MHz

Comments:

- Simulation and Analytic Results are nearly identical! Whilst a bit far in the frequency calculations due to neglecting transistor capacitances
- Cascode amplifier has a much greater gain than the CS Amplifier. Due to the higher output resistance
- The Bandwidth of the Cascode Amplifier is much lesser than the CS Amplifier also due to the higher output resistance.
- This results in both amplifiers having nearly identical Gain-Bandwidth-Product as well as Unity Gain Frequency.

Part 3: Cascode for BW:

Calculating VRD:

$$V_{RD} = \frac{1.8}{2} = 0.9 \rightarrow R_D = \frac{0.9}{20\mu} = 45K\Omega$$

OP Point:

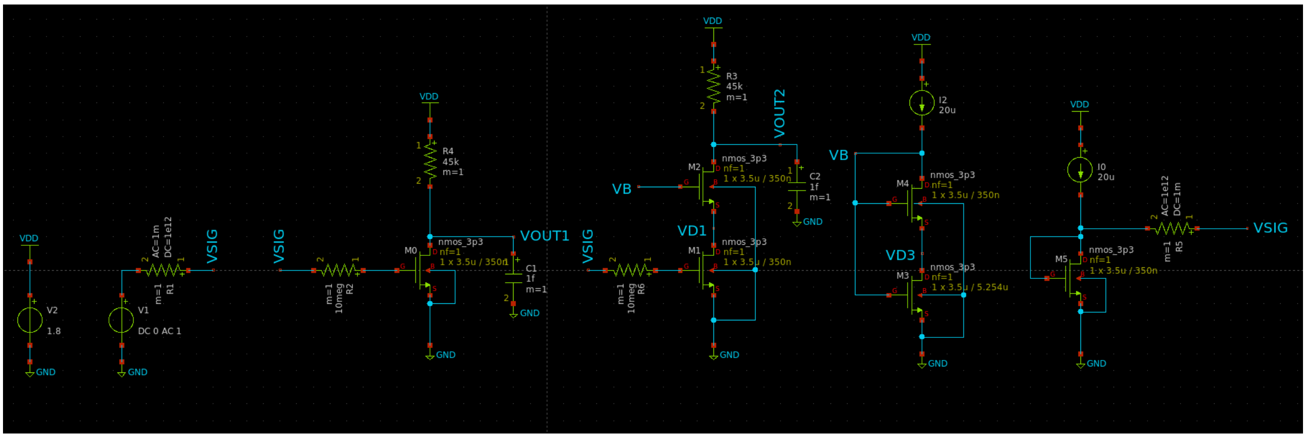

Figure 10 DC OP with Points Annotated

All Results:

	M0	M1	M2	M3	M4	M5
cdb	-3.08E-16	-3.10E-16	-2.39E-16	-9.64E-15	-2.37E-16	-3.08E-16
cgd	1.63E-17	1.15E-17	1.78E-17	-5.91E-15	2.13E-17	1.61E-17
cgs	-2.57E-15	-2.57E-15	-2.62E-15	-5.18E-14	-2.63E-15	-2.57E-15
csb	-4.62E-16	-4.62E-16	-3.56E-16	-1.26E-14	-3.55E-16	-4.62E-16
gds	3.57E-06	4.43E-06	4.41E-06	1.39E-05	3.75E-06	3.63E-06
gm	2.01E-04	1.89E-04	1.89E-04	4.41E-05	1.99E-04	1.99E-04
gmbs	5.77E-05	5.45E-05	4.19E-05	1.72E-05	4.39E-05	5.72E-05
id	2.03E-05	1.86E-05	1.86E-05	2.00E-05	2.00E-05	2.00E-05
vds	8.87E-01	4.58E-01	5.04E-01	4.59E-01	9.20E-01	8.07E-01
vdsat	1.63E-01	1.61E-01	1.64E-01	5.60E-01	1.66E-01	1.63E-01
vgs	8.07E-01	8.07E-01	9.21E-01	1.38E+00	9.20E-01	8.07E-01
vth	6.78E-01	6.82E-01	7.94E-01	6.54E-01	7.90E-01	6.79E-01

- **Check that all transistors operate in saturation.**

All Operate in saturation except for M3 operates in triode, The cascode configuration is meant to increase the length of the equivalent transistor that we can get from the series connection of the transistors, as the voltage of the middle point is too low for M3 to operate in saturation especially when M4 pulls it down to operate in saturation.

AC Analysis:

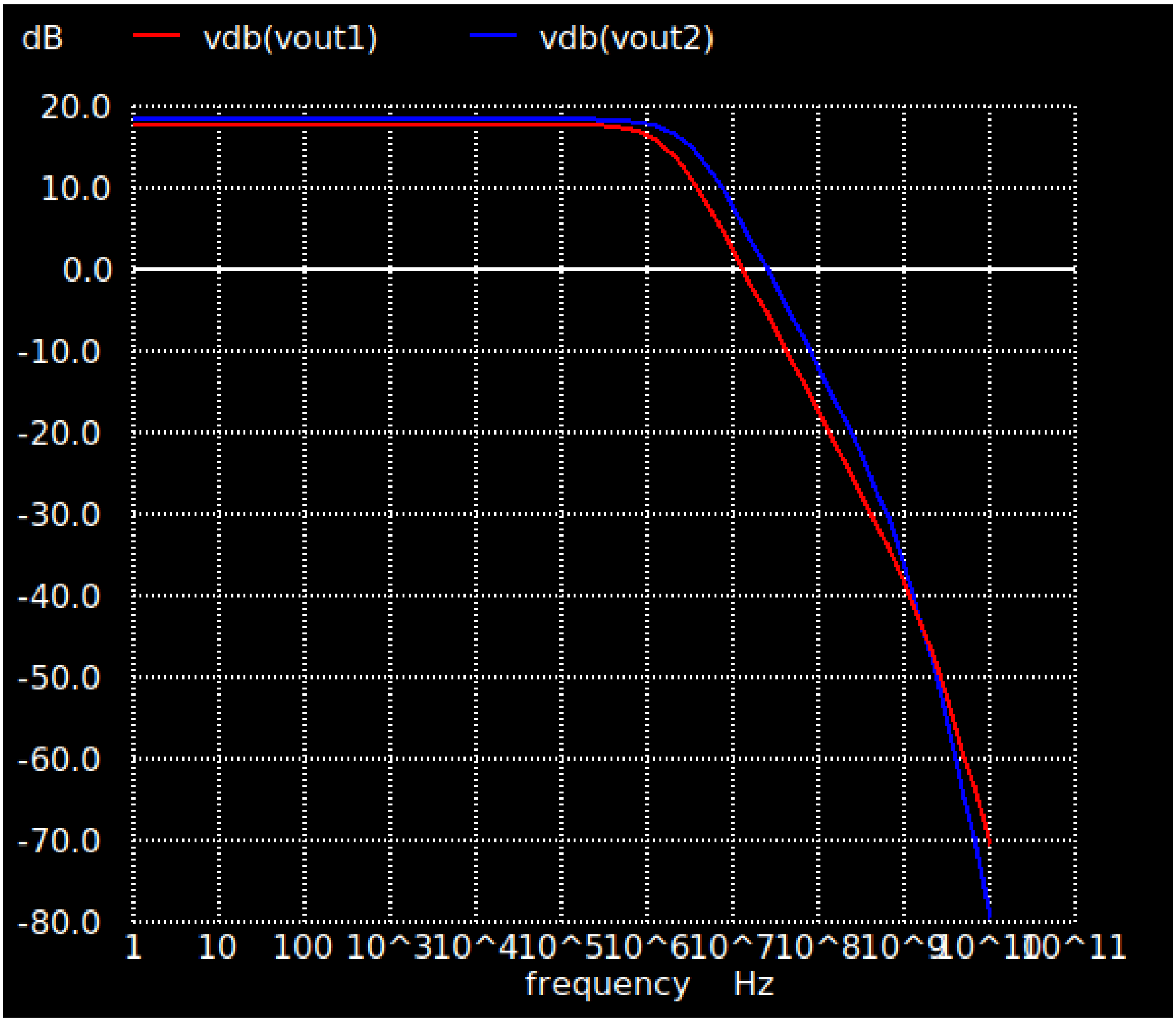

Figure 11 Bode Blot Blue: Cascode, Red: CS

```
peak1                    =   7.806966e+00
f3db1                    =   1.695066e+06
ugf1                     =   1.318210e+07
gbw1 = 1.323332e+07
peak2                    =   8.332359e+00
f3db2                    =   3.008278e+06
ugf2                     =   2.486529e+07
gbw2 = 2.506605e+07
```

Figure 12 Simulation Values of DC Gain, BW, UGF, GBW (1 is CS and 2 is Cascode)

Hand Analysis:

CS Amplifier:

$$DC\ Gain = |A_v| = gm * ro//R_D = 201\mu * (280K//45K) \approx \mathbf{7.792}$$

$$Gain\ in\ dB = 20Log(A_v) = 20Log(7.792) \approx \mathbf{17.83dB}$$

$Bandwidth\ (Input\ Node\ is\ Dominant):$

$$F_P = \frac{1}{\tau * 2\pi} = \frac{1}{2\pi * R_{sig} * (C_{gs} + (A_v + 1) * C_{gd})}$$

$$= \frac{1}{2\pi * 10M * (3.09f + (8.792) * 592.7a)} = \mathbf{1.917\ MHz}$$

$$GBW = Gain * BW = 7.792 * 1.917\ M = \mathbf{14.939MHz}$$

$$Since\ this\ is\ a\ Single\ Pole\ System: \quad UGF = GBW = \mathbf{14.939MHz}$$

Cascode Amplifier:

$$R_{out} \approx R_D = \mathbf{45K\Omega}$$

$$DC\ Gain = |A_v| = Gm * R_{out} = gm_1 * R_{out} = 189\mu * 45K \approx \mathbf{8.5}$$

$$Gain\ in\ dB = 20Log(A_v) = 20Log(8.5) = \mathbf{18.588\ dB}$$

$Bandwidth\ (Input\ Node\ is\ Dominant):$

$$R_{LFS} = \frac{1}{gm}\left(1 + \frac{R_D}{ro_2}\right) = 6.34K\Omega\,, \qquad F_P = \frac{1}{\tau * 2\pi} = \frac{1}{2\pi * R_{sig} * (C_{gs} + (gm_1 * R_{LFS} + 1) * C_{gd})}$$

$$= \frac{1}{2\pi * 10M * (3.5f + (2.2) * 745.4a)} = \mathbf{3.0965\ MHz}$$

$$GBW = Gain * BW = 7.792 * 1.917\ M = \mathbf{26.32MHz}$$

$$Since\ this\ is\ a\ Single\ Pole\ System: \quad UGF = GBW = \mathbf{26.32\ MHz}$$

Comparison of the Results:

	CS		Cascode	
	Simulation	Analytic	Simulation	Analytic
Gain (dB)	17.84	17.83	18.413	18.588
Gain	7.8	7.792	8.33	8.5
BW	1.695 MHz	1.917 MHz	3 MHz	3.0965 MHz
GBW	13.233 MHz	14.939 MHz	25 MHz	26.32 MHz
UGF	13.182 MHz	14.939 MHz	24.86 MHz	26.32 MHz

Comments:

- The cascode for bandwidth has slightly higher gain than CS
- It has better Bandwidth than CS as well as higher GBW as well as higher UGF
- The higher bandwidth is due to the severe reduction of the miller effect in this configuration
- Overall better performance than the CS Amplifier