The University of British Columbia

ELECTRONICS II

ELEC 301

MINI PROJECT 3

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Contents

1 Objectives

To become familiar with, and understand, some of the characteristics of several multi-transistor amplifiers/circuits.

2 Part I: The Cascode Amplifier

We will create a cascode amplifier using the specifications in Table 2.1 and 2N3904 transistors. We use $V_{CC} = 20V$, $R_S = 50\Omega$, and a load of $R_L = 50k\Omega$.

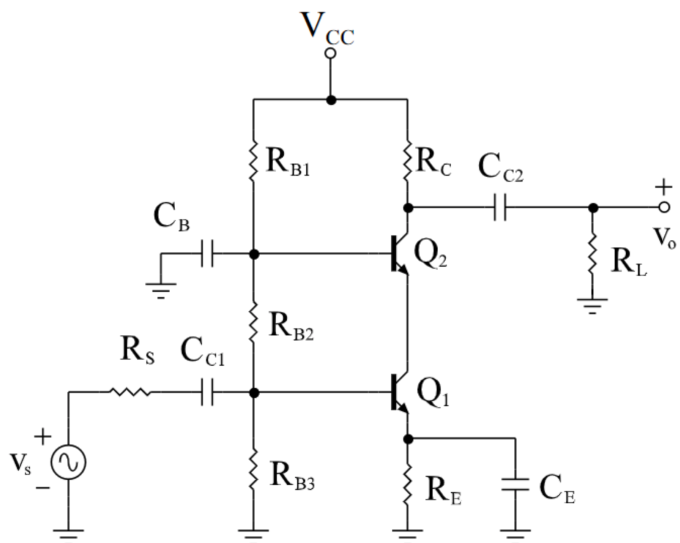

Figure 2.1: The Cascode Amplifier

R_{out} (value at mid band)	R_{in} (minimum value at mid band[1])	$\|A_M\|$ (minimum value at mid band)	ω_{L3dB} (maximum value for low-f cut-in)
2.5 kΩ ± 250Ω	3.5 kΩ	50 V/V	1200 rad/sec

Table 2.1: Cascode Amplifier Specifications

2.a Finding DC Operating Point

Using the specifications above we can deduce resistances for our cascode filter and find the DC Operating point. We will use The $\frac{1}{4}$ Rule and $\beta = 167$ which we previously found in Mini Project 2 for the transistor 2N3904. Resistances are converted to commonly found values.

$$V_{C1} = 15V \quad V_{E1} = V_{C2} = 10V \quad V_{E2} = 5V \quad V_{B1} = 10.7V \quad V_{B2} = 5.7V$$

$$I_{C1} \approx I_{E1} \approx I_{C2} \approx I_{E2} = \frac{V_{CC}-V_C}{R_C} = \frac{5V}{2.5k} = \boxed{\text{2.0mA}} \qquad I_{B1} \approx I_{B2} = \frac{I_C}{\beta} = \frac{2mA}{167V} = \boxed{\text{11.98uA}}$$

$$I_1 = \frac{I_E}{\sqrt{(\beta)}} = \frac{2mA}{\sqrt{(166.67)}} = 154.76uA \qquad I_2 = I_1 - I_{B1} = 154.76uA - 11.98uA = 142.79uA$$

$$I_3 = I_2 - I_{B2} = 142.79uA - 11.98uA = 130.81uA$$

$$R_{B1} = \frac{V_{CC}-V_{B1}}{I_1} = 60.1k\Omega \rightarrow \boxed{\text{62k}} \qquad R_{B2} = \frac{V_{B1}-V_{B2}}{I_2} = 35.0k\Omega \rightarrow \boxed{36\text{k}\Omega}$$

$$R_{B3} = \frac{V_{B2}}{I_3} = 43.6k\Omega \rightarrow \boxed{43\text{k}\Omega} \qquad g_m = \frac{I_C}{V_T} = \boxed{\text{0.08S}} \qquad r_\pi = \frac{\beta}{g_m} = \boxed{2.09\text{k}\Omega}$$

To satisfy our R_{in} requirement of $3.5k\Omega$ we can add a resistance to the base.

$$R_{in} = 3.5k\Omega = R_{B2}||R_{B3}||r_\pi + R_{add} \rightarrow R_{add} = 1.6k\Omega \approx \boxed{2\text{k}\Omega}$$

Putting together and simulating values based on updated resistance:

Transistor	V_C	V_B	V_E	I_C	I_B	I_E
Top Transistor (Q2)	15.4V	10.4V	9.75V	1.96mA	11.66uA	1.97mA
Bot Transistor (Q1)	9.75V	5.38V	4.71V	1.97mA	11.72uA	1.98mA

Table 2.2: Simple Bias DC Operating Points

Given we have all of our resistances we can also calculate the midband gain of our circuit:

$$A_M = \frac{V_o}{V_s} = \frac{V_o}{V_{\pi 2}} * \frac{V_{\pi 2}}{V_{\pi 1}} * \frac{V_{\pi 1}}{V_S} = -g_m * (R_L||R_C) * (1) * \frac{r_\pi||R_{B2}||R_{B1}}{r_\pi||R_{B2}||R_{B1}+R_S+R_{add}} =\approx \boxed{\text{-78 v/v}}$$

2.b Simulate and Approx vs Calculate: Poles and ω_{3DB}

To measure the Bode response of the circuit we first need to find the capacitance values.

$$\omega_{C_E}^{SC} = \frac{1}{\frac{C_E*(R_{B2}||R_{B3}||(R_S+R_{add}))}{1+\beta}}||R_E \approx \frac{1}{23.25*C_E} \rightarrow \boxed{\text{DOMINANT POLE}}$$

$$\omega_{C_{C2}}^{SC} = \frac{1}{C_{C2}*(R_C+R_L)} \approx \frac{1}{52k\Omega*C_{C2}} \qquad \omega_{C_{C1}}^{SC} = \frac{1}{C_{C1}*R_{B2}||R_{B3}||R_\pi+2k} \approx \frac{1}{4k\Omega*C_{C1}}$$

From our requirements we know that 1200rad/s is the max ω_{3DBL} frequency:

$$\omega_{3DBL} = 1200rad/s = \sqrt{(23.249 * C_E)^{-2} - 2*(2400*C_E)^{-2}} \rightarrow C_E = 35.84uF \approx \boxed{\text{39uF}}$$

For simplicity and to keep parts at a minimum $C_{C1} = C_{C2} = C_{CE}$. The capacitor is rounded to the closest common capacitor value, recalculating the ω_{3DBL}:

$$\omega_{3DBL} = \sqrt{(23.249*39uF)^{-2} - 2*(2400*39uF)^{-2}} = 1103rad/s = \boxed{\text{175.5Hz}}$$

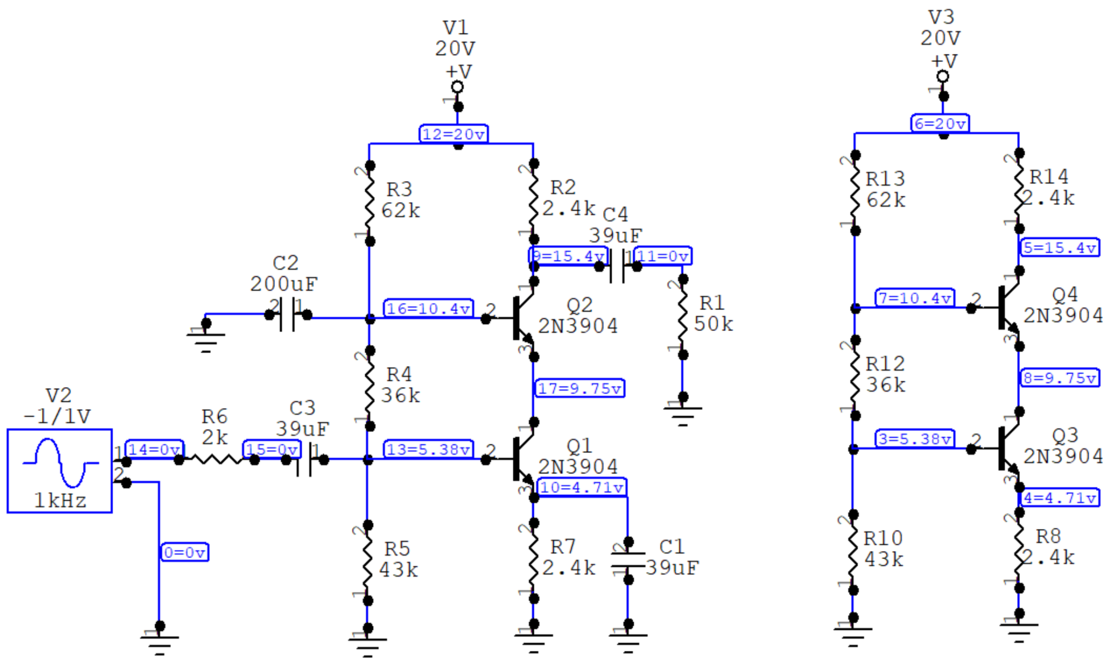

Figure 2.2: Completed circuit for 2.a (right) and 2.b (left)

Now we will calculate the ω_{3DBH} :

$$C_\pi = 2 * CJE + TF * g_m = 2 * 4.5pF + 400pF * 0.08 = \boxed{\text{41pF}}$$

$$C_\mu = \frac{CJC}{(1+\frac{V_{CB}}{VJC})^{MJC}} = \frac{3.5pF}{(1+\frac{5V}{750m})^{330m}} = \boxed{\text{1.79pF}}$$

Translating Figure 2.2 into our Small Signal Model to evaluate high frequency poles:

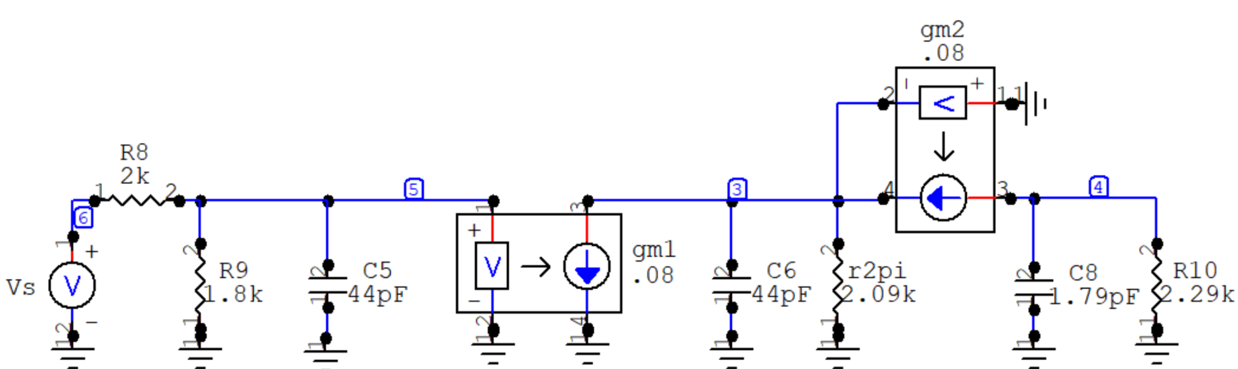

Figure 2.3: Small Signal Model of Figure 2.2

To find the high frequency poles we will take the small signal model of the circuit:

$$\omega_{HP1} = \frac{1}{(C_{\pi 1}+2*C_{u1})*((R_S+R_{add})||R_{BB}||R_{\pi 1})} \approx \frac{1}{1k\Omega*44pF} \rightarrow \boxed{\text{DOMINANT POLE 1}}$$

$$\omega_{HP2} = \frac{1}{(C_{\pi 1}+2*C_{u1})*(\frac{r_{pi2}}{1+\beta})} \approx \frac{1}{12\Omega*44pF}$$

$$\omega_{HP3} = \frac{1}{C_u*(R_L||R_C)} \approx \frac{1}{2.3k\Omega*1.8pF} \rightarrow \boxed{\text{DOMINANT POLE 2}}$$

$$\omega_{3DBL} = (\sqrt{(2.3k\Omega * 1.8pF)^2 + (1k\Omega * 44pF)^2})^{-1} = 22.63 * 10^6 rad/s = \boxed{3.6\text{MHz}}$$

We have the calculated estimates of the 3DB points based on small signal and OSOC approximations, we will now compare the simulated results:

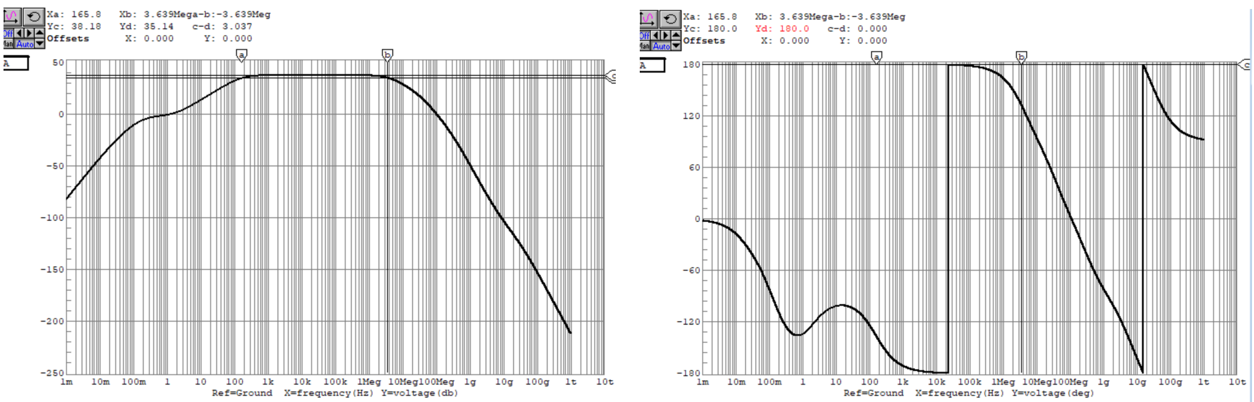

Figure 2.4: Bode Magnitude (left) and Phase Plot (right) for our Cascode Amplifier

Comparing our simulated values to our calculated values:

Method	ω_{3DBL}	ω_{3DBH}
Calculated	176Hz	3.6MHz
Simulated	165Hz	3.6MHz

Table 2.3: Small Signal H-Parameters vs Simulated Parameters

We can see that both methods yield the same results telling us that the method of OCSC Time Constants, Small Signal Approximation method, and 1/4 rule work very well when configuring the cascode amplifier.

2.c Going Non-Linear

Picking a midband frequency of 10kHz and adjusting the amplitude of the signal from 1mV to 400mV we can find the point at which our input vs output voltage becomes non-linear. We can see that the output Vo becomes non-linear at an input Vs of 65mV.

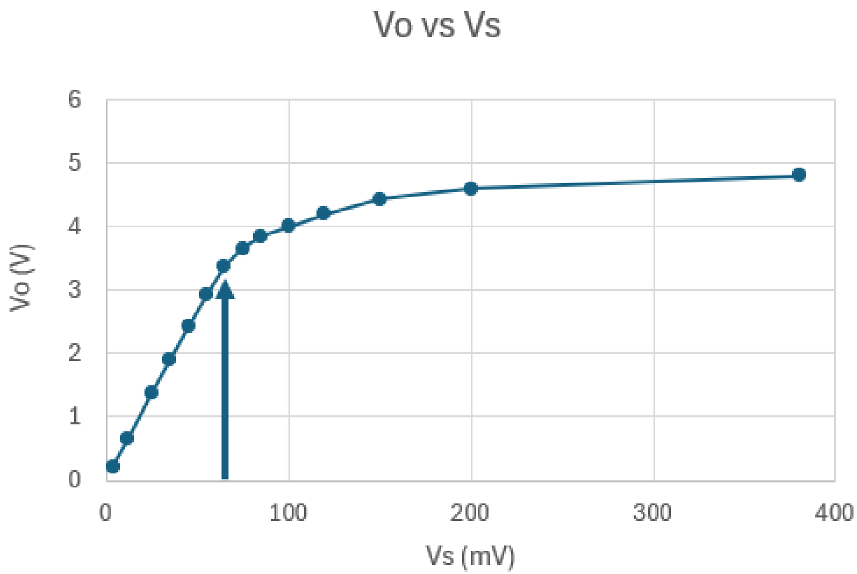

Figure 2.5: Vo vs Vs

2.d Input Impedance of the Amplifier

Comparing our measured vs simulated input impedance of the amplifier:

Measured: $R_{in} = R_{B2}||R_{B3}||r_\pi + R_{add} = \boxed{3.69\text{k}\Omega}$ Simulated: $R_{in} = \frac{V_{in}}{I_{in}} = \boxed{4.01\text{k}\Omega}$

Both values satisfy a our requirement of an input resistance of at least 3.5kΩ. They are also close in value which tells us our calcuations are accurate.

2.e Discussion

Exploring the Cascode amplifier we have successfully simulated and calculated reasonable values for the resistances/capacitances that satisfy our design specifications. Given how close our 1/4 method was to the simulated methods we can conclude that 1/4 is effective and can be effectively used in place of simulation.

3 Part II: Cascaded Amplifiers: CB → CC

The circuit shown in Figure 3.1 will be used as a repeater in an analog, 50Ω coaxial cable system. We will design it so that at mid band it has an input impedance, R_i and an output impedance, R_o that are both equal to 50Ω. We will use 2N3904s transistors with $V_{CC} = 15V$. The low frequency cut in being 1000Hz.

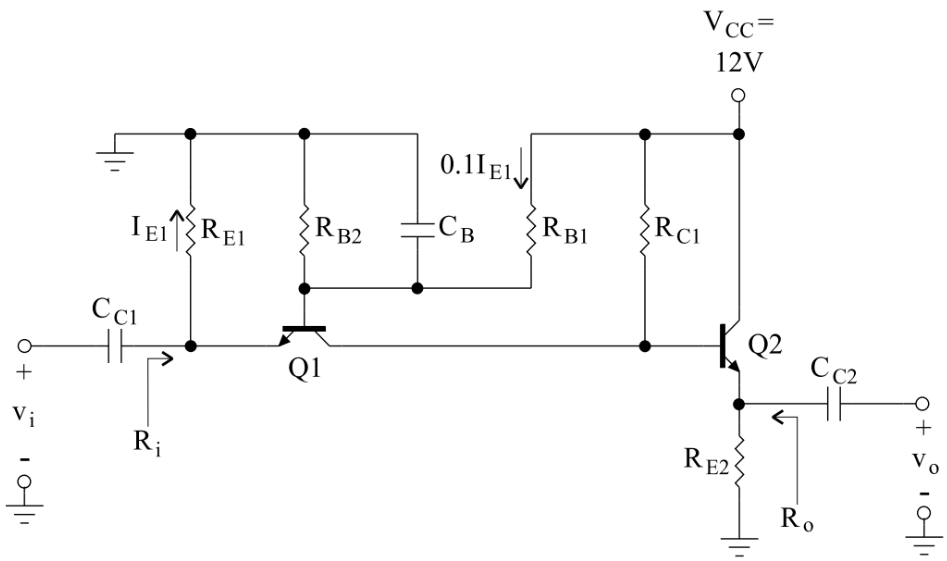

Figure 3.1: Cascaded Amplifiers

3.a Building The Circuit: Resistance/Capacitance

We will use the 1/3 Rule with to find the resistances and capacitance of our circuit. Resistances and capacitances are rounded to common values.

$$V_{C1} = 10V \quad V_{B1} = 5.7V \quad V_{E1} = 5V \quad V_{C2} = 15V \quad V_{B2} = 10V \quad V_{E2} = 9.3V$$

Using R_{in} requirements and solving our 3 equations and 3 unknowns:

$$R_{in} = 50 = R_E||(\frac{r_{\pi 1}}{1+\beta}) \; ; \; R_{E1} = \frac{V_E}{I_{E1}} \; ; \; r_{\pi 1} = \frac{\beta * V_T}{I_{E1}}$$

$$\text{solver} \rightarrow \quad R_{\pi 1} = 8.2k\Omega \; ; \; R_{E1} = \boxed{10\text{k}\Omega} \; ; \; I_{E1} = 0.495mA \approx I_{C1} \approx \beta * I_{B1}$$

Using our values to find resistances:

$$I_1 = \frac{I_{E1}}{\sqrt{\beta}} = 38.19uA \quad R_{B1} = \frac{V_{CC} - V_{B1}}{I_1} = \boxed{240\text{k}\Omega} \quad R_{B2} = \frac{V_{B1}}{I_1 - I_{B1}} = \boxed{160\text{k}\Omega}$$

Using R_o requirements and solving our 4 equations and 4 unknowns:

$$R_o = 50 = R_{E2}||\frac{R_{C1} + R_{\pi 2}}{1+\beta} \; ; \; R_{C1} = \frac{V_{CC} - V_{C1}}{I_{C1} + I_{B2}} \; ; \; R_{E2} = \frac{V_{E2}}{I_{B2} * (\beta)} \; ; \; r_{\pi 2} = \frac{V_T}{I_{B2}}$$

$$\text{solver} \rightarrow \quad R_{E2} = \boxed{750\Omega} \; ; \; R_{C1} = \boxed{9.1\text{k}\Omega} \; ; \; R_{\pi 2} = 330\Omega \; ; \; I_{B2} = 75.7uA = \frac{I_{E2}}{\beta}$$

Now to find our capacitance. C_{C1} and C_{C2} will see similar resistance $\approx 50\Omega$ so will have a similar frequency. We will design C_B to be as small as possible without changing the low cut frequency of 1000Hz; adjusting the frequency by a factor of ten.

$$\omega_{3DBL} = 1000 * 2 * \pi \approx \sqrt{(\frac{1}{50\Omega * C_{C1}})^2 + (\frac{1}{50\Omega * C_{C2}})^2} \; C_{C1} = C_{C2} = \boxed{4.70\text{uF}} \; \omega_{C1} = \omega_{C2} = 4444/s$$

$$\omega_{C_B} = \frac{1}{(R_{B1}||R_{B2}||(r_{pi1} + R_{E1} * (1+\beta))) * C_B} = \frac{1}{90.83k\Omega * C_B} << 4444/s \quad \rightarrow \quad C_B \approx \boxed{0.027\text{uF}}$$

Final calculated values:

R_{E1}	R_{C1}	R_{B1}	R_{B2}	R_{E2}	C_{C1}	C_B	C_{C2}
10kΩ	9.1kΩ	240kΩ	160kΩ	750Ω	4.70uF	0.027uF	4.70uF

Table 3.1: Calculated Capacitance/Resistance

3.b "Wiring Up" the Design

Wiring up the design we test that the calculated values meet our impedance requirements.

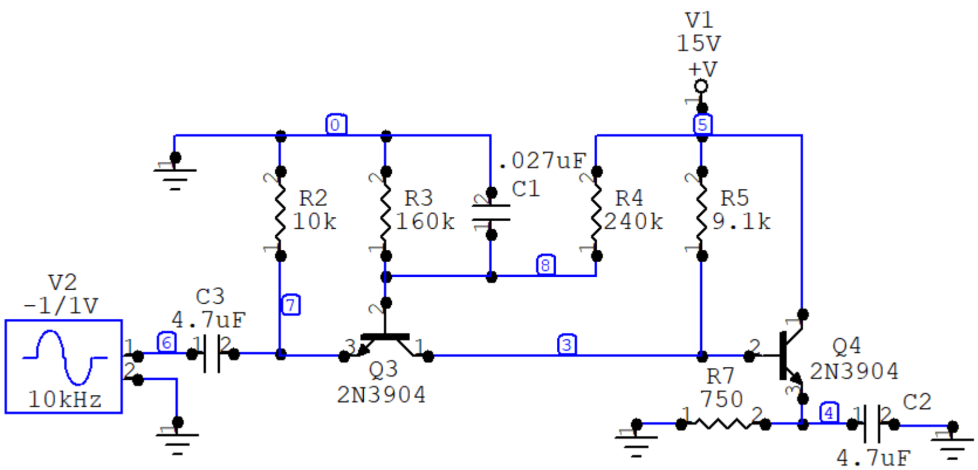

Figure 3.2: Cascaded Amplifier Imported into CircuitMaker

$$R_o = \frac{V_{Rms}}{I_{Rms}} = \frac{635.20uV}{15.07uA} = 42.15\Omega \qquad R_{in} = \frac{V_{Rms}}{I_{Rms}} = \frac{698.30uV}{12.88uA} = 54.20\Omega$$

The requirements are that R_O and R_{in} are $50 \pm 5\Omega$. R_O does not meet the current requirements and so we increase to R_{E2} to $1k\Omega$ and retest.

$$R_o = \frac{V_{Rms}}{I_{Rms}} = \frac{672.10uV}{14.59uA} = 46.07\Omega \qquad R_{in} = \frac{V_{Rms}}{I_{Rms}} = \frac{698.30uV}{12.88uA} = 54.20\Omega$$

Input and output impedances pass. Final simulated values:

R_{E1}	R_{C1}	R_{B1}	R_{B2}	R_{E2}	C_{C1}	C_B	C_{C2}
10kΩ	9.1kΩ	240kΩ	160kΩ	1kΩ	4.70uF	0.027uF	4.70uF

Table 3.2: Simulated Capacitance/Resistance

Midband gain: $A_M = \frac{V_o}{V_{in}} = \frac{103mV}{1mV} = \boxed{103v/v}$

3.c Low/High Frequency Cut-in/off

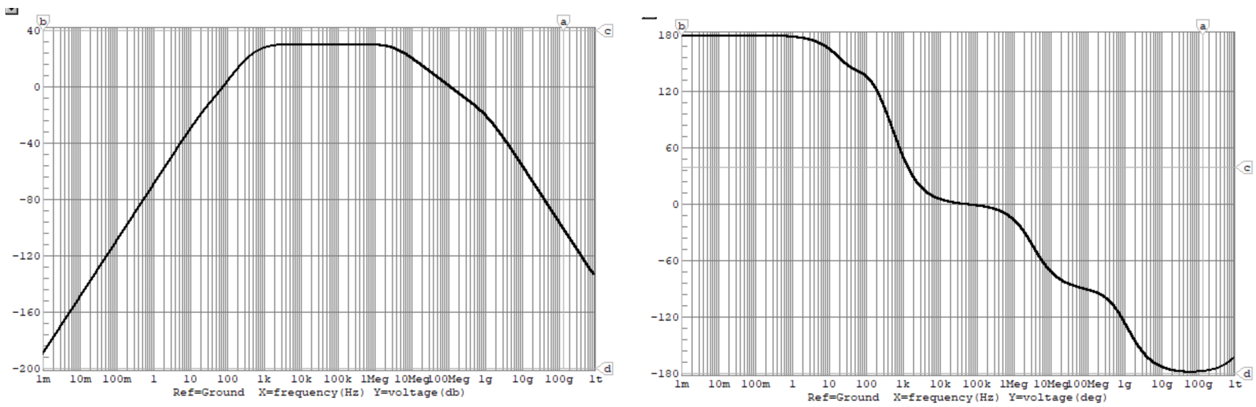

Figure 3.3: Bode Magnitude (left) and Phase Plot (right) for our Cascaded Amplifier

$$\omega_{3DBL} = 788Hz \qquad \omega_{3DBH} = 3.86MHz$$

3.d Discussion

Using Figure 3.1 and $V_{CC} = 15$V we were able to use the 1/3 rule to deduce the resistance and capacitance. To adhere to our impedance requirements we tested the circuit and added resistance. Once all requirements and values have been found we can check the Bode response and midband gain that the circuit provides.

4 Part III: CMRR Of a Differential Amplifier

Now we will analyze the CMRR Of two cascaded differential amplifiers with current mirrors.

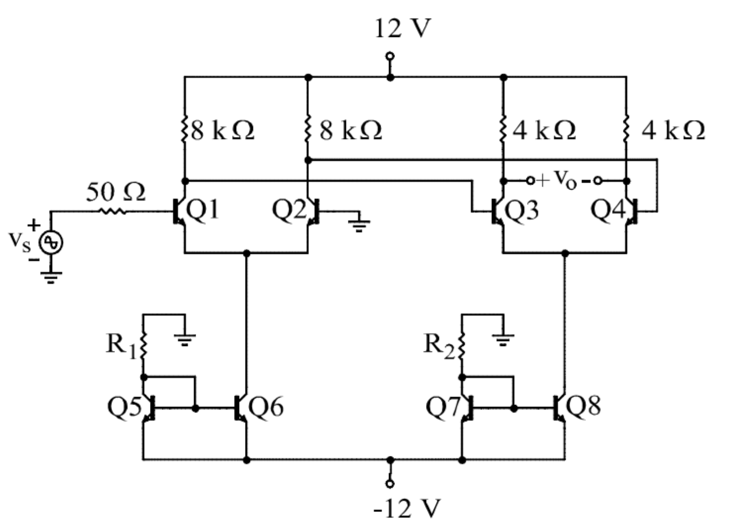

Figure 4.1 Differential Amplifier and Current Mirror Pair

4.a Applying a Differential Signal to the Differential Amplifier

The differential amplifier has two inputs and one or two outputs depending on the configuration. You can choose between using the difference in outputs $V_{O+} - V_{O-}$ or just one of the outputs V_{O+}/V_{O-} to amplifies small signals. Below we have applied a differential signal to the differential amplifier and simulated the magnitude Bode plot at one of the outputs.

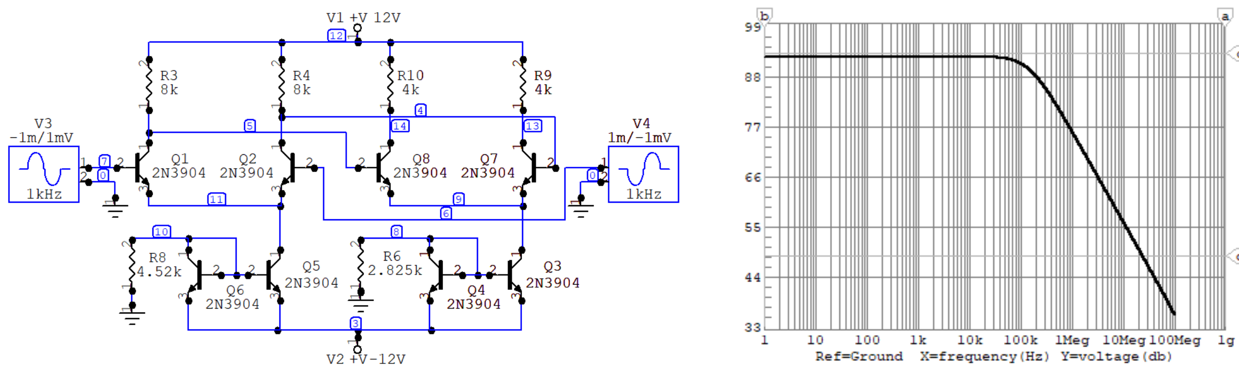

Figure 4.2: Bode Magnitude (right) and circuit (left) for our Cascaded Amplifier

$$\text{Midband gain @ 1mV, 1kHz: } A_M = \frac{V_o}{V_{in}} = \frac{6.079V}{1mV} = \boxed{6{,}079\text{v/v}}$$

4.b Circuit Impedance

Input impedance:

$$R_{in} = \frac{V_{Rms}}{I_{Rms}} = \frac{704.10uV}{248.5nA} = 2.833k\Omega$$

Output impedance:

$$\text{Single Output: } R_o = R_C = 4k\Omega \qquad \text{Dual Output: } R_o = 2 * R_C = 8k\Omega$$

4.c Adjusting Resistance

Increasing one of $8k\Omega$ collector resistances by 0.1% and decreasing the other by 0.1% and applying common mode small signal input. Below is the CMRR of the single output cascaded differential amplifier:

$$A_D = \frac{V_o}{V_{in}} = \frac{6.079V}{1mV} = \boxed{6{,}079\text{v/v}}$$
$$A_{CM} = \frac{V_o}{V_{in}} = \frac{7.680uV}{1mV} = \boxed{0.00768\text{v/v}}$$
$$\text{CMRR} = \frac{A_D}{A_{CM}} = \frac{6{,}079v/v}{0.00768v/v} = \boxed{791{,}536} = 20log(791,536)dB = \boxed{118\text{dB}}$$

Bode plots for the differential amplifier with one output and two outputs:

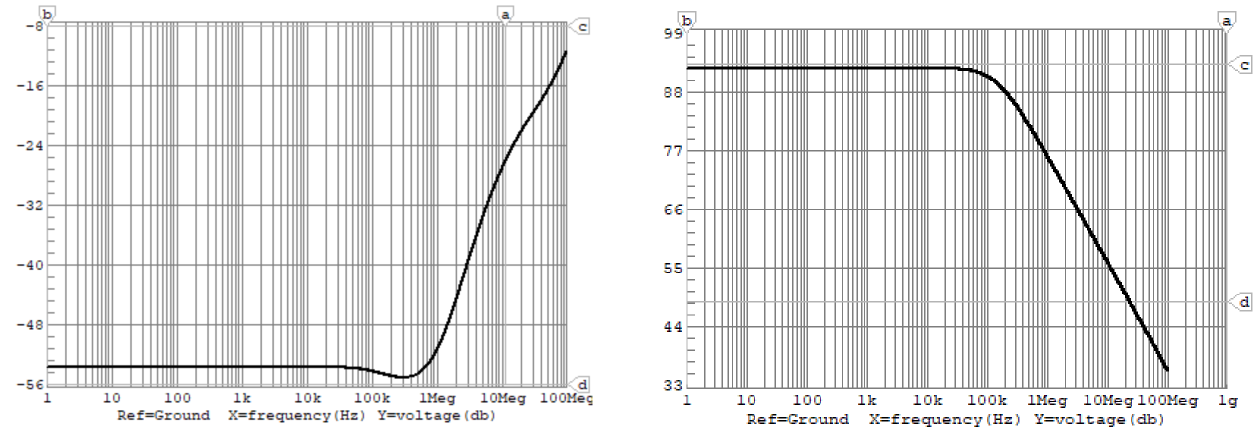

Figure 4.3: Single Output Bode Magnitude (right) and Dual Output Bode Magnitude (left)

4.d Comparing our Result

A CMRR of 118dB is very close to the 122dB CMRR of Figure 1 in Problem Set 6. This shows that our measured values are very close to the calculated values.

4.e Adjusting Resistance Round V2

Keeping the modified $8k\Omega$ collector resistances as well as increasing one of the $4k\Omega$ collector resistances by 0.1% and decreasing the other by 0.1% and applying common mode small signal input. Below is the CMRR of the single output cascaded differential amplifier:

$$A_D = \frac{V_o}{V_{in}} = \frac{6.079V}{1mV} = \boxed{6{,}079\text{v/v}}$$
$$A_{CM} = \frac{V_o}{V_{in}} = \frac{7.688uV}{1mV} = \boxed{0.007688\text{v/v}}$$
$$\text{CMRR} = \frac{A_D}{A_{CM}} = \frac{6{,}079v/v}{0.007688v/v} = \boxed{790{,}712} = 20log(790,712)dB = \boxed{118\text{dB}}$$

Bode plots for the differential amplifier with one output and two outputs:

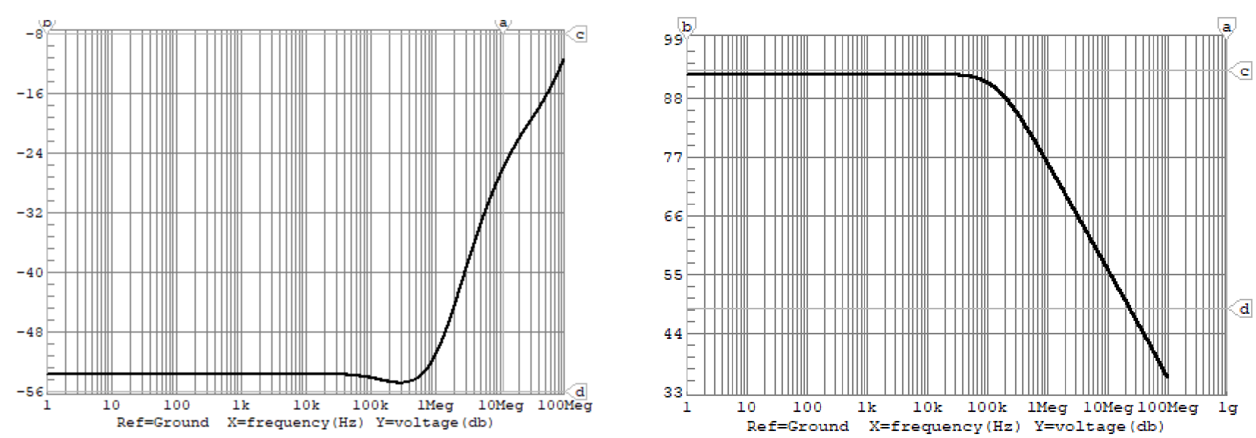

Figure 4.4: Bode Magnitude (right) and circuit (left) for our Cascaded Amplifier

4.f Comparing our CMRR

We see that small resistance changes in the circuit have a negligible impact on the CMRR. This is critial information to know so that we can pick our resistances with an informed tolerance to variability.

4.g Discussion

Concluding, we see that with differential gain and common mode gain we are able to calculate the common mode rejection ration (CMRR). We see that CMRR is fairly resilient and not impacted heavily by resistance changes at the collector.

5 Part IV: The AM Modulator

Below we have the AM Modulator with an input of 50mVp at 1kHz.

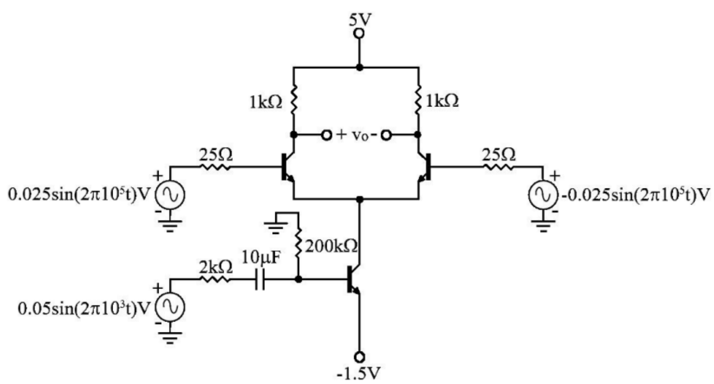

Figure 5.1: AM Modulator

5.a Differential Output

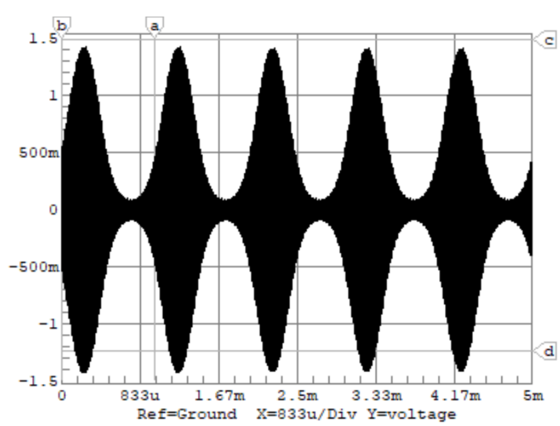

Figure 5.2: Differential Output

5.b Varying Input

We will now vary the input of the modulator between 10mVp and 100mVp in 20mVp steps starting with 10mVp:

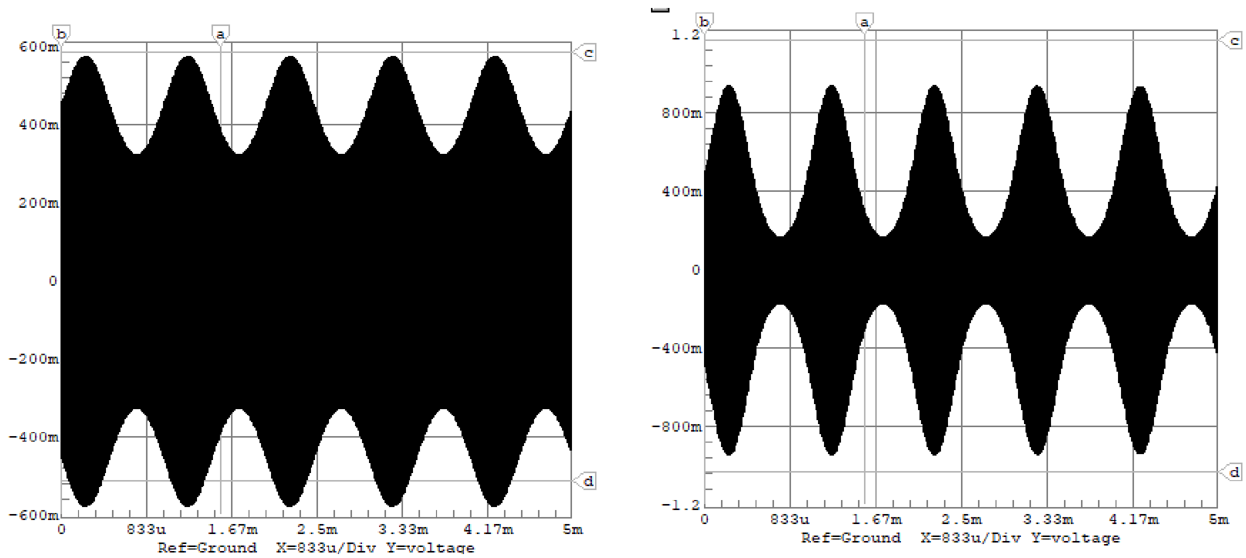

Figure 5.3: 10mVp (left) 30mVp (right)

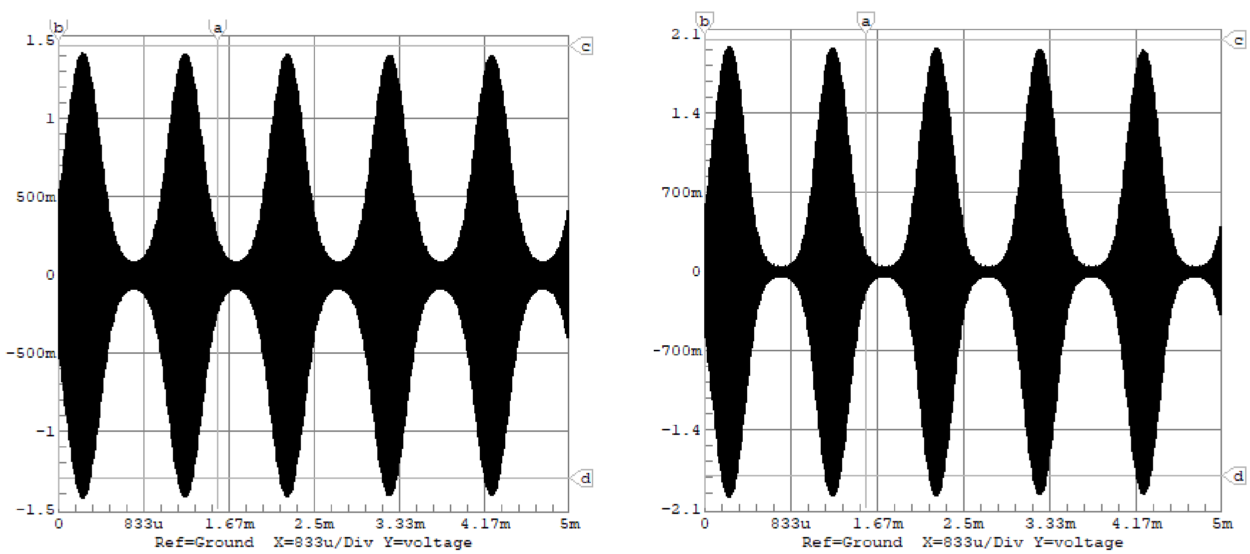

Figure 5.4: 50mVp (left) 70mVp (right)

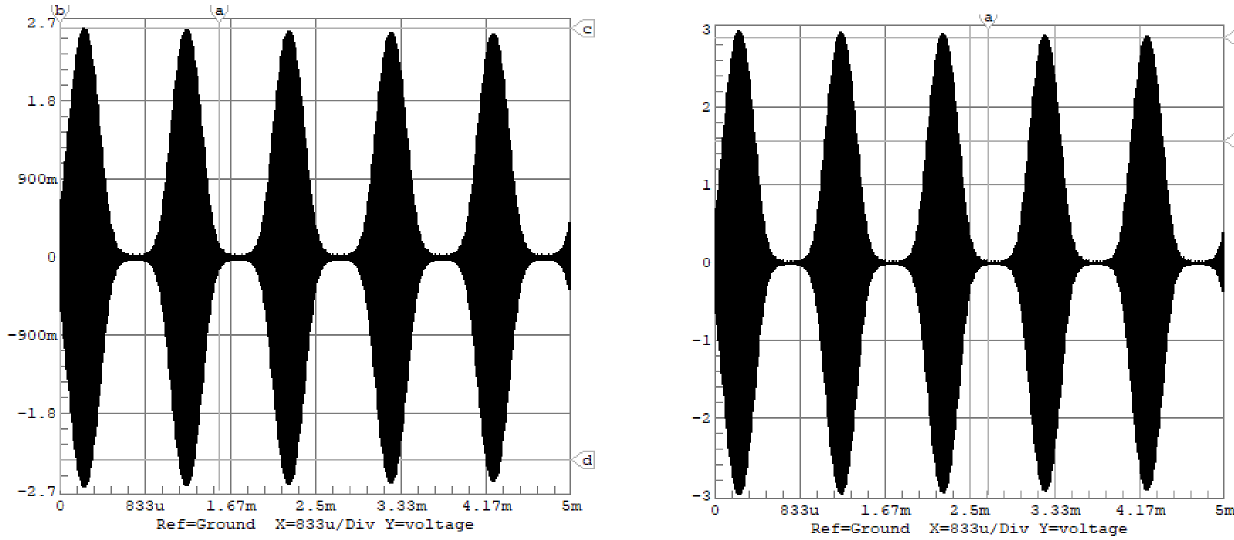

Figure 5.5: 90mVp (left) 100mVp (right)

None of the input signals within the range of 10mVp-100mVp are distorted, however, as you increase the mVp input into the modulator you increase the distortion. As shown in Figure 5.6, you need to reach around 150mVp to find any sort of distortion.

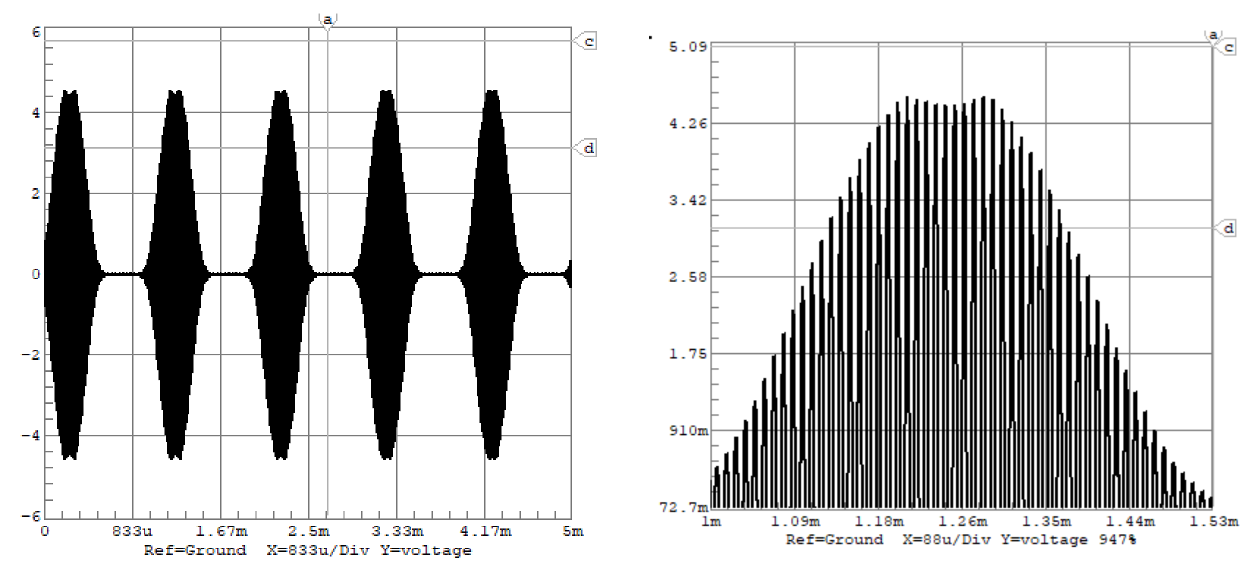

Figure 5.6: 150mVp response (left) close up (right)

5.c Varying Input with Square Waves

We will do the same process as 5.b with square input waves and record the response

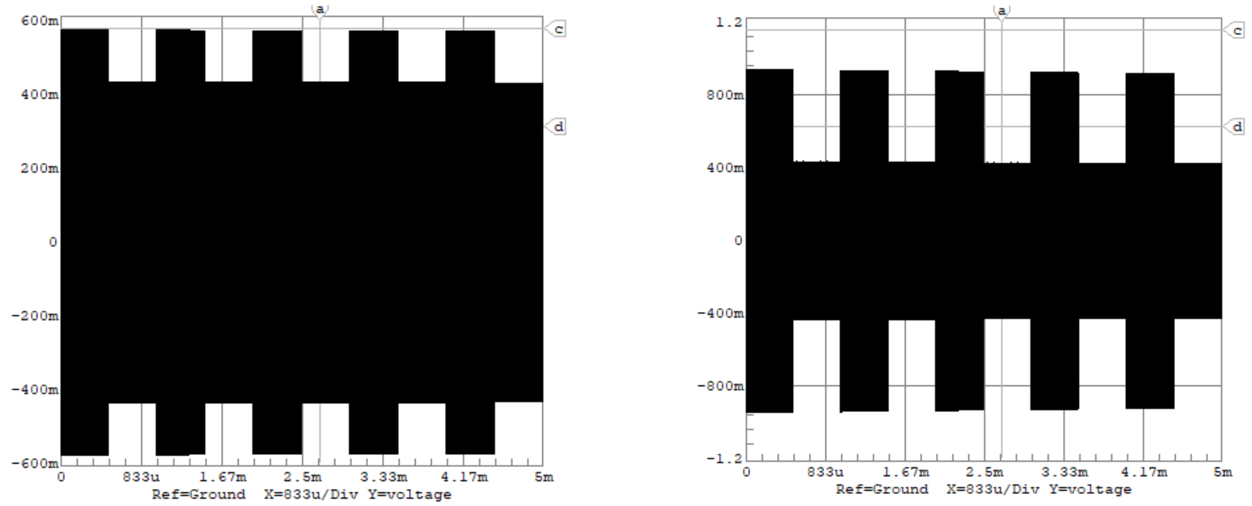

Figure 5.7: 10mVp (left) 30mVp (right)

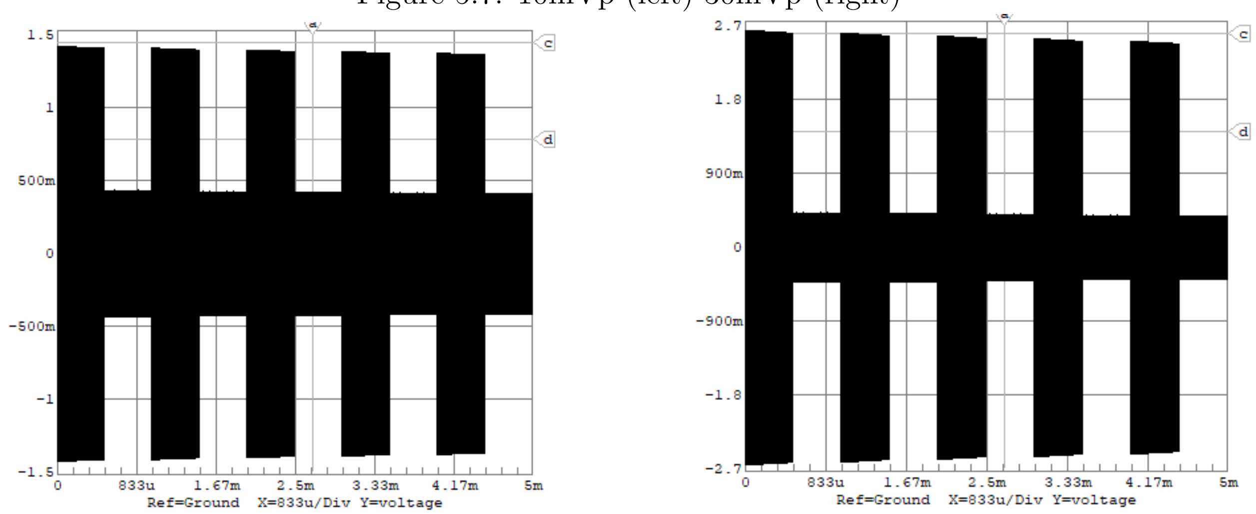

Figure 5.8: 50mVp (left) 90mVp (right)

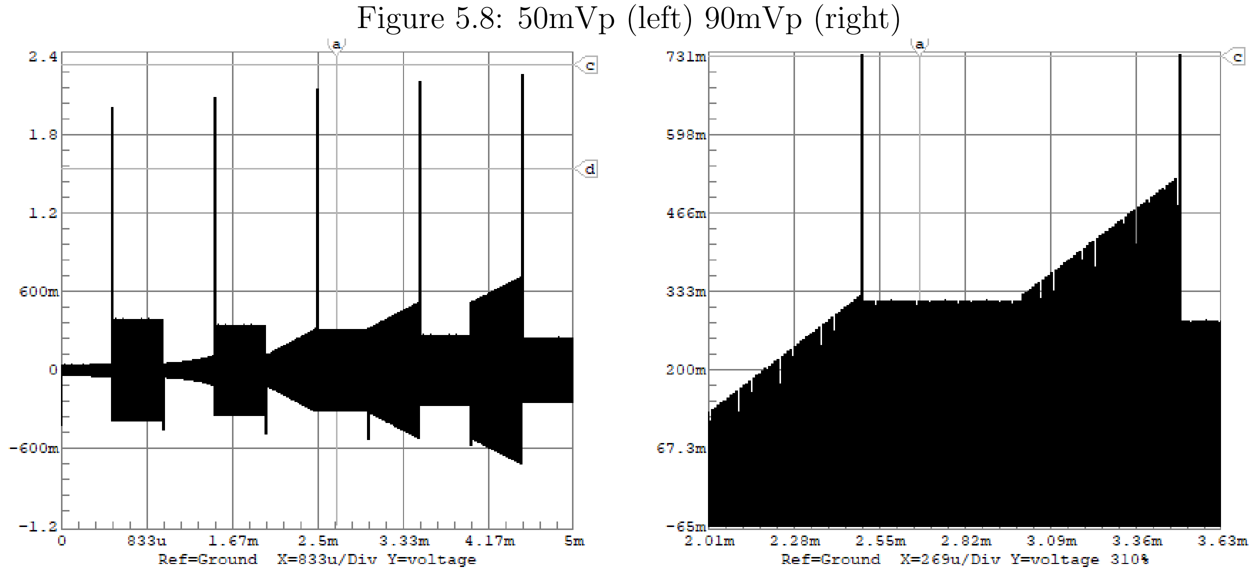

Figure 5.9: 250mVp distortion response

We see that when we approach 250mV with the square wave we begin to get distortion

5.d Discussion

AM Modulation, usually referred to as just as AM, is a radio transmission format. The AM Modulation circuit is controlled by the base AC input of the differential amplifier and the input into the emitter of the differential amplifier. The modulating signal is taken in from the emitter and provides the group velocity, the carrier wave is input into the base and provides the phase velocity. The benefit of AM Modulation is that you can transmit information long distances with relatively low power. It's also used because it was invented like a zillion years ago and uses like 3 components.

6 Conclusion

After analyzing different methods and measuring/simulating the behaviour of multiple transistors we can see that our estimation methods such as the 1/3 rule and the small-signal model approximations work very well and can be used to attain accurate results. We also explored and learned how to calculate the differential gain as well as the common mode gain and use those to find the CMRR. Furthermore we analyzed how different input voltages into an AM Modulator influence the response.

References

[1] https://www.mouser.ca/datasheet/2/389/CD00003223 − 491114.pdf

[2] https://www.youtube.com/watch?v = OrsAtjiChLkab$_c$hannel = SalimKoteish

[3] https://www.youtube.com/watch?v = F$_9$7vyRhyl8ab$_c$hannel = SimulateElectronics

[4] https://www.youtube.com/watch?v = y2eenHbFiF8ab$_c$hannel = APDahlen

[5] https://www.cxi1.co.uk/ltspice/dccircuits.htm

[6] https://www.youtube.com/watch?v=tSJC-JFSRP0ab$_c$hannel = MateoAboy