5 July 2023

Pspice Project

Course Name: Analog circuits
Course Number: 0512.3513

Students ID:

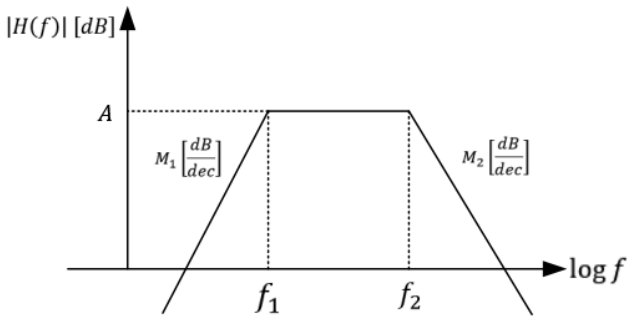
ID1	ID2
208536474	203596192

Goal of the project:
designing amplifier with specs based on the sum of I.Ds

	A	B	C	D	E	F	G	H	I
ID.1	2	0	8	5	3	6	4	7	4
ID.2	2	0	3	5	9	6	1	9	2
ID.1+ID.2	4	1	2	1	3	2	6	6	6

The specifications to consider:

specs	formula	value	units
A	35+2*D	37	[dB]
f1	(G+H)	12	[kHz]
f2	(G+H)*100	1200	[kHz]
M1	C is even	40	[dB/dec]
M2	C is even	20	[dB/dec]
Rout	F is even:5+F	7	[kOhm]



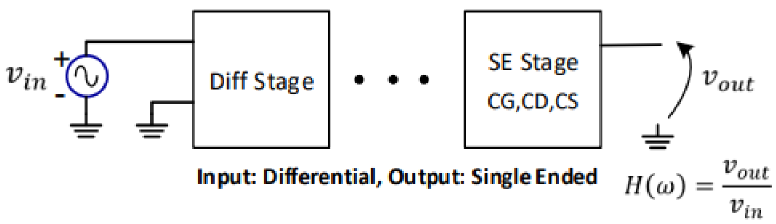
In this document, we comprehensively address the analytical resolution of the amplifier's specifications, encompassing each stage, along with its bias point determination.

Type of the amplifier:

according to the sum of the IDs A is even and D is odd.

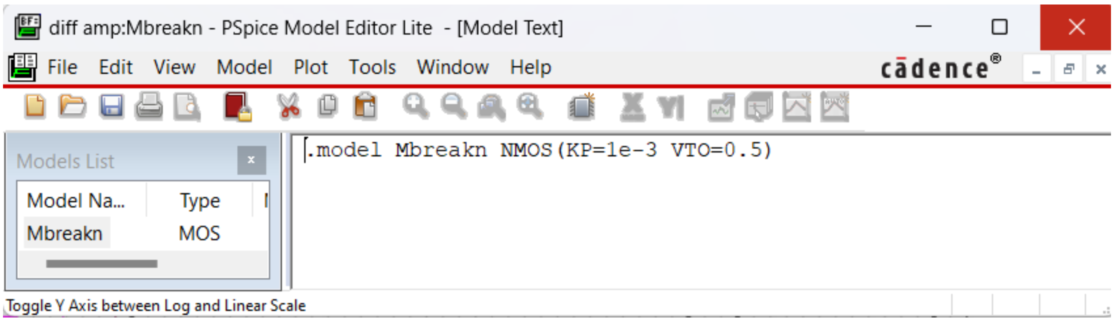
Consequently, out of all the options provided, the design of the amplifier is based on option 3.

input :diff stage
output : S.E stage



Components:

1. Using only MbreakN transistors with $\boldsymbol{K_P} = \frac{\boldsymbol{1mA}}{\boldsymbol{V^2}}$, $|\boldsymbol{V_{TH}}| = \mathbf{0.5}\boldsymbol{V}$, $\boldsymbol{\lambda} = \mathbf{0}$.



2. V_{DD} as DC source (which equal to 5[V]).

Design limitations:

1. The sum of used resistances should not go over 5MΩ:

3k+2k+23k+34k+34k+3k+2k+2.6k+100k+50k+28.4+8.5k=290.5kΩ=0.2905MΩ

2. The sum of used capacitances should not go over 1mF

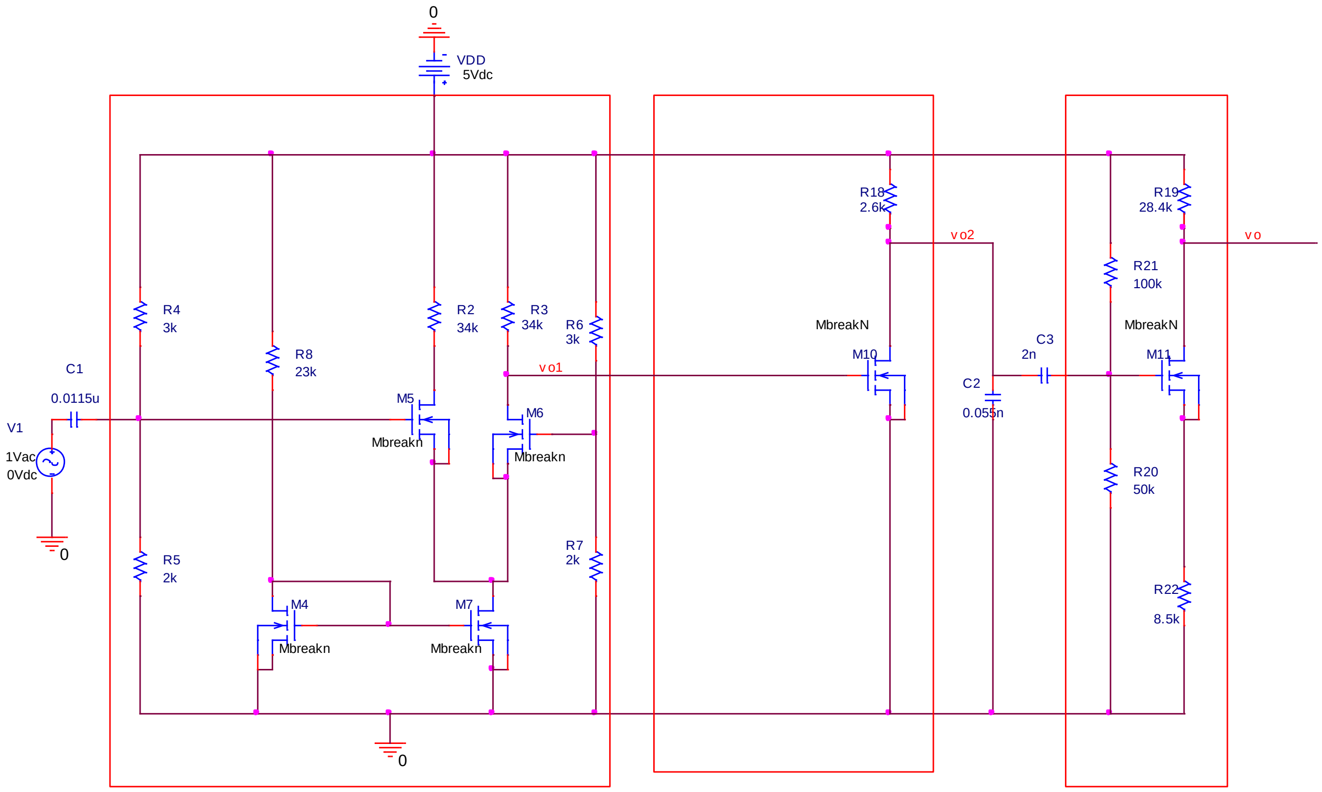
0.0115µ+2n+0.055n=13.5nF

3. Supply voltage are 5V.

4. The tolerance of all required specs is 5% (5% from linear gain and not dB gain)

5. using as many amplification stages as wanted(in this design we use 2 additional stages except the input and output stage).

Full Amplifier scheme design

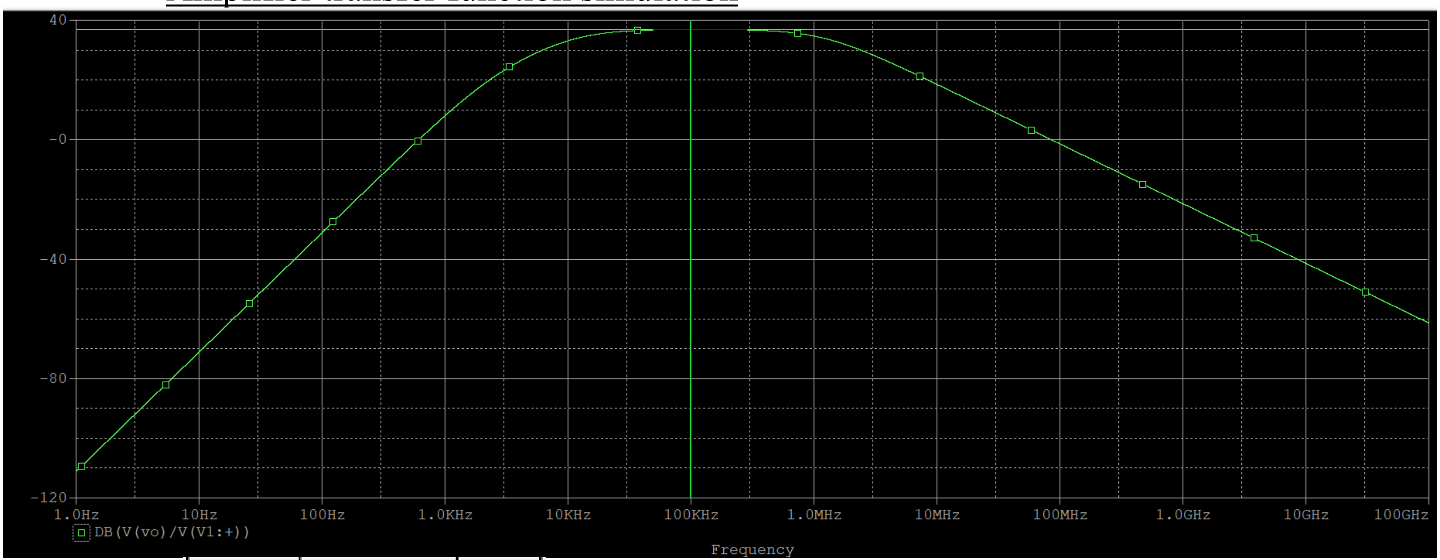


diff amp C.S1 C.S2

Design's background

The scheme above including diff amp as input stage as required in project with current mirror.
The output off the diff amp is connected to next stage which is common source stage for amplify gain.
The output of the common source is connected to last stage which is common source stage with source degeneration for amplify gain and increase output resistance.
The output of last stage is the output of the whole circuit which is single ended output as required in project .

Amplifier transfer function simulation



Trace Color	Trace Name	Y1
	X Values	100.023K
CURSOR 1,2	DB(V(vo)/V(V1:+))	36.918

Input stage: diff stage -bias point

From voltage divider:

$$V_{R_5} = V_{DD} \cdot \frac{R_5}{R_5 + R_4} = 5 \cdot \frac{2k}{2k + 3k} = 2[V]$$

Form Ohm's law:

$$I_{R_5} = \frac{V_{R_5}}{R_5} = \frac{2}{2k} = 1[mA]$$

No current flow through Gate means that:

$$I_{R_4} = I_{R_5} = 1[mA]$$

From similar calculations:

$$I_{R_6} = I_{R_7} = 1[mA]$$

For M4:

$$V_{G,M4} = V_{D,M4} \rightarrow V_{GS,M4} = V_{DS,M4}$$

Means that:

$$V_{GS,M4} - V_{TH} < V_{DS,M4}$$

Then assuming M4 in saturation.

Form Kirchhoff's law:

$$V_{DD} - I_{DS,M4} \cdot R_8 - V_{DS,M4} = 0$$

$$5 - I_{DS,M4} \cdot 23k - V_{DS,M4} = 0$$

Plugging current equation of saturation mode:

$$I_{DS,M4} = K\left(V_{GS,M4} - V_{TH}\right)^2$$

$$5 - K\left(V_{GS,M4} - V_{TH}\right)^2 \cdot 23k - V_{DS,M4} = 0$$

Plugging $V_{GS,M4} = V_{DS,M4}$ to the equation:

$$5 - K\left(V_{GS,M4} - V_{TH}\right)^2 \cdot 23k - V_{GS,M4} = 0$$

Plugging the value of K=0.5[mA/V^2] and $V_{TH} = 0.5[V]$

$$5 - 0.5 \cdot 10^{-3}\left(V_{GS,M4} - 0.5\right)^2 \cdot 23k - V_{GS,M4} = 0$$

$$5 - 11.5\left(V_{GS,M4} - 0.5\right)^2 - V_{GS,M4} = 0$$

$$5 - 11.5\left(V_{GS,M4}^2 - V_{GS,M4} + 0.25\right) - V_{GS,M4} = 0$$

$$5-11.5V_{GS,M4}^2+11.5V_{GS,M4}-2.875-V_{GS,M4}=0$$

$$-11.5V_{GS,M4}^2+10.5V_{GS,M4}+2.125=0$$

$$V_{GS,M4}=1.083[V]\,,-0.17[V]$$

The negative result can be rejected.

$$V_{GS,M4}=V_{DS,M4}=1.083[V]$$

Verify the assumption:

$$\begin{cases} V_{GS,M4}>V_{TH} \\ V_{GS,M4}-V_{TH}<V_{DS,M4} \end{cases}$$

The assumption is correct.

$$I_{DS,M4}=K\left(V_{GS,M4}-V_{TH}\right)^2=0.5\cdot10^{-3}(1.083-0.5)^2=0.1702[mA]$$

For M7:

$$V_{G,M4}=V_{G,M7}$$

$$V_{S,M4}=V_{S,M7}$$

These 2 equations lead to:

$$V_{GS,M4}=V_{GS,M7}=1.083[V]$$

Also:

$$V_{GS,M7}>V_{TH}$$

Means M7 is not in cut-off.

Then assuming M7 in saturation.

$$I_{DS,M7}=K\left(V_{GS,M7}-V_{TH}\right)^2=K\left(V_{GS,M4}-V_{TH}\right)^2=0.1702[mA]$$

At the end we check the assumption.

For M5&M6:

Calculated before:

$$V_{G,M5}=2[V]$$

$$V_{G,M6}=2[V]$$

Also assuming M5&M6 in saturation.

The 2 branches of the diff stage are equal, therefore:

$$I_{DS,M5} = I_{DS,M6} = \frac{I_{DS,M7}}{2} = 85.1[\mu A]$$

From saturation equation on M5 current:

$$I_{DS,M5} = K\left(V_{GS,M5} - V_{TH}\right)^2 = 85.1[\mu A]$$

$$\left(V_{GS,M5} - V_{TH}\right)^2 = 85.1[\mu A]$$

$$\left(V_{GS,M5} - V_{TH}\right)^2 = 0.1702$$

$$V_{GS,M5} - V_{TH} = 0.4125$$

$$V_{GS,M5} = 0.9125[V]$$

$$V_{GS,M5} = V_{G,M5} - V_{S,M5} = 0.9125[V]$$

$$V_{S,M5} = V_{G,M5} - 0.9125 = 1.087[V]$$

It's clearly that:

$$V_{S,M5} = V_{D,M7} = 1.087[V]$$

Then Verify the assumption on M7:

$$V_{DS,M7} = 1.087[V]$$

$$V_{GS,M7} = 1.083[V]$$

Then:

$$\begin{cases} V_{GS,M7} > V_{TH} \\ V_{GS,M7} - V_{TH} < V_{DS,M7} \end{cases}$$

The assumption on M7 is correct.

Then Verify the assumption on M5&M6:

$$I_{DS,M5} = I_{DS,M6} = 85.1[\mu A]$$

Form Kirchhoff's law:

$$V_{D,M5} = V_{DD} - I_{DS,M5} \cdot R_2$$

$$V_{D,M5} = 5 - 85.1 \cdot 10^{-6} \cdot 34 \cdot 10^3 = 2.105[V]$$

$$V_{DS,M5} = V_{D,M5} - V_{S,M5} = 1.018[V]$$

$$V_{GS,M5} = 0.9125[V]$$

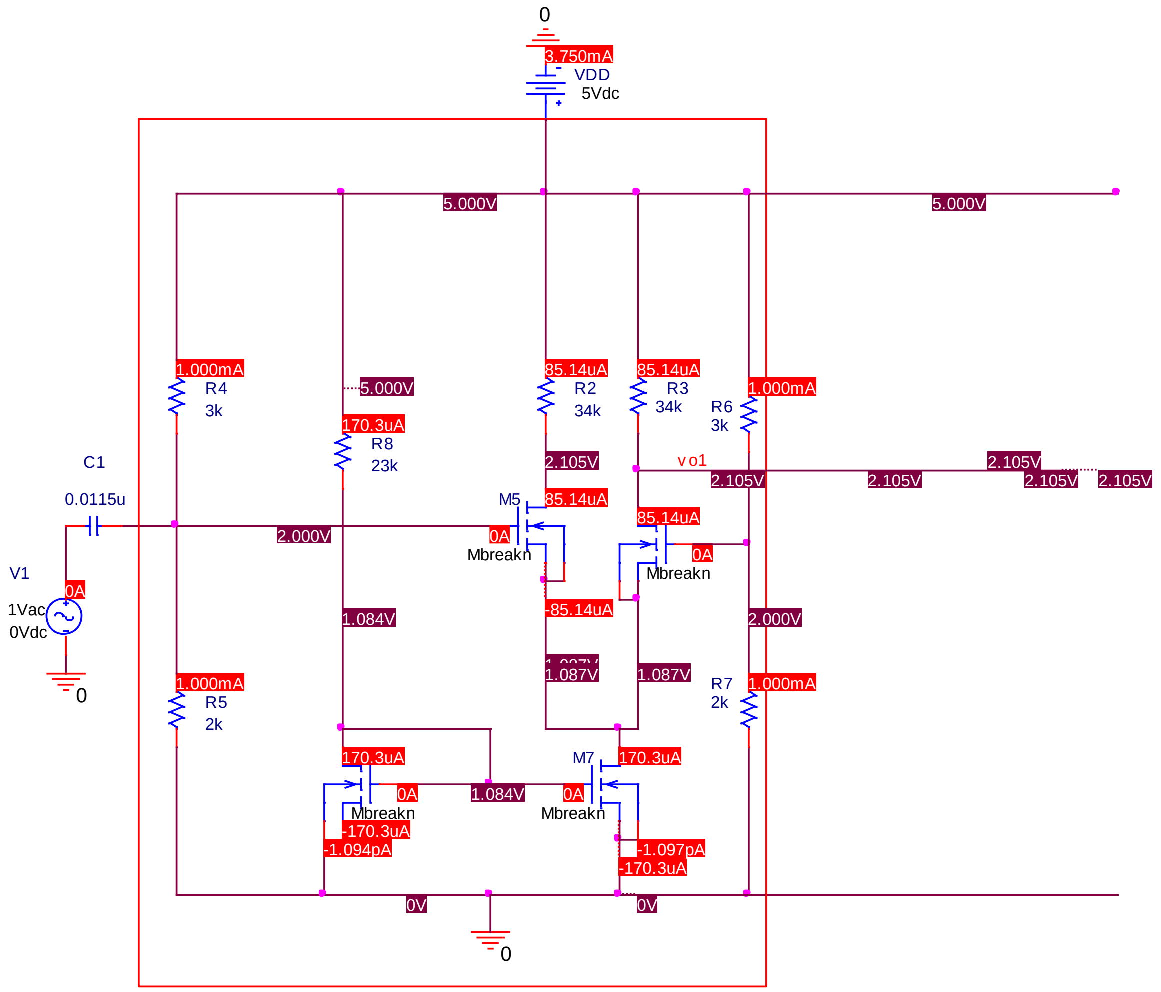
Then:

$$\begin{cases} V_{GS,M5} > V_{TH} \\ V_{GS,M5} - V_{TH} < V_{DS,M5} \end{cases}$$

The assumption on M5&M6 is correct. (its correct for M6 from symmetric).

<u>Input stage: </u>diff stage -bias point Summary & simulation

	V_D[V]	V_G[V]	V_S[V]	V_GS[V]	V_DS[V]	Mode	I_DS [A]
M4	1.083	1.083	0	1.083	1.083	Sat	170.2µ
M5	2.105	2	1.087	0.9125	1.018	Sat	170.2µ
M6	2.105	2	1.087	0.9125	1.018	Sat	170.2µ
M7	1.087	1.083	0	1.083	1.087	Sat	85.1µ



diff amp

next stage 1: common source -bias point

it clearly from the scheme that:

- $V_{G,M10} = V_{D,M6} = 2.105[V]$
- $V_{S,M10} = 0$

So $V_{GS,M10} = 2.105[V] > V_T = 0.5[V]$

Then M10 is not in cut-off mode. Then assume M10 in saturation:

$$I_{DS,M10} = K(V_{GS} - V_T)^2 = 1.288[mA]$$

Then,

$$V_{D,M10} = V_{DD} - R_{18} I_{DS,M10} = 5 - 2.6 \cdot 1.288 = 1.65[V]$$

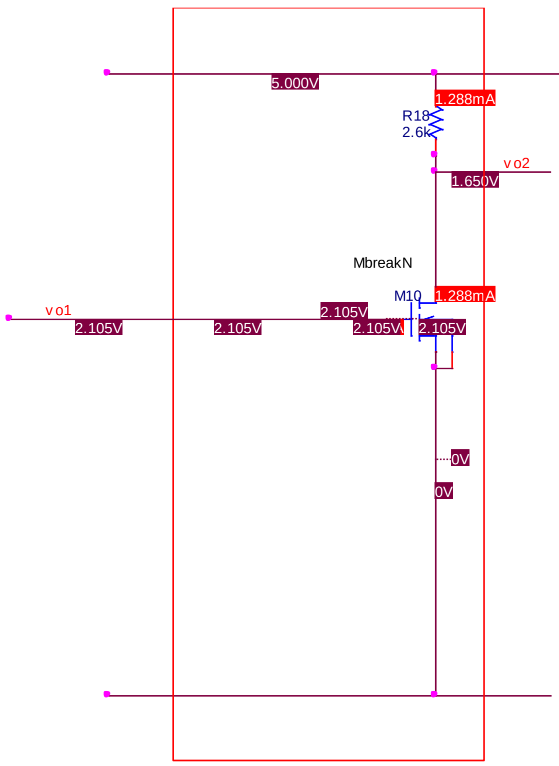
Then,

$$V_{DS,M10} = 1.65[V] > V_{GS,M10} - V_T = 1.605[V]$$

So The assumption on M10 is correct.

next stage 1: common source -bias point Summary & simulation

	V_D[V]	V_G[V]	V_S[V]	V_GS[V]	V_DS[V]	Mode	I_DS [A]
M10	1.65	2.105	0	2.105	1.65	Sat	1.288m



C.S1

<u>next stage 2:</u> common source -bias point

From voltage divider:

$$V_{G,M11} = V_{DD} \cdot \frac{R_{20}}{R_{20} + R_{21}} = 5 \cdot \frac{50k}{150k} = 1.667[V]$$

Form Ohm's law:

$$I_{R_5} = \frac{V_{R_5}}{R_5} = \frac{1.667}{50k} = 33.33[\mu A]$$

No current flow through Gate means that:

$$I_{R_{20}} = I_{R_{21}} = 33.33[\mu A]$$

assume M11 in saturation:

$$V_{GS,M11} = V_{G,M11} - V_{S,M11} = V_{G,M11} - I_{DS,M11} R_{22}$$

$$V_{GS,M11} - V_T = V_{G,M11} - I_{DS,M11} R_{22} - V_T$$

$$\left(V_{GS,M11} - V_T\right)^2 = \left(V_{G,M11} - I_{DS,M11} R_{22} - V_T\right)^2$$

$$K\left(V_{GS,M11} - V_T\right)^2 = K\left(V_{G,M11} - I_{DS,M11} R_{22} - V_T\right)^2$$

$$I_{DS,M11} = K\left(V_{G,M11} - I_{DS,M11} R_{22} - V_T\right)^2$$

$$2k \cdot I_{DS,M11} = \left(\frac{7}{6} - 8.5k I_{DS,M11}\right)^2$$

$$2k \cdot I_{DS,M11} = \frac{49}{36} - \frac{7}{3} \cdot 8.5k I_{DS,M11} + 72.25M I_{DS,M11}$$

$$2k \cdot I_{DS,M11} = \frac{49}{36} - \frac{7}{3} \cdot 8.5k I_{DS,M11} + 72.25M I_{DS,M11}$$

$$0 = \frac{49}{36} - \frac{131}{6} k I_{DS,M11} + 72.25M I_{DS,M11}$$

$$I_{DS,M11} = 0.2[mA]\ , 87.92[\mu A]$$

Then:

$$V_{GS,M11} = V_{G,M11} - I_{DS,M11} R_{22} = -0.03[V], 0.919[V]$$

The negative result can be rejected.

$$I_{DS,M11} = 87.92[\mu A]$$

$$V_{GS,M11} = 0.919[V]$$

Then :

$$V_{S,M11} = I_{DS,M11} R_{22} = 0.747[V]$$

$$V_{D,M11} = V_{DD} - R_{19} I_{DS,M10} = 5 - 28.4k \cdot, 87.92\mu = 2.503[V]$$

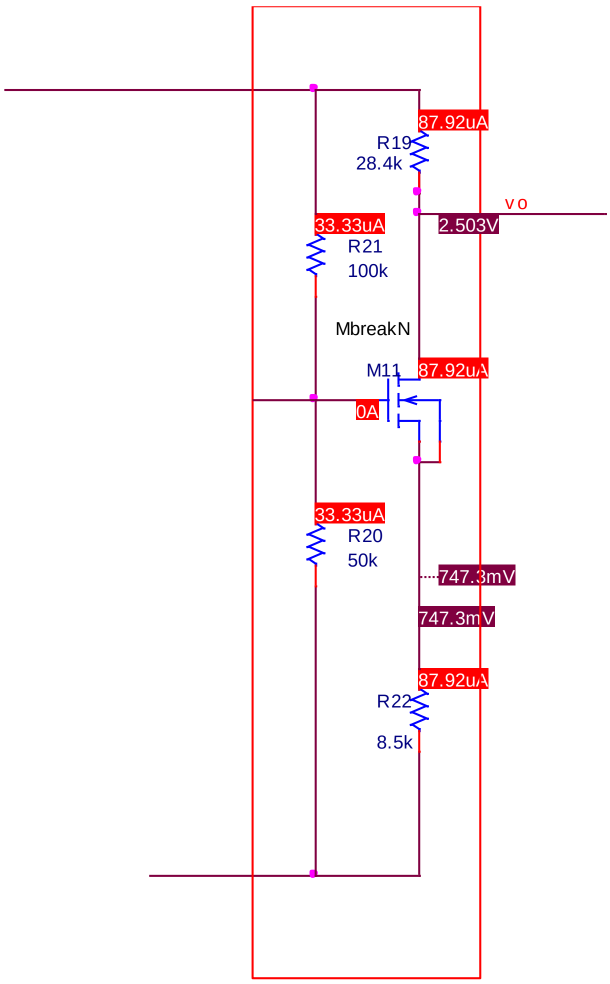
Then it's clearly:

$$\begin{cases} V_{GS,M11} > V_{TH} \\ V_{GS,M11} - V_{TH} < V_{DS,M11} \end{cases}$$

The assumption on M11 is correct.

<u>next stage 2: </u>common source -bias point Summary & simulation

	V_D[V]	V_G[V]	V_S[V]	V_GS[V]	V_DS[V]	Mode	I_DS [A]
M11	2.503	1.667	0.747	0.919	1.756	sat	87.92 μ



C.S2

Amplitude:

we will perform calculations to determine the gain associated with each degree, and subsequently establish the overarching or general gain.

Input stage: diff stage -Amplitude intermediate frequencies

The Amplitude in intermediate frequencies for symmetric diff amp with single ended output is:

$$A_{v,diff\ SE} = -\frac{1}{2} g_m R_D$$

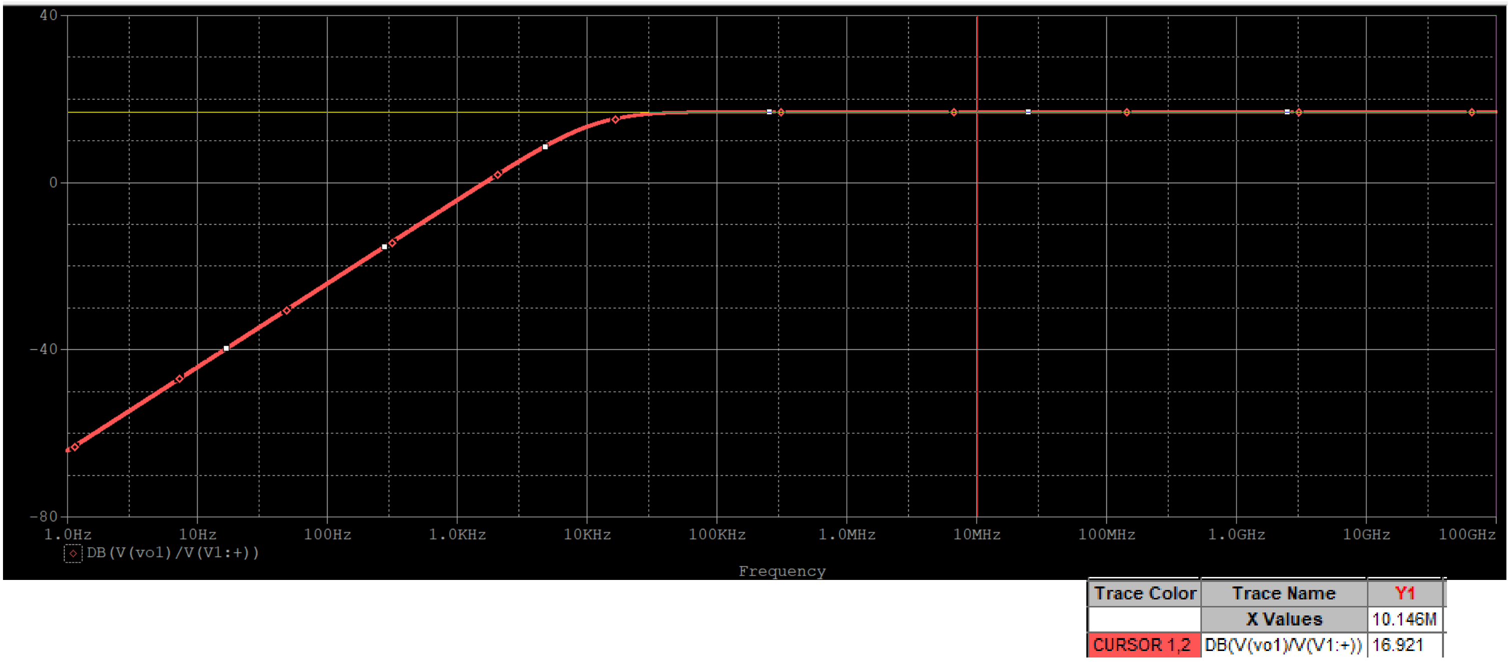
For this stage:

$$g_m = 2\sqrt{\mathrm{KI}_{\mathrm{DS,M6}}} = 2\sqrt{0.5 \cdot 10^{-3} \cdot 85.14 \cdot 10^{-6}} = 0.412 \cdot 10^{-3} \left[\frac{1}{\Omega}\right]$$

$$R_D = 34k\Omega$$

$$\left|A_{v,diff\ SE}\right| = \frac{1}{2} \cdot 0.412 \cdot 34 = 7.015 = 16.920[dB]$$

Input stage: diff stage -Amplitude simulation intermediate frequencies



<u>next stage 1:</u> common source -Amplitude intermediate frequencies

The Amplitude in intermediate frequencies for common source is:

$$A_v = -g_m R_D$$

For this stage:

$$g_m = 2\sqrt{\mathrm{KI}_{\mathrm{DS,M10}}} = 2\sqrt{0.5 \cdot 10^{-3} \cdot 1.288 \cdot 10^{-3}} = 1.604 \cdot 10^{-3} \left[\frac{1}{\Omega}\right]$$

$$R_D = 2.6k\Omega$$

$$|A_v| = 1.604 \cdot 2.6 = 4.172 = 12.40[dB]$$

**Ignore the voltage divider on the output of first common source -we handle it at the next pages.

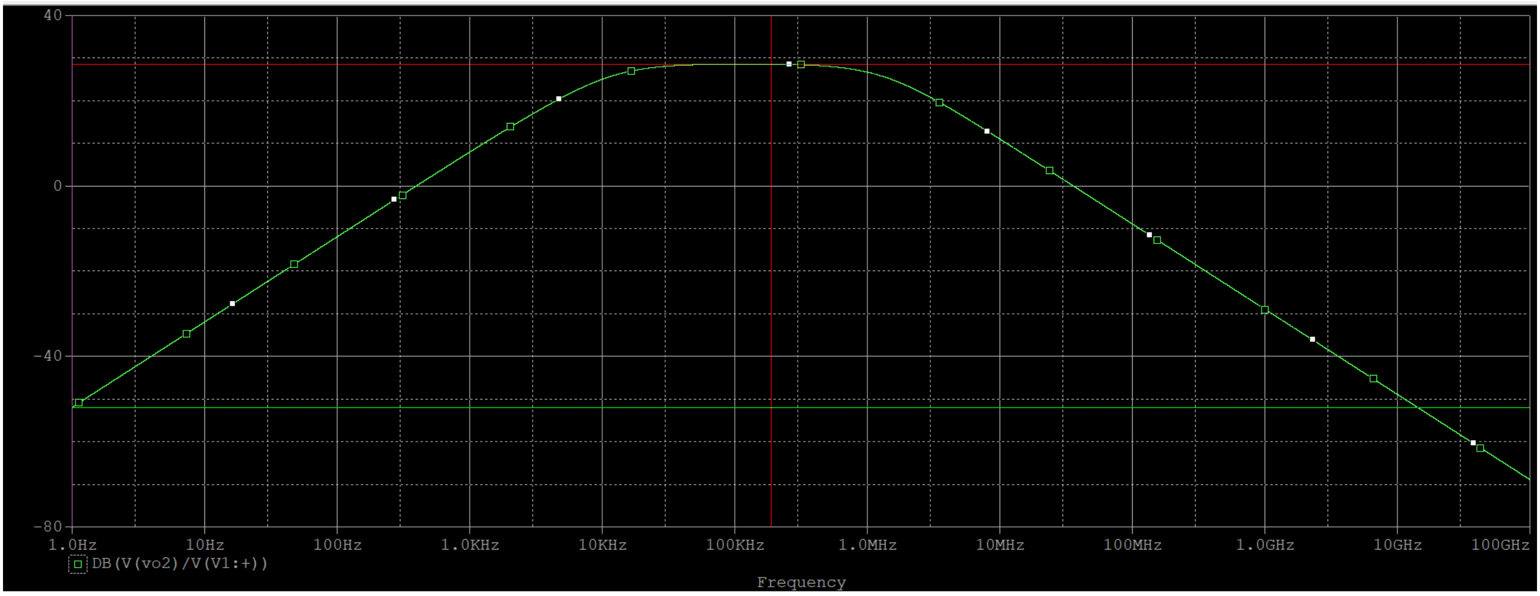
Concatenate two stages is multiplication of the transfer functions- means multiplication of the Amplitude also -but in logarithmic scale :

$$\log_{10}(Amp_1 \cdot Amp_2) = \log_{10}(Amp_1) + \log_{10}(Amp_2)$$

Consequently, the amplitude of input stage and the first common source stage is:

$$A_v = 16.920[dB] + 12.40[dB] = 29.32[dB]$$

<u>next stage 1:</u> common source -Amplitude simulation intermediate frequencies



Trace Color	Trace Name	Y1
	X Values	188.408K
CURSOR 1,2	DB(V(vo2)/V(V1:+))	28.574

**the result is close to our estimation .

next stage 2: common source -Amplitude

The Amplitude in intermediate frequencies for common source with source degeneration is:

$$A_v = -\frac{g_m R_D}{1 + R_s g_m}$$

For this stage:

$$g_m = 2\sqrt{\mathrm{KI}_{\mathrm{DS,M11}}} = 2\sqrt{0.5 \cdot 10^{-3} \cdot 87.92 \cdot 10^{-6}} = 4.193 \cdot 10^{-4} \left[\frac{1}{\Omega}\right]$$

$$R_D = 28.4k$$

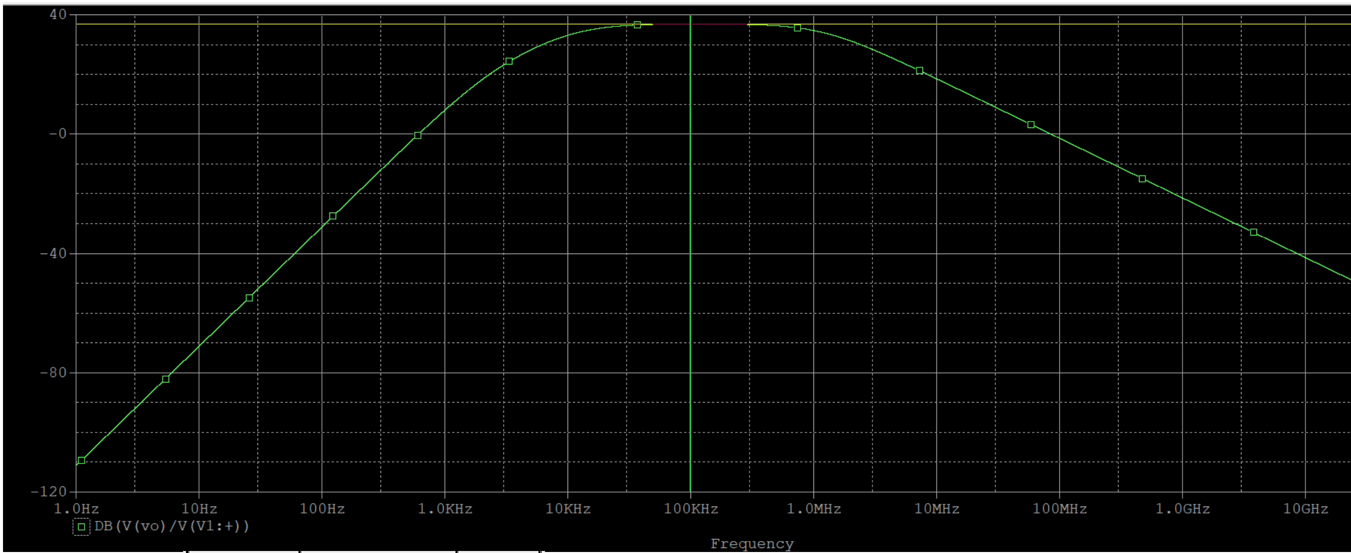
$$R_S = 8.5k$$

$$A_v = -\frac{g_m R_D}{1 + R_s g_m} = 2.609 = 8.33[dB]$$

The last stage is concatenating to the other stages and as explained before the amplitude of the whole scheme is:

$$A_v = 29.32[dB] + 8.33[dB] \approx 37.6[dB]$$

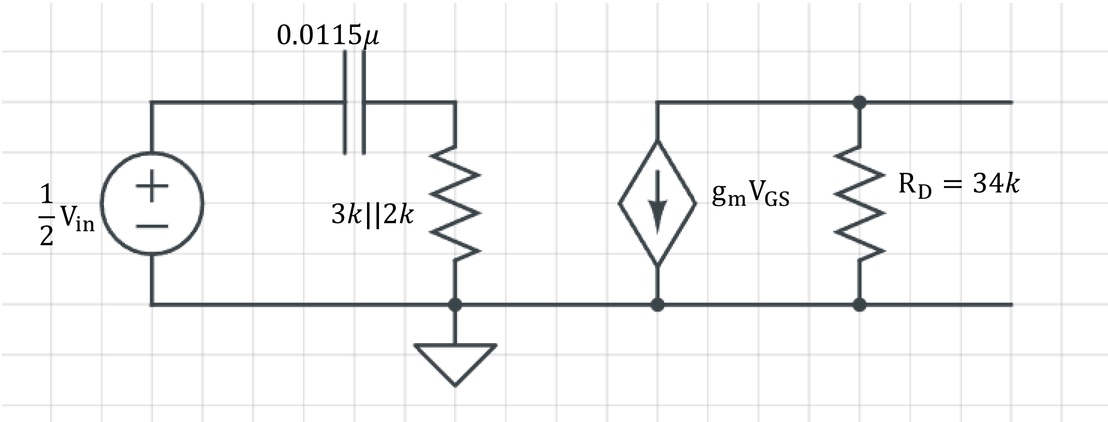
next stage 2: common source -Amplitude simulation



Trace Color	Trace Name	Y1
	X Values	100.023K
CURSOR 1,2	DB(V(vo)/V(V1:+))	36.918

<u>Transfer function:</u>

For the input stage small signal scheme:



From voltage divider

$$V_{GS} = \frac{1.2k}{1.2k + \frac{1}{0.0115\mu s}} \cdot \frac{1}{2} V_{in}$$

$$V_{out} = -g_m V_{GS} R_D = -\frac{1.2k g_m R_D}{1.2k + \frac{1}{0.0115\mu s}} \cdot \frac{1}{2} V_{in}$$

$$\frac{V_{out}}{V_{in}} = G(s) = -\frac{1}{2}\frac{1.2k \cdot 0.412 \cdot 10^{-3} \cdot 34k}{1.2k + \frac{1}{0.0115\mu s}} = -\frac{1}{2}\frac{1.2k \cdot 0.412 \cdot 10^{-3} \cdot 34k \cdot 0.0115\mu s}{1.2 \cdot 10^{-3} \cdot 0.0115 s + 1} =$$

$$G_0(s) = -\frac{9.665 \cdot 10^{-5} s}{1.2 \cdot 10^{-3} \cdot 0.0115 s + 1}$$

For ensure the amplitude of first stage take $s \to \infty$

$$A_v = -\frac{9.665 \cdot 10^{-5}}{1.2 \cdot 10^{-3} \cdot 0.0115} = 7.004 = 16.9[dB]$$

we get the same results.

For next stage 1:

The transfer function of the two systems is the previous transfer function multiply with $-g_m R_D$

$$G(s) = \frac{9.665 \cdot 10^{-5} s}{1.2 \cdot 10^{-3} \cdot 0.0115 s + 1} \cdot 4.172$$

Also multiply with voltage divider on the output:

$$\frac{\frac{1}{sC_2}}{\frac{1}{sC_2} + \frac{1}{sC_3} + 50k||100k} = \frac{C_3}{C_3 + C_2 + C_3 C_2 (50k||100k) s}$$

To sum up the transfer function is:

$$G_1(s) = \frac{4.032 \cdot 10^{-4}s}{1.2 \cdot 10^{-3} \cdot 0.0115s + 1} \cdot \frac{C_3}{C_3 + C_2 + C_3C_2(50k||100k)s}$$

By simplify (using wolfram alpha) the transfer function we get:

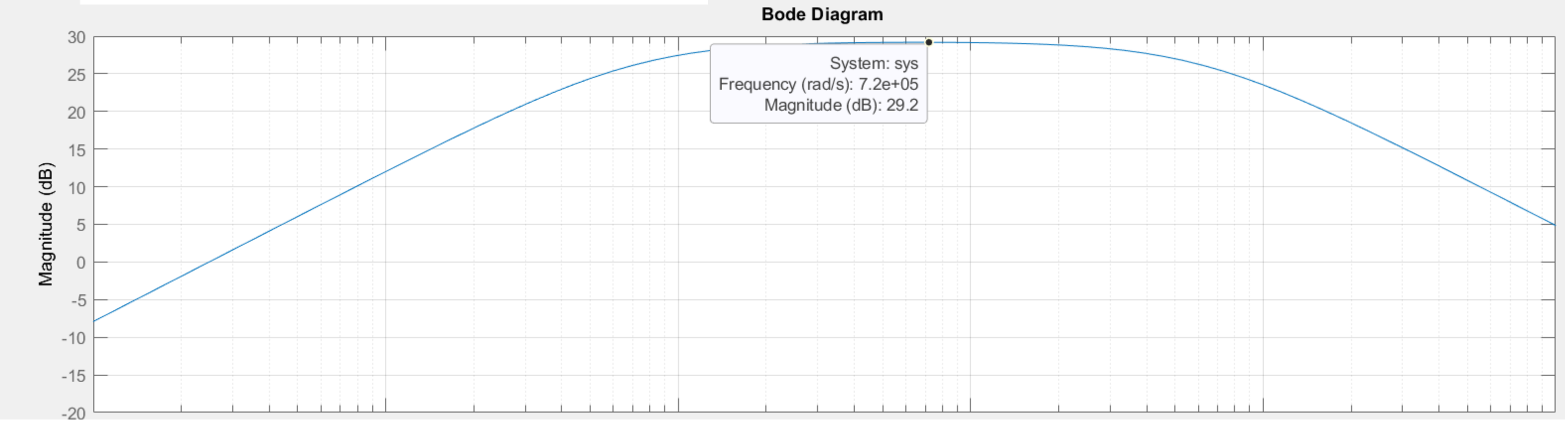
$$G_1(s) = \frac{5.84382 \cdot 10^{-8}s}{3.33333 \cdot 10^{-16}s^2 + 2.02915 \cdot 10^{-9}s + 0.00014529}$$

First, we can see there is zero at s=0 and two poles so it verifies the previous simulation (BPF)

```
>> % Define the transfer function coefficients
num = [5.84382e-8, 0];
den = [3.33333e-16, 2.02915e-9, 0.00014529];

% Create a transfer function object
sys = tf(num, den);

% Plot the Bode plot
bode(sys);
grid on;
>>
```



The result corresponds to calculations.

Then for the last stage and the whole transfer function we need to the prev transfer function and multiply by voltage divider and the known gain for C.S with source degeneration:

$$G_2(s) = \frac{5.84382 \cdot 10^{-8}s}{3.33333 \cdot 10^{-16}s^2 + 2.02915 \cdot 10^{-9}s + 0.00014529} \cdot \frac{33.33k}{33.33k + \frac{1}{2ns}} \cdot 2.609$$

Then we are using wolfram alpha to simplify it:

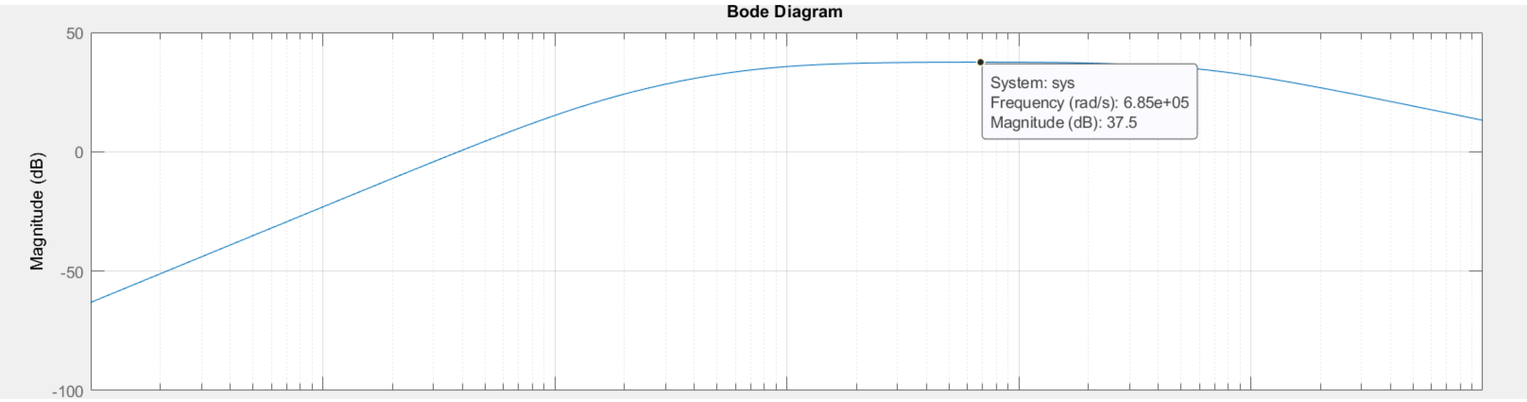
$$G_2(s) = \frac{1.52465 \cdot 10^{-7}s^2}{3.33333 \cdot 10^{-16}\, s^3 + 2.03415 \cdot 10^{-9}\, s^2 + 0.000175727s + 2.17935}$$

Now using matlab again to verify the transfer function:

```
>> % Define the transfer function coefficients
num = [1.52465e-7, 0, 0];
den = [3.33333e-16, 2.03415e-9, 0.000175727, 2.17935];

% Create a transfer function object
sys = tf(num, den);

% Plot the Bode plot
bode(sys);
grid on;
```

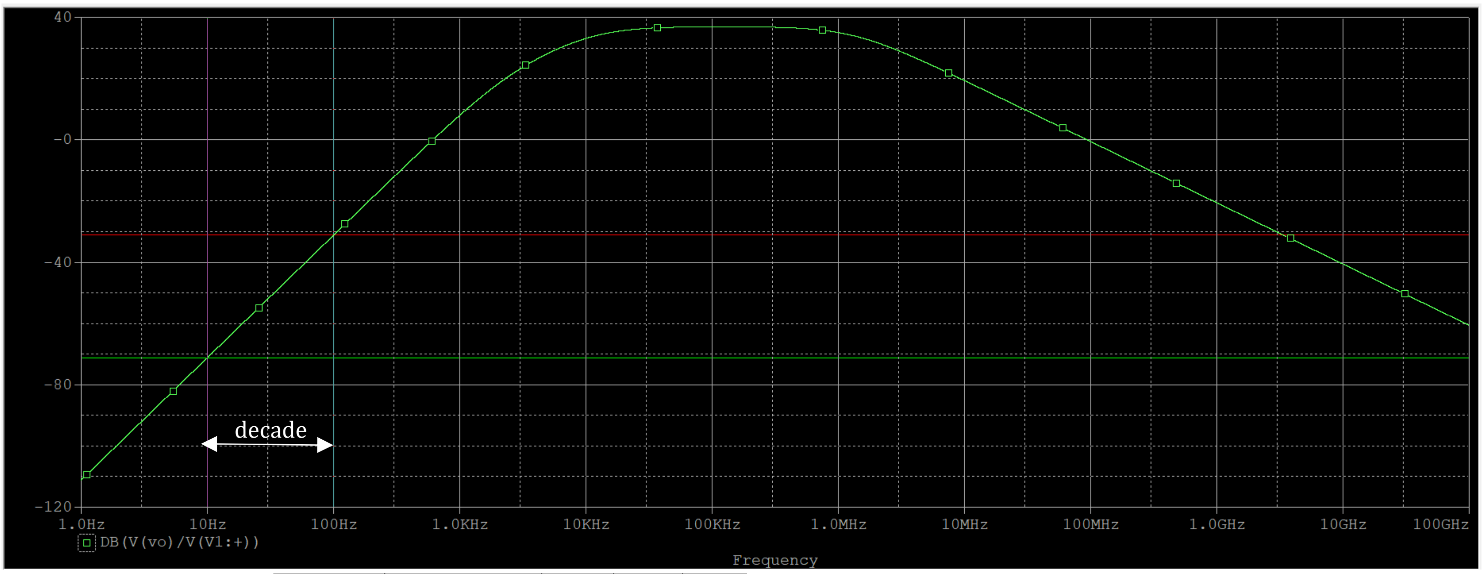


The same result from pspice also we can see that in we get 37dB amplitude in intermediate frequencies.

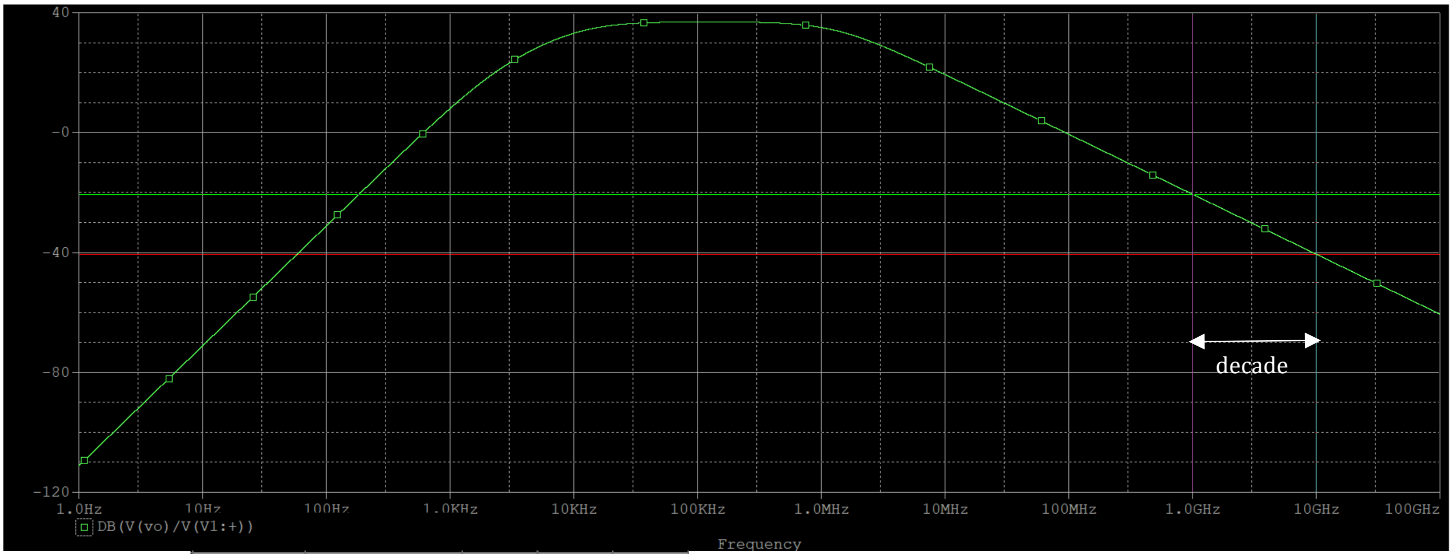
Slopes M1 and M2:

We can see from transfer function that there are 2 zeros at s=0 which give us slope of 40dB and also we have cubic polynomial on the denominator which give us 3 poles – so we have +40dB slope then Constant amplitude(0dB) and then -20dB slope. As required in the project.

Slopes M1 and M2-simulation pspice

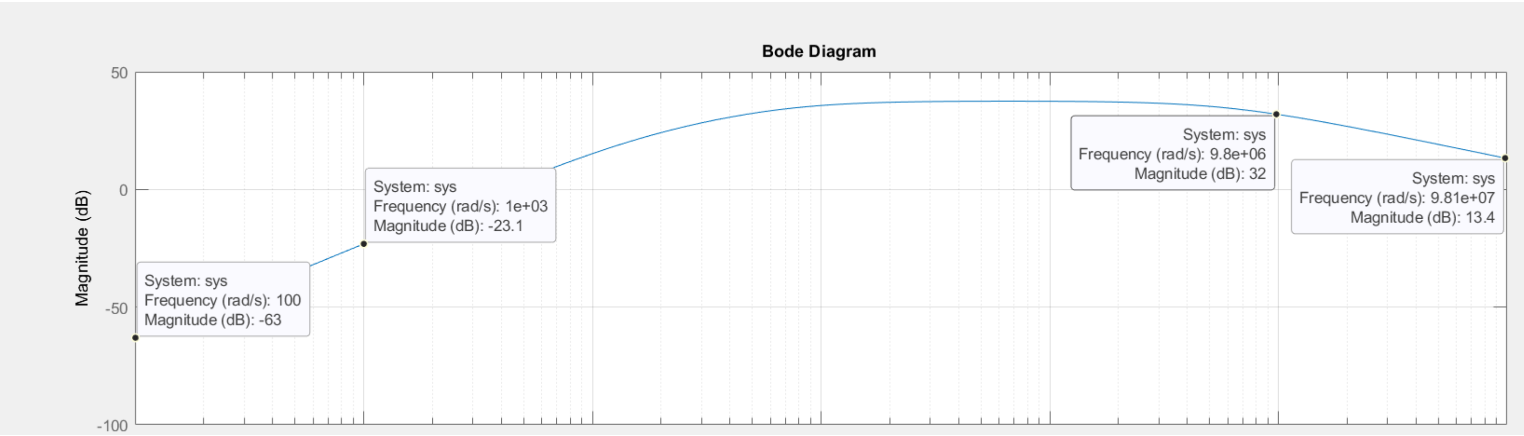


Trace Color	Trace Name	Y1	Y2	Y1 - Y2
	X Values	100.023	10.002	90.021
CURSOR 1,2	DB(V(vo)/V(V1:+))	-31.145	-71.136	39.991



Trace Color	Trace Name	Y1	Y2	Y1 - Y2
	X Values	10.002G	1.0002G	9.0021G
CURSOR 1,2	DB(V(vo)/V(V1:+))	-40.582	-20.582	-20.000

also verified at matlab:



Slop of +40dB then constant amplitude and then -20dB slop.

3dB frequencies (f1 and f2)

Using the full transfer function, we can calculate the poles of the denominator of transfer function:

$$3.33333\times 10^{-16}\, s^3 + 2.03415\times 10^{-9}\, s^2 + 0.000175727\, s + 2.17935$$

$$s \approx -6.01499\times 10^6$$

$$s \approx -72463.8$$

$$s \approx -15000.$$

For f2 it’s clearly that:

$$\omega_h = 6.015 \cdot 10^6$$

Then:

$$f_h = \frac{\omega_h}{2\pi} \approx 1\text{MHz}$$

**pay attention that coefficients in the denominator of the transfer function were rounded. but this close to 1.2MHz

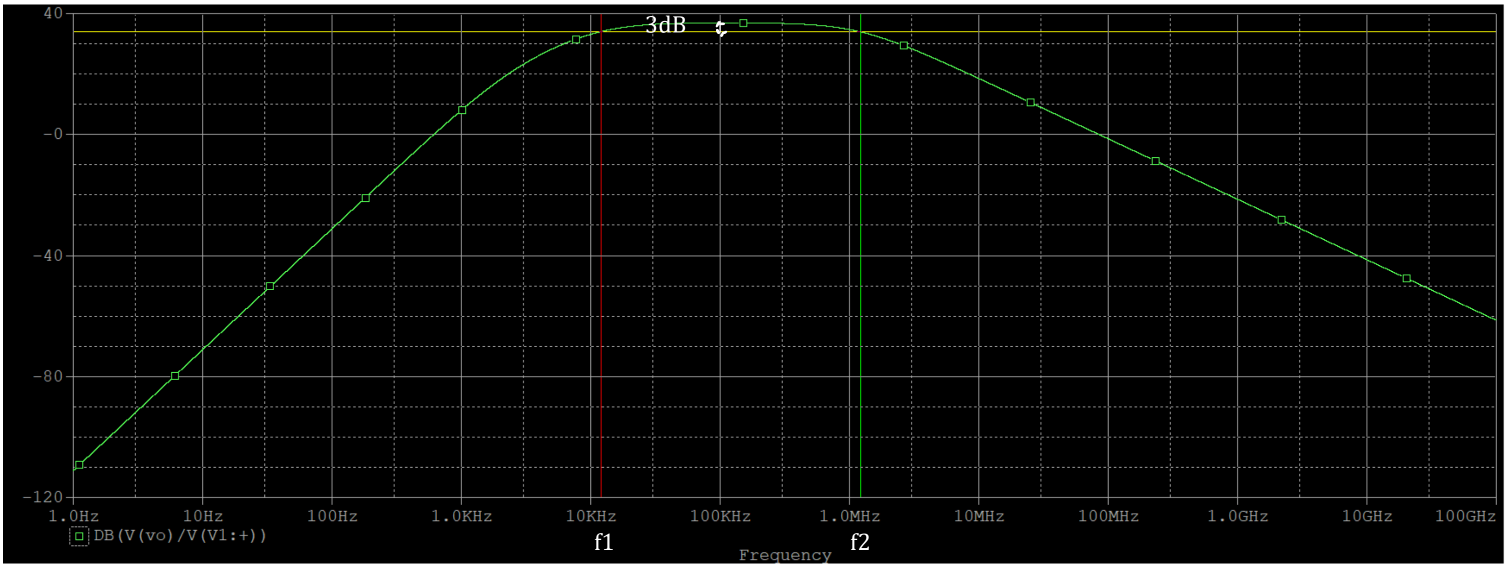
For f1 we need to take the highest pole in the lower frequency which is:

$$\omega_L = 72468$$

$$f_L = \frac{72468}{2\pi} \approx 11.5\text{kHz}$$

Which also close to 12k in our project guidelines.

3dB frequencies (f1 and f2)-simulation



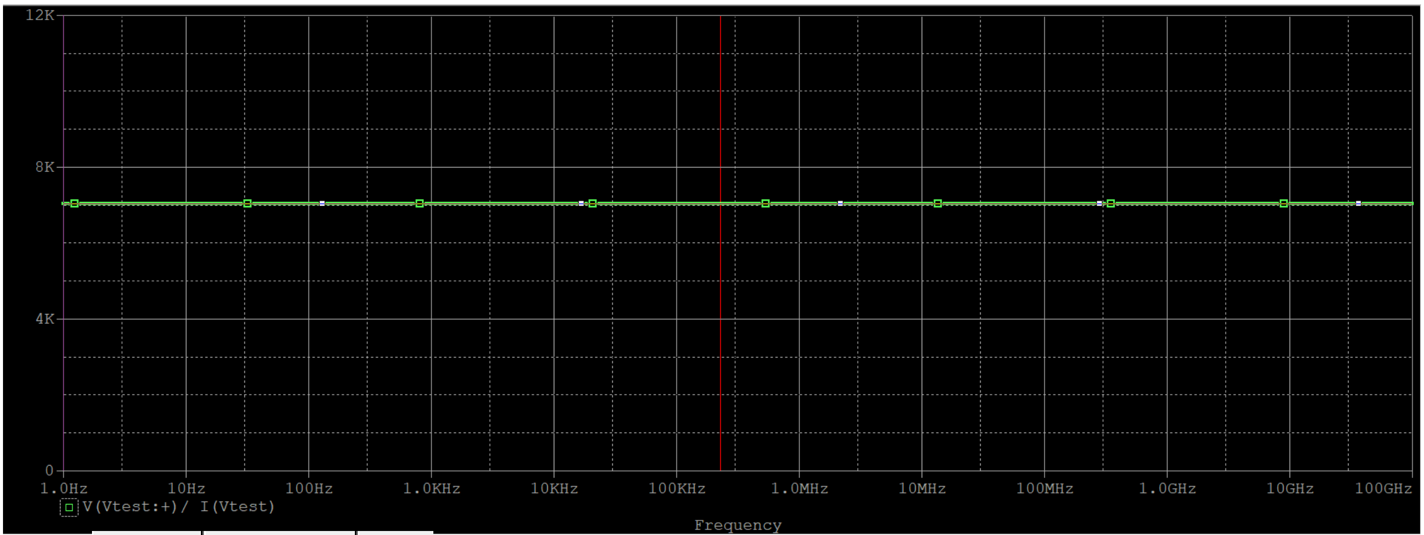
Trace Color	Trace Name	Y1	Y2	Y1 - Y2
	X Values	12.025K	1.2210M	-1.2089M
CURSOR 1,2	DB(V(vo)/V(V1:+))	34.029	33.921	107.930m

Output Resistance of the amplifier:

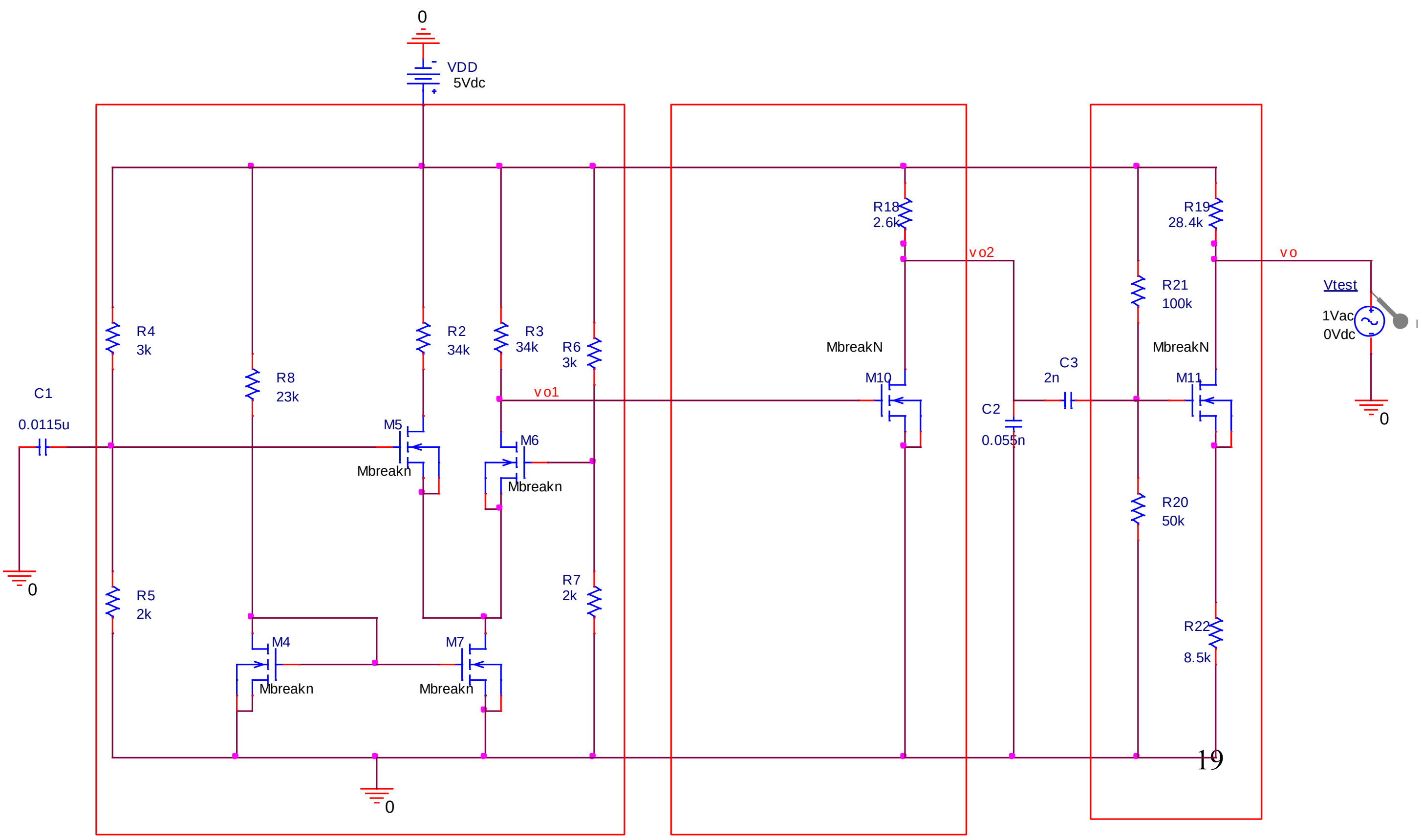
calculating output resistance of the amplifier by the following steps:

1. Disconnect the input AC voltage source and replace it with ground.
2. Apply a known test voltage (V_test) across the output resistance.
3. Measure the resulting current flowing through the output resistance (I_test).
4. Calculate the output resistance using Ohm's Law: Output Resistance = V_test / I_test.

Output Resistance of the amplifier-simulation



Trace Color	Trace Name	Y1
	X Values	623.448K
CURSOR 1,2	V(Vtest:+)/I(Vtest)	7.0382K



diff amp C.S1 C.S2