Lab 3

Cascode Amplifier

Part 1: Sizing Chart

Required Spec:

L	0.5um
V*	160mV
Supply	3v
Current Consumption	10uA

Analytic Calculations:

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

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

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

All we need to calculate now is W, which we will do using sizing charts.

Testbench Schematic:

Using **W/L = 10u/0.5u** and **VDS = 1.5 V** NMOS only since we aren't using PMOS in this Lab

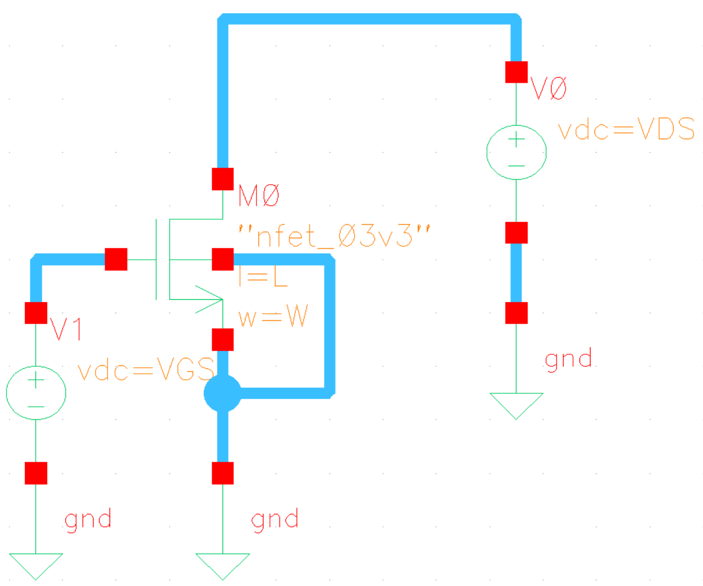

Figure 1 Sizing Testbench Schematic

Sweeping VGS from 0:10mV:(Vth + 0.4):

I ran a simple DC Op once to determine the value of VTH

$$V_{th} = 712.3m$$

$$Sweep\ Range\ \rightarrow \mathbf{0{:}\,10}\boldsymbol{mV}\mathbf{{:}\,1.1123}\boldsymbol{V}$$

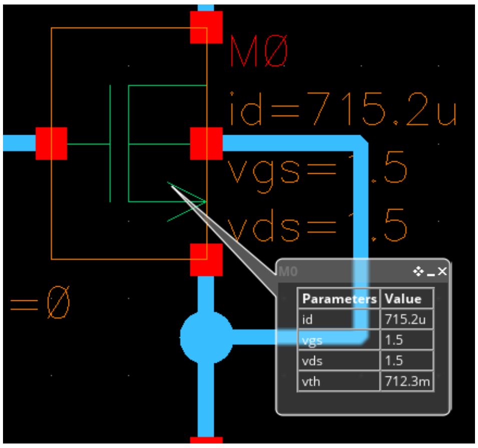

Figure 2 Value of Vth from simulation

V* and Vov Overlaid vs VGS:

Vov	expr	(v("M0:vgs" ?result "dc") - v("M0:vth" ?result "dc"))
V*	expr	((2 * getData("M0:id" ?result "dc")) / getData("M0:gm" ?result "dc"))

*Figure 3 Output Setup and Expressions for Vov and V**

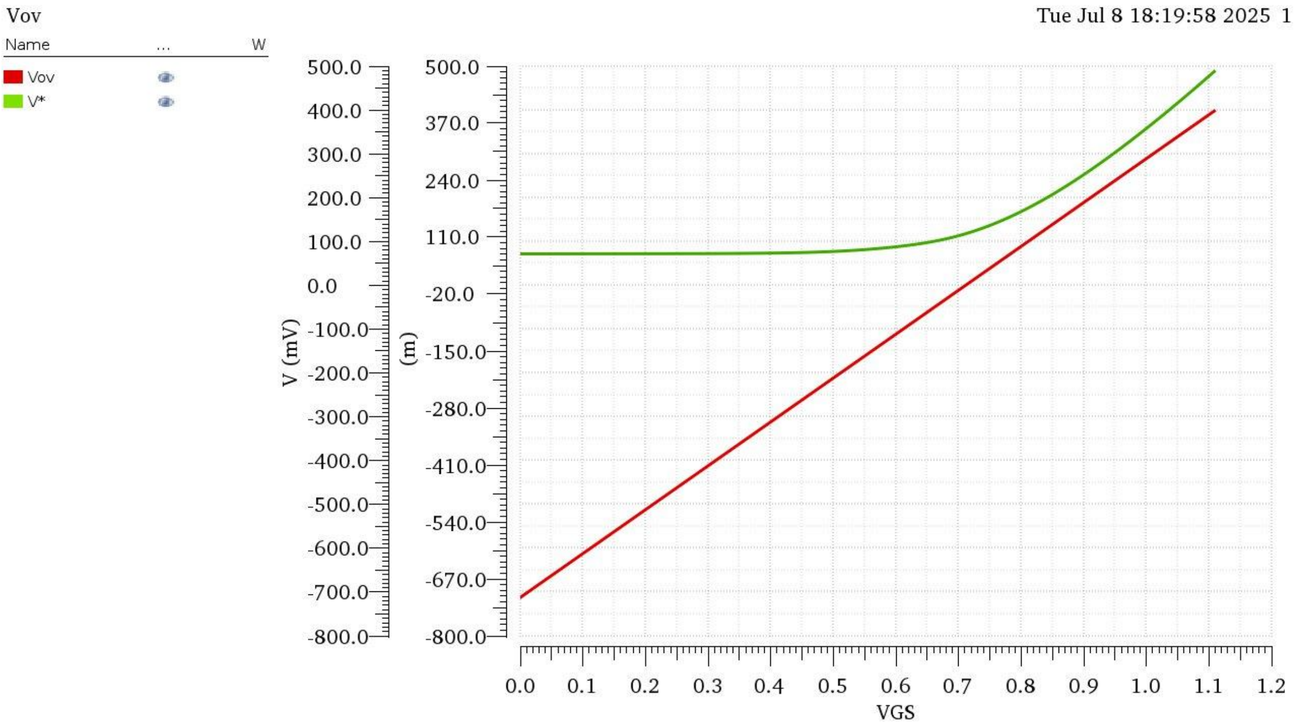

Figure 4 Vov and V vs VGS NMOS*

Comment: Vov and V* are relatively close in value to each other at the region of moderate inversion meaning the square law is relatively valid there . But for Deep Strong inversion (Large Vov) or weak inversion, the behavior is quite far from the square law.

Locating V^*_Q and V_{GSQ}, V_{ovq}:

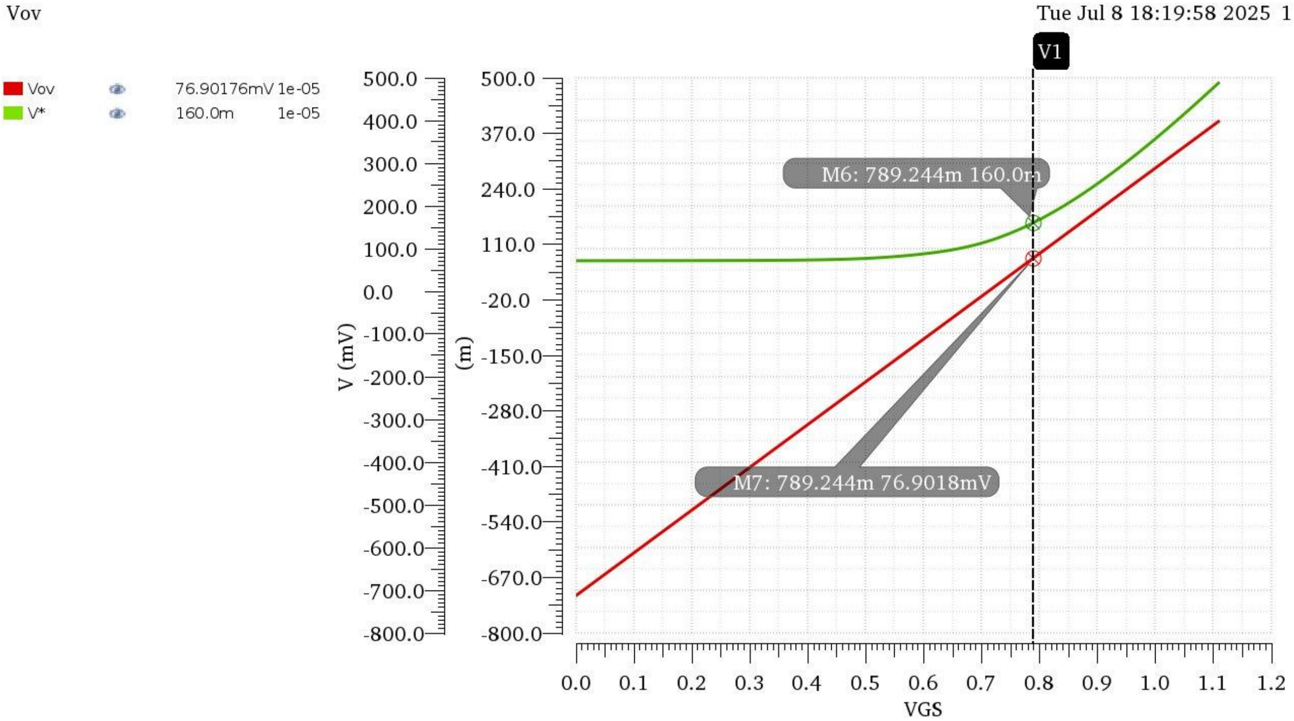

*Figure 5 V*q, Vovq and Vgsq NMOS*

$$@V_Q^* = 160mV, \quad V_{ovQ} = 76.902mV, \qquad V_{GSQ} = 789.244mV$$

Plotting ID, gm, gds vs V_{GS}:

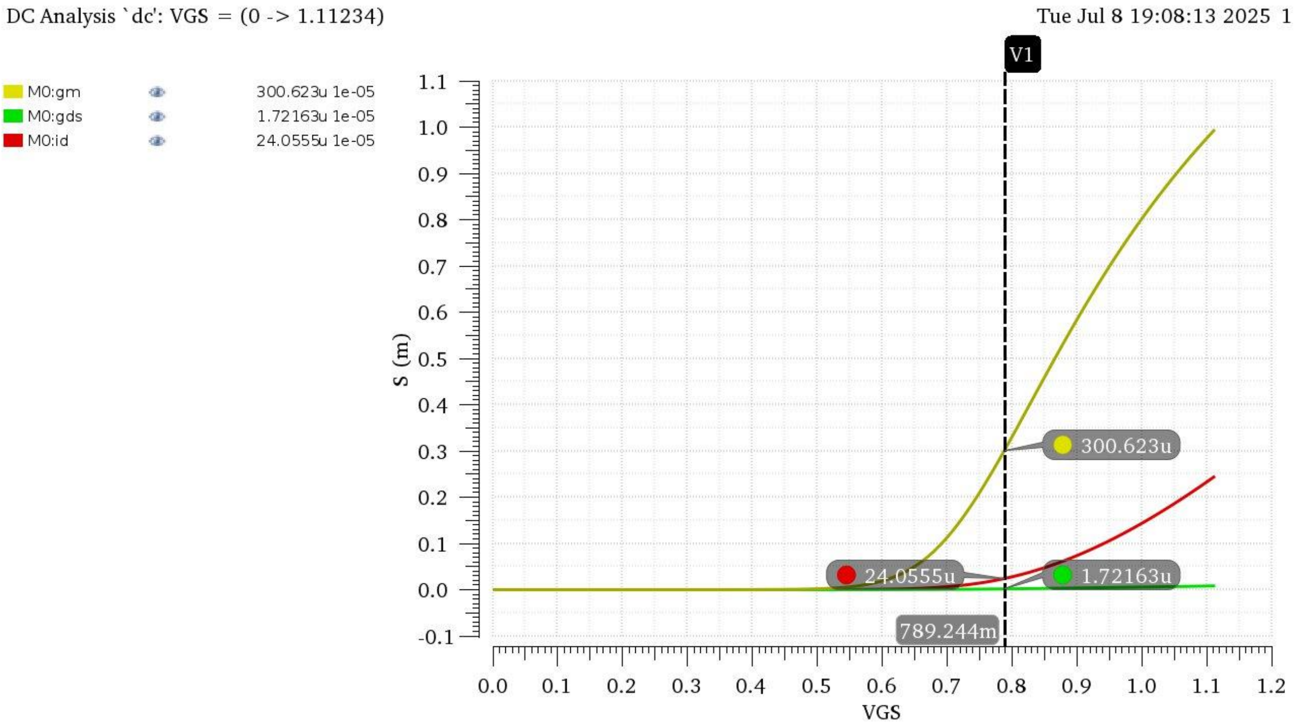

Figure 6 ID, gm, gds vs VGS and their corresponding values at Vgsq

IDx	24.0555 uA
gmx	300.523 uS
gdsx	1.72163 uS

Getting the Value of W:

These Values were Calculated at W = 10um, to get the actual value of W for the design we can simply do cross multiplication since Id is directly proportional to W regardless square law is valid or no.

W	ID
$\mathbf{10\mu m}$	$I_{DX}\,@V_{Q*}$ (from the chart)
?	$I_{DQ} = 10\mu A$ (from the specs)

$$W = W * \frac{I_{DQ}}{I_{DX}} = \frac{10\mu * 10\mu}{24.0555\mu} = \mathbf{4.157\mu m}$$

Calculating the remaining Design parameters:

Using cross-multiplication we can get the values of gmQ and gdsQ as follows…

W	gm	gds
$\mathbf{10\mu m}$	gmX = 300.523 uS	gdsX = 1.72163 uS
$\mathbf{4.157\mu m}$	gmQ	gdsQ

$$gm_Q = \frac{4.157\mu * 300.523\mu}{10\mu} \approx \mathbf{124.93\ uS} \quad , \quad gds_Q = \frac{4.157\mu * 1.72163\mu}{10\mu} = \mathbf{0.7157\mu S}$$

$$ro = \frac{1}{gds} = \frac{1}{0.7157\mu s} = 1.397M\Omega$$

Final Parameter List:

Supply	3 V
V*	160 mV
ID	10 uA
W	4.157 um
L	0.5 um
gm	124.93 mS
gds	0.7157 uS
ro	1.397 MΩ
Vgs	789.244 mV

Part 2: Cascode for Gain

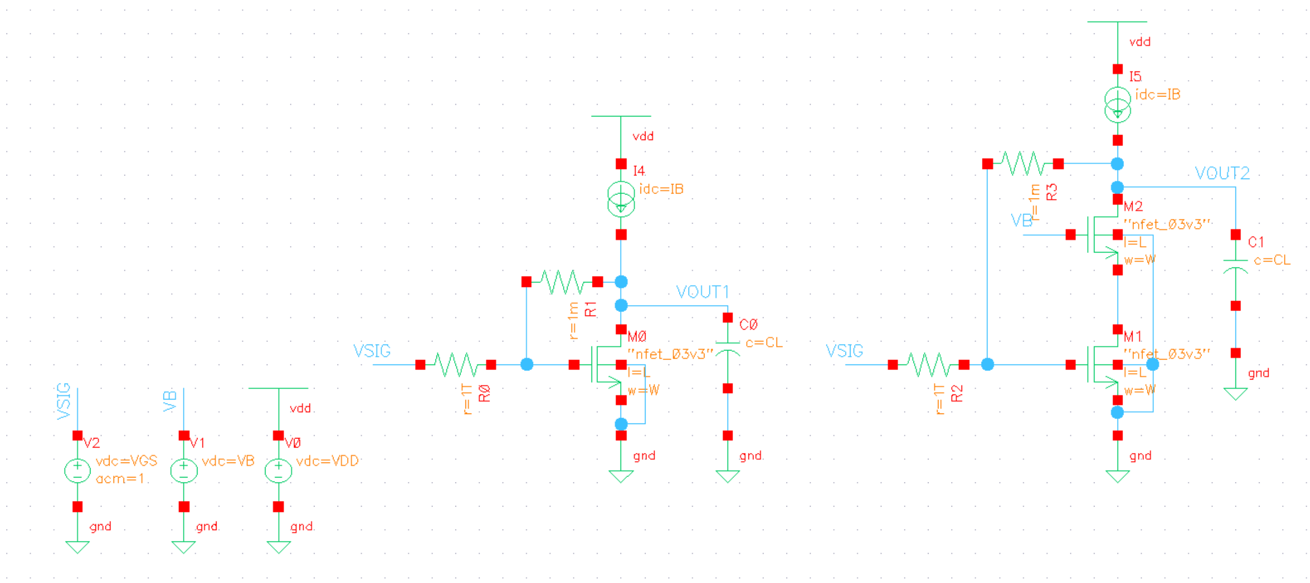

Figure 7 CS Amplifier and Cascode Amplifier

Finding VB:

Vds of should be $V_{DS} \approx V^* + 100mV \approx \mathbf{260mV}$

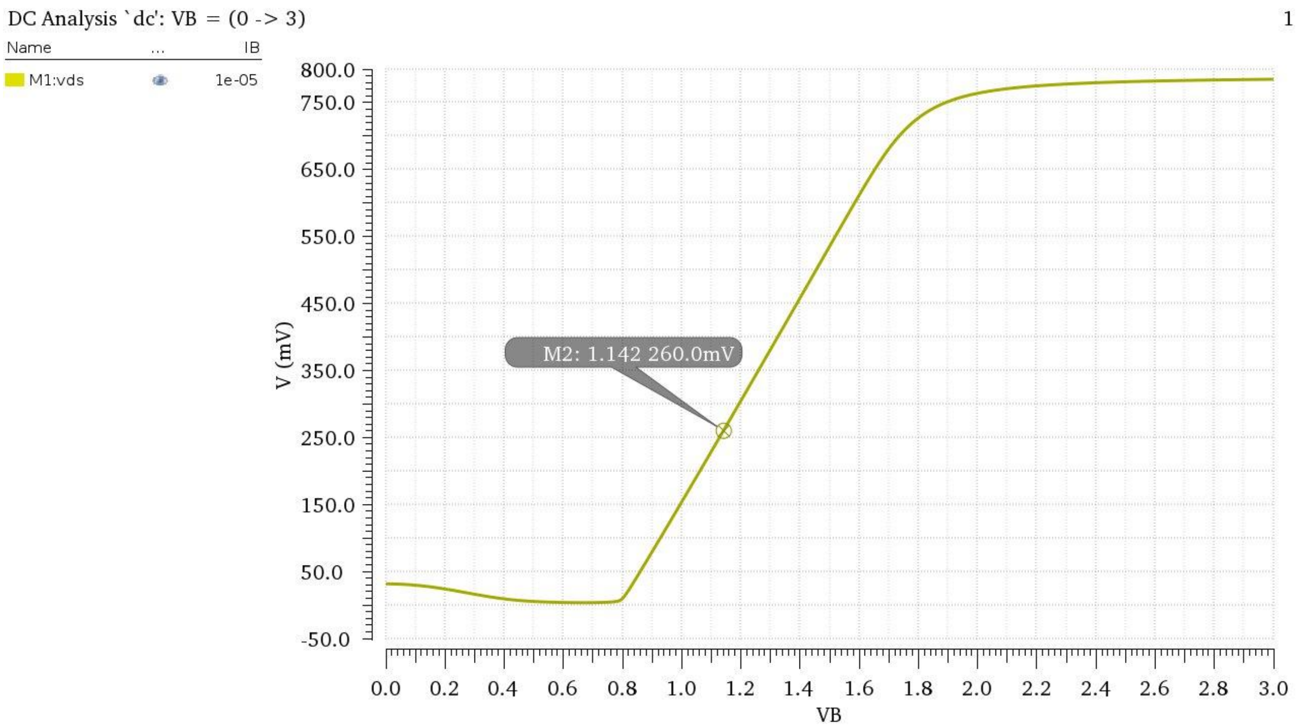

Figure 8 VDS of M1 vs VB

Ideal value of VB = **1.142V**

DC Operating Point:

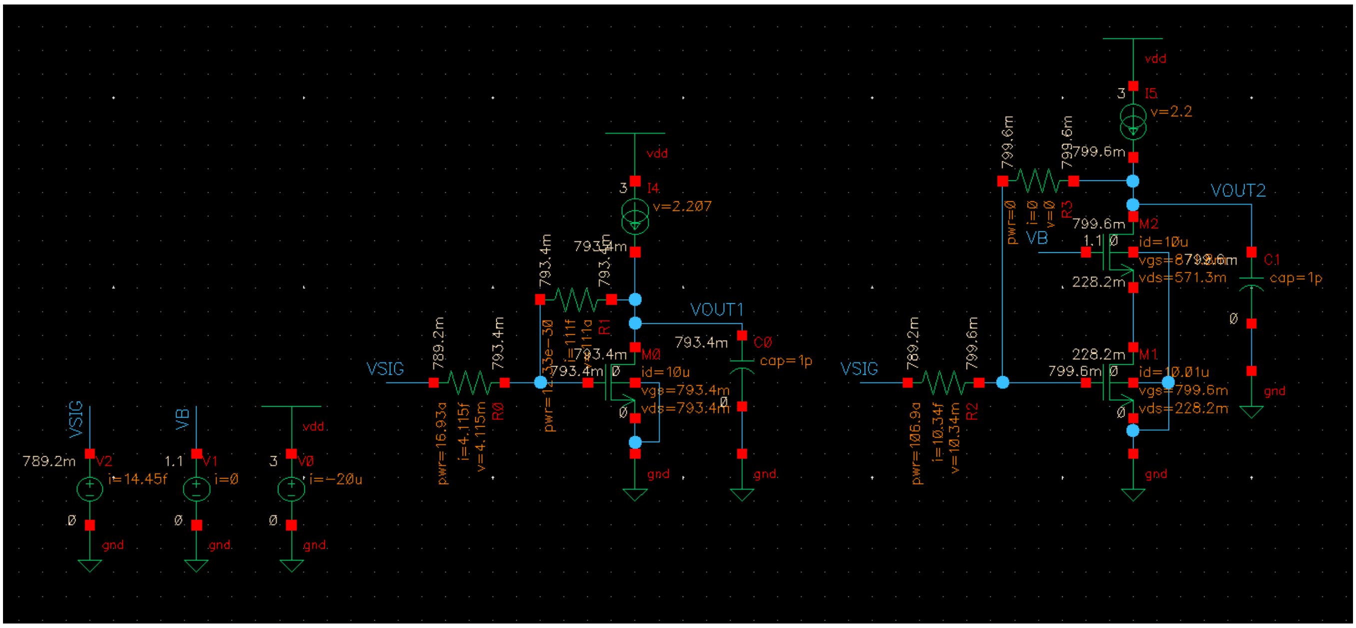

Figure 9 DC Voltages Annotated on Schematic

The following table holds the required DC Operating Point parameters for each transistor where: M0 is the CS Amplifier, M1 is Cascode Bottom Transistor, M2 Cascode Top Transistor.

	M0	M1	M2
ID	10.0 uA	10.0 uA	10.01 uA
VGS	793.4 mV	798.8 mV	881.6 mV
VDS	793.4 mV	258.4 mV	540.3 mV
VTH	710.1 mV	710.8 mV	795.4 mV
VDSAT	135 mV	138.1 mV	138.6 mV
gm	124.8 uS	122.3 uS	124.2 uS
gds	886.7 nS	2.61 uS	1.09 uS
gmb	44.68 uS	43.81 uS	38.68 uS
Cdb	544.6 aF	565.3 aF	477.9 aF
Cgd	776.7 aF	847.1 aF	823.9 aF
Cgs	4.33 fF	4.42 fF	4.4 fF
Csb	815.8 aF	834.1 aF	714.8 aF
Region	2	2	2

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

They all operate in saturation.

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

M0 and M1 have the same VTH as they have the same VSB, but M2 has a higher VTH due to the higher voltage seen at its source.

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

gm >> (Much Greater Than) gds

- **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

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

Csb > (Greater Than) cdb

AC Analysis:

CS Bode Plot	expr	dB20(VF("/VOUT1"))
CS Gain dB	expr	ymax(dB20(VF("/VOUT1")))
CS Gain	expr	ymax(mag(VF("/VOUT1")))
CS BW	expr	bandwidth(VF("/VOUT1") 3 "low")
CS GBW	expr	gainBwProd(VF("/VOUT1"))
Cascode Bode Plot	expr	dB20(VF("/VOUT2"))
Cascode Gain dB	expr	ymax(dB20(VF("/VOUT2")))
Cascode Gain	expr	ymax(mag(VF("/VOUT2")))
Cascode BW	expr	bandwidth(VF("/VOUT2") 3 "low")
Cascode GBW	expr	gainBwProd(VF("/VOUT2"))

Figure 10 AC Output Setup

Outputs:

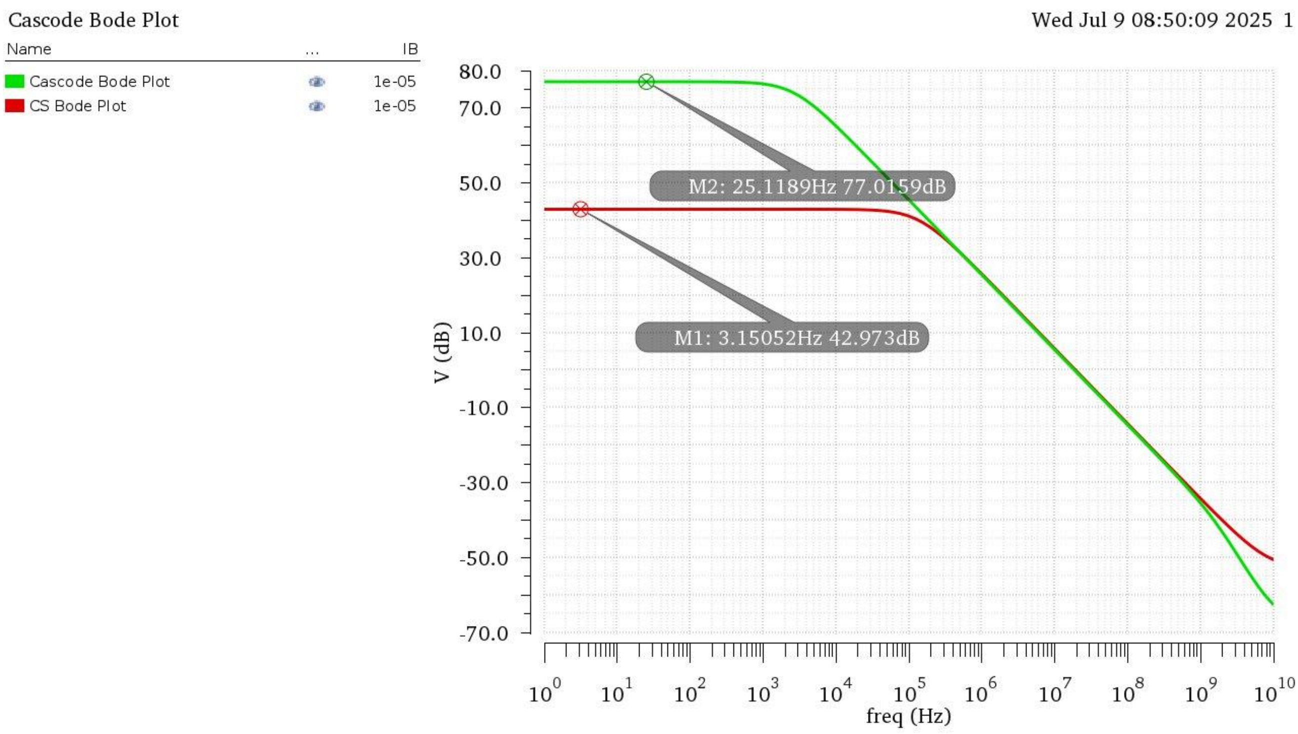

Figure 11 Bode Plots of both CS and Cascode Amplifiers

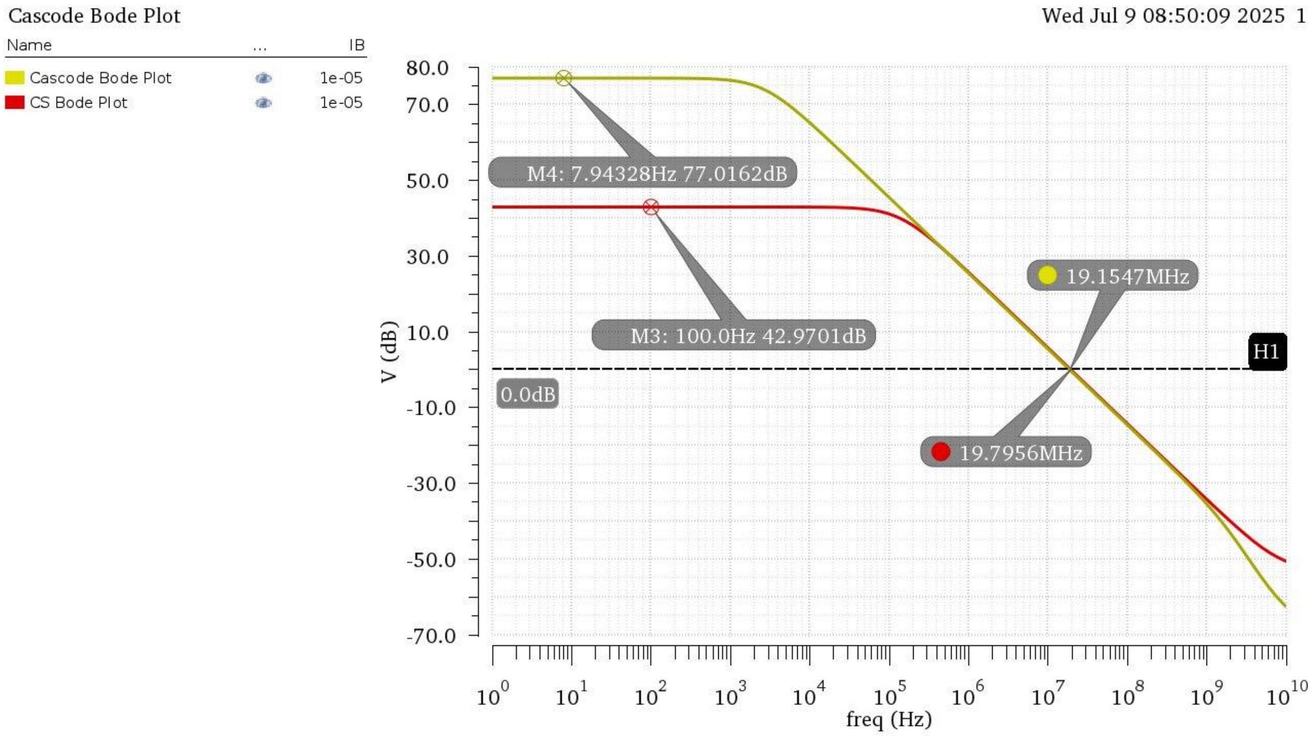

Figure 12 Gain and UGF Highlighted on Bode Plot

All Results:

	CS	Cascode
Gain (dB)	42.97	77.02
Gain	140.8	7.09 K
BW	140.6 KHz	2.69 KHz
GBW	19.84 MHz	19.14 MHz
UGF	19.7956 MHz	19.1547 MHz

Hand Analysis:

CS Amplifier:

$$DC\ Gain = |A_v| = gm * ro = \frac{gm}{gds} = \frac{124.8\mu}{886.7n} \approx \mathbf{140.75}$$

$$Gain\ in\ dB = 20Log(A_v) = 20Log(140.75) = \mathbf{42.97dB}$$

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

$$F_P = \frac{1}{\tau * 2\pi} = \frac{1}{2\pi * ro * C_L} = \frac{gds}{2\pi * C_L} = \frac{886.7n}{2\pi * 1p} = \mathbf{141.122\ KHz}$$

$$GBW = Gain * BW = 140.75 * 141.122K = \mathbf{19.863MHz}$$

$$Since\ this\ is\ a\ Single\ Pole\ System: \quad UGF = GBW = \mathbf{19.863MHz}$$

Cascode Amplifier:

$$R_{out} \approx ro_2(gm_2 + gmb_2)ro_1 = \frac{gm_2 + gmb_2}{gds_1 * gds_2} = \frac{124.2\mu + 38.68\mu}{2.61\mu * 1.09\mu} = \mathbf{57.253M\Omega}$$

$$DC\ Gain = |A_v| = Gm * R_{out} = gm_1 * R_{out} = 122.3\mu * 57.253M \approx \mathbf{7K}$$

$$Gain\ in\ dB = 20Log(A_v) = 20Log(7K) = \mathbf{76.9\ dB}$$

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

$$F_P = \frac{1}{\tau * 2\pi} = \frac{1}{2\pi * R_{out} * C_L} = \frac{1}{2\pi * 1p * 57.253M} = \mathbf{2.78\ KHz}$$

$$GBW = Gain * BW = 7K * 2.78K = \mathbf{19.46\ MHz}$$

$$Since\ this\ is\ a\ Single\ Pole\ System: \quad UGF = GBW = \mathbf{19.46MHz}$$

Comparison of Results:

	CS		Cascode	
	Simulation	Analytic	Simulation	Analytic
Gain (dB)	42.97	42.97	77.02	76.9
Gain	140.8	140.75	7.09 K	7 K
BW	140.6 KHz	141.122 KHz	2.69 KHz	2.78 KHz
GBW	19.84 MHz	19.863 MHz	19.14 MHz	19.46 MHz
UGF	19.7956 MHz	19.863 MHz	19.1547 MHz	19.46 MHz

Comments:

- Simulation and Analytic Results are nearly identical!
- 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.