MINI PROJECT 3

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ELEC 301

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Introduction

This mini-project involves conducting experiments with multi-transistor amplifiers, specifically focusing on the Cascode amplifier, cascaded amplifier, and differential amplifier. To simulate circuits and models, we will be utilizing *CircuitMaker* software, while Excel will be used for other forms of analysis.

Project Problems:

Part 1: The Cascode Amplifier.

Table 3.1 Cascode Amplifier Specifications.

$\mathbf{R_{out}}$ (value at mid band)	$\mathbf{R_{in}}$ (minimum value at mid band[1])	$\lvert\mathbf{A_v}\rvert$ (minimum value at mid band)	$\mathbf{f_L}$ (maximum value for low-f cut-in)
2.5 kΩ ± 250Ω	5 kΩ	50	500 Hz

Calculations:

Using ¼ Rule

$I_1 = 0.1 I_E$

$V_{E1} = \frac{V_{CC}}{4} = 5\ V$

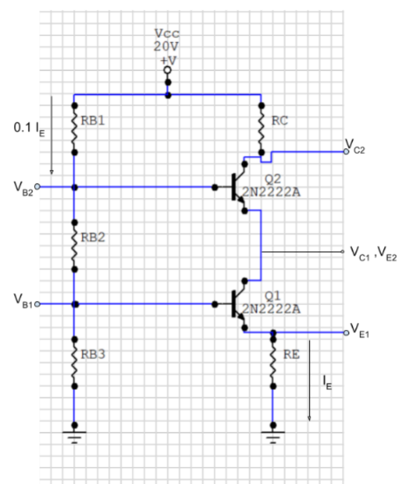
$V_{C1} = V_{E2} = \frac{V_{CC}}{2} = 10\ V$

$V_{C2} = \frac{3}{4} V_{CC} = 15\ V$

$V_{B1} = V_{E1} + 0.7 = 5.7\ V$

$V_{B2} = V_{E2} + 0.7 = 10.7\ V$

$\beta = 167$ (From Mini Project 2)



Circuit 1: 1/4 rule for biasing Cascode Amplifier

To design the Cascode to meet the above specifications, max values of R_{out} = 2.750 kΩ.

Since $R_c = R_{out}$ and the nearest standard resistor is 2.7kΩ, therefore

$I_{C2} = \frac{20-15}{2700} = 1.852\ mA$

$I_{B2} = \frac{I_{C2}}{\beta} = 11.089\ \mu A$

$I_{E2} = I_{C1} = I_{C2} + I_{B2} = 1.863\ mA$

$I_{B1} = \frac{I_{C1}}{\beta} = 11.553\ \mu A$

$I_{E1} = 1.874\ mA$

Hence,

$I_1 = 0.1\, I_{E1} = 0.187\, mA$

$I_2 = I_1 - I_{B2} = 0.176\, mA$

$I_3 = 0.165\, mA$

Therefore, the values of remaining resistors are:

$R_E = \frac{5V}{1.874\, mA} = 2.668\, k\Omega$

$R_{B1} = \frac{20\,V - 10.7\,V}{0.187\, mA} = 49.733\, k\Omega$

$R_{B2} = \frac{10.7\,V - 5.7\,V}{0.176\, mA} = 28.409\, k\Omega$

$R_{B3} = \frac{5.7\,V}{0.165\, mA} = 34.545\, k\Omega$

For Capacitor values, C_E will see the least resistance because of emitter de-magnification effect, thus to determine the values of C_E and to meet the specifications required,

$$f_{Lp3} = \frac{1}{C_E.\,(R_E || \frac{r_{\pi 1} + R_{B23}||(R_s + R_{in})}{\beta + 1})} = 500Hz$$

C_E will determine the dominant pole value with location at 500 Hz and to ensure it, we set

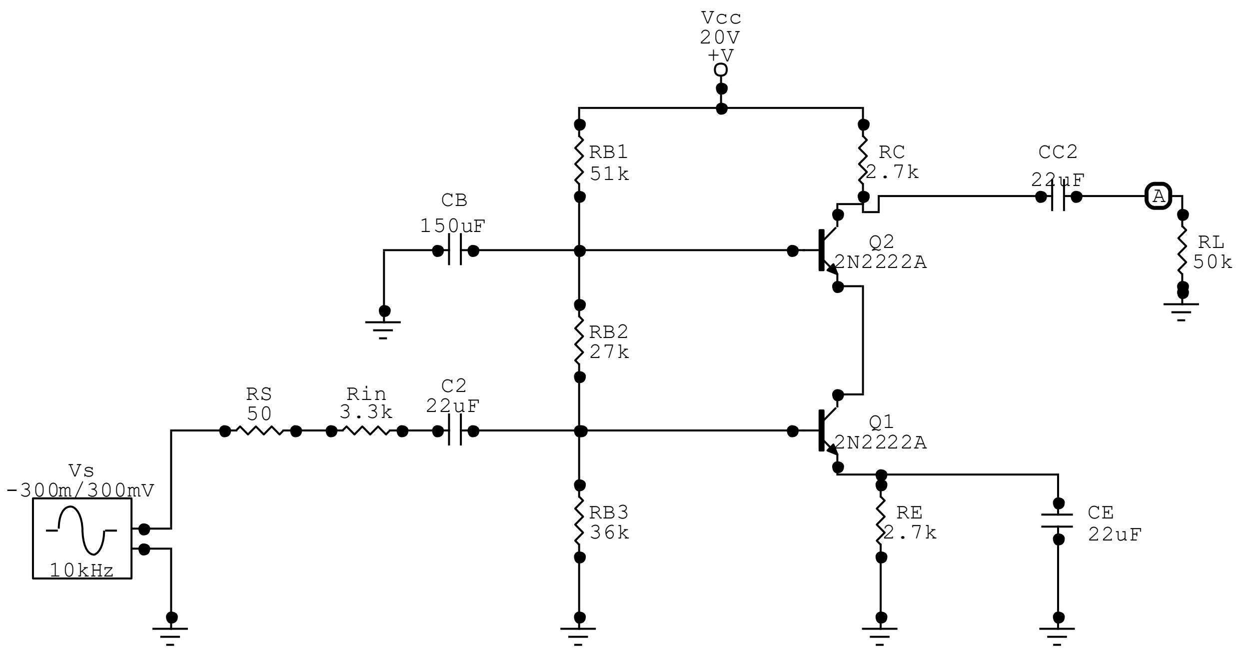
$C_E = C_{C1} = C_{C2}$

$r_{\pi 1} = \frac{\beta V_T}{I_{C1}} = 2.241\, k\Omega$

Hence,

$$C_E = \frac{1}{2\pi * 500 * 28.827\, \Omega} = 11.042\ \mu F$$

After changing values to Standard Resistors and Capacitors,



Circuit 2:Biased Cascode Amplifier with standard values

A. DC Operating Points

Using *CircuitMaker*,

	V_C	V_B	V_E	I_C	I_B	I_E
Q_1	9.949 V	5.869 V	5.250 V	1.949 mA	11.08 µA	1.960 mA
Q_2	14.81 V	10.57 V	9.949 V	1.939 mA	11.01 µA	1.950 mA

B. Comparison of ω_{L3dB} and ω_{H3dB}

i. Calculated Frequencies

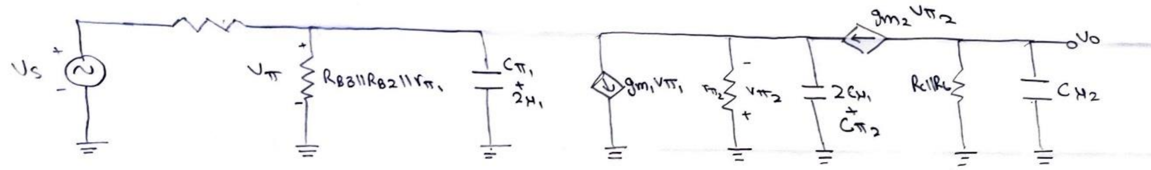
$$\omega_{LpC_E} = \frac{1}{22\mu F \times \left(R_E || \frac{r_{\pi 1} + R_{B23} || (R_S + R_{in})}{\beta + 1}\right)} = 1.577\ krad/s$$

$$\omega_{LpC_{C1}} = \frac{1}{22\mu F \times \ (R_S + R_{BB} || (r_{\pi 1} + (1+\beta) R_E)} = 2.023\ rad/s$$

$$\omega_{LpC_{C2}} = \frac{1}{22\mu F \times \ (R_L + R_C)} = 0.575\ rad/s$$

$$\omega_{zC_E} = \frac{1}{22\mu F \times \ (R_E)} = 11.2233\ rad/s$$

$$\omega_{L3dB} = \sqrt{\omega_{LpC_E}^2 + \omega_{LpC_{C1}}^2 + \omega_{LpC_{C2}}^2 - 2\omega_{zC_E}^2} = 1.577 \frac{krad}{s} = 250.95\ Hz$$



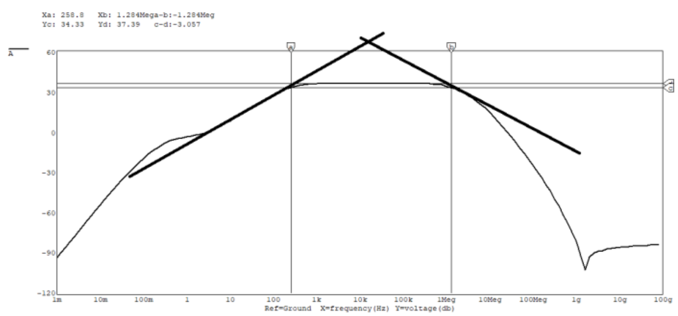
Circuit 3:Cascode high frequency small signal model

$$\omega_{HP1} = \frac{1}{((R_S + R_{in})||R_{B3}||R_{B2}||r_{\pi1})(C_{\pi1} + 2C_{\mu1})} = 1.21MHz$$

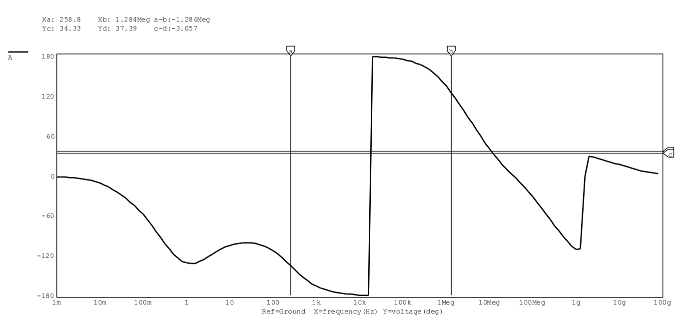
$$\omega_{HP2} = \frac{1}{(\frac{r_{\pi2}}{1+\beta})(C_{\pi2} + 2C_{\mu1})} = 117.08\ MHz$$

$$\omega_{HP3} = \frac{1}{(R_C||R_L)(C_{\mu2})} = 7.63\ MHz$$

$$\omega_{H3dB} = \frac{1}{\sqrt{\tau_{HP1}^2 + \tau_{HP2}^2 + \tau_{HP2}^2}} = 1.3\ MHz$$



Plot 1: Amplitude Bode plot for Cascode amplifier.

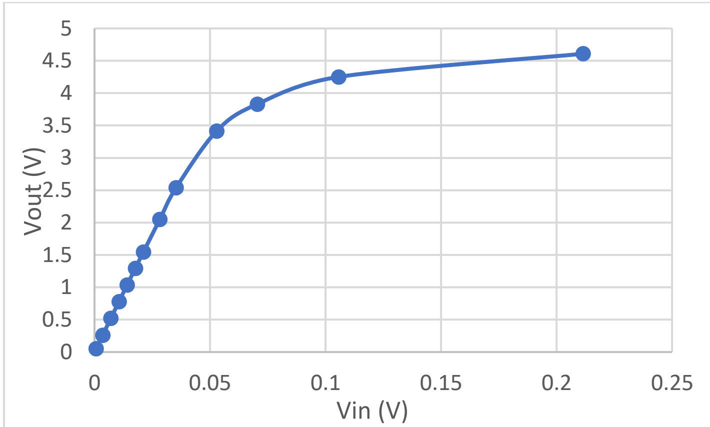


Plot 2: Phase Bode plot for cascode Amplifier.

	$\boldsymbol{\omega_{L3dB}}$	$\boldsymbol{\omega_{H3dB}}$
Calculated	250 Hz	1.3 MHz
Estimated	249 Hz	1.355 MHz

C. **Amplitude Response**

Using Bode plot, at 10kHz, Amplitude Response plot is estimated.



Plot 3: Amplitude Response at 10kHz for Cascode amplifier

D. **Input Impedance**

Calculated:

$$R_{in} = R_{in} + R_{B2}\left|\left|R_{B3}\right|\right|r_{\pi} = \ 5.181\ k\Omega$$

Measured (Using *CircuitMaker*):

$$R_{in} = \frac{V_{Test}}{I_{Test}} = \frac{25mV}{4.267\mu A} = 5.8\ k\Omega$$

Part 2: Cascaded Amplifiers — The Common-Base followed by the Common-Collector.

Design Specifications:

We need to build a common-collector (followed by a common-base) amplifier with an input impedance and output impedances of $50 \pm 5\ \Omega$. The 2N3904 NPN transistors are to be used in this project. Note that, from previous investigations, 2N3904 has β=164

A. **Cascaded Biasing**

$R_i = R_{E1}||\frac{r_{\pi1}}{\beta+1}$

$R_i \approx \frac{V_T}{I_{c1}}$

$I_{E1} = I_{C1} = \frac{0.025}{50} = 0.5\ mA$

Using 1/3 Rule

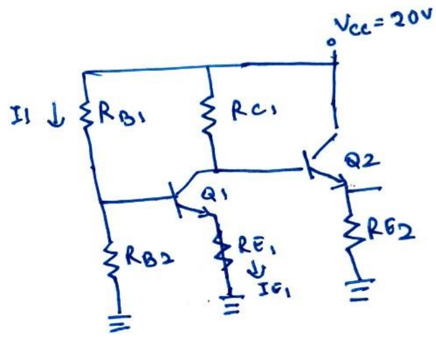
$V_{E1} = \frac{1}{3}V_{CC} = 4V$

$V_{B1} = 4.7V$

$V_{C1} = V_{B2} = \frac{2}{3}V_{CC} = 8V$

$V_{E2} = 7.3V$

$I_1 = 0.1I_E = 50\ \mu A$



Circuit 4: Cascaded Biasing using 1/3 rule

Therefore, the values of <u>Resistors</u> are,

$R_{E1} = \frac{4}{0.5\ mA} = 8\ k\Omega$

$R_{B1} = \frac{12-4.7}{50\ \mu A} = 146\ k\Omega$

$R_{B2} = \frac{4.7}{47\ \mu A} = 100\ k\Omega$

$R_{C1} = \frac{4}{I_{C1}+I_{B2}}$

$R_{E2} = \frac{7.3}{I_{E2}}$

Moreover, to get the specified $R_o = 50 \pm 5\Omega$ and the equivalent circuit,

$$R_o = \frac{R_{C1+r_{\pi2}}}{1+\beta}||R_{E2} = 50$$

$$R_o = \left(\frac{R_{C1}}{1+\beta} + \frac{R_{E2}V_T}{V_{E2}}\right)||R_{E2}$$

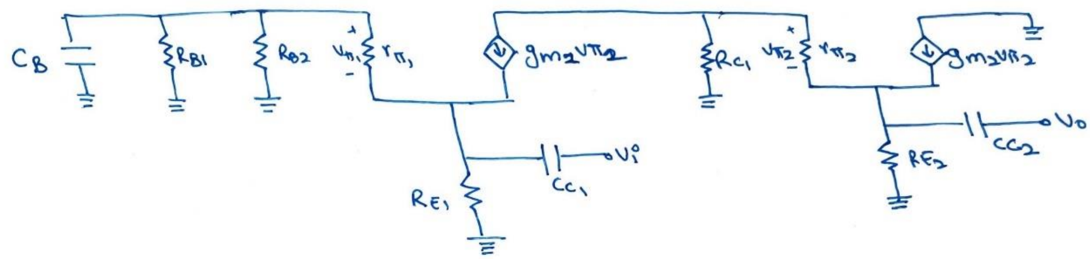
Solving for $R_{C1}, R_{E2}\ and\ I_{E2}$ yields,

$$R_{E2} = 1.59\ k\Omega\ ; I_{E2} = 4.6\ mA$$

$$R_{C1} = 7.62\ k\Omega$$

<u>Capacitance Values:</u>

We design the model such that $C_{C1}$and C_{C2} contribute equally for dominant poles and to do so, we set $C_{C1} = C_{C2} = C$.

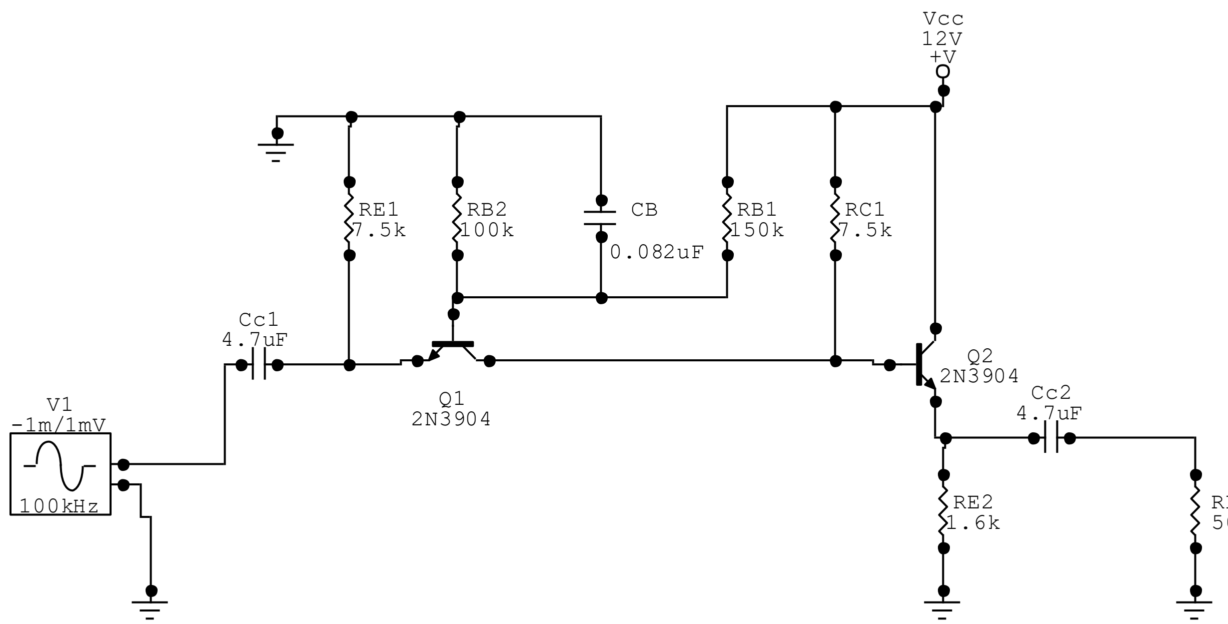


Circuit 5: small signal model for cascade amplifier

$$f_{L3dB} = \sqrt{2\left(\frac{1}{C \times \left(\frac{R_{C1} + r_{\pi2}}{1+\beta} \,||R_{E2}\right)}\right)^2}$$

$$C = 4.496\ \mu F$$

Changing the resistor and capacitors to standard values,



Circuit 6: Cascaded Amplifier

$C_B = 0.082\ \mu F$ was the lowest possible value to observe 1000Hz low frequency cut-in.

B. **Midband Gain**

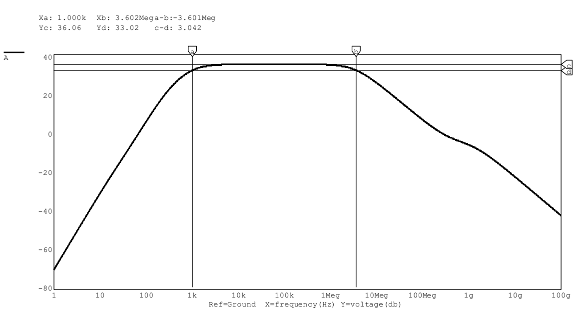
Using *CircuitMaker*, the observed R_i and R_o by setting the source at -1m/1mV at 100kHz,

$$R_i = \frac{1mV}{20\mu A} = 50\ \Omega$$
$$R_o = \frac{1mV}{19.46\ \mu A} = 50\ \Omega$$

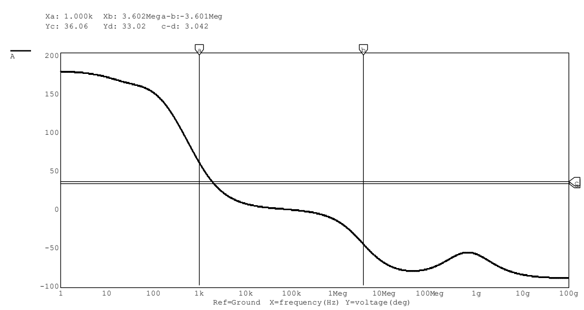
Both the input and output impedances are within the required ranges.

The midband voltage gain without load and source impedance attached,

$$|A_M| = 62.73\ V/V$$



Plot 5:Bode Plot for Cascaded Amplifier



Plot 4: Phase Bode plot for Cascaded Amplifier.

As observed from the bode plots,

$$\omega_{L3dB} = 1000\ Hz \qquad \omega_{H3dB} = 3.602\ MHz$$

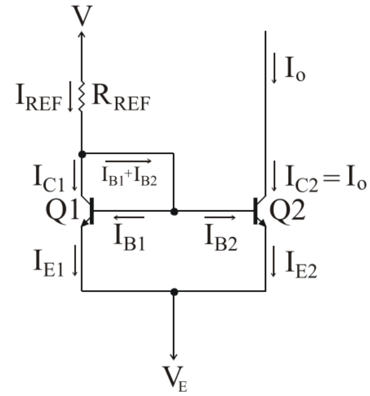
Part 3: The Differential Amplifier.

Using the methods taught in class,

$$I_{REF} = I_o\left(1+\frac{2}{\beta}\right) \approx I_o$$

$$I_{REF} = \frac{V-(V_{EE}+B_{BE})}{R_{REF}}$$

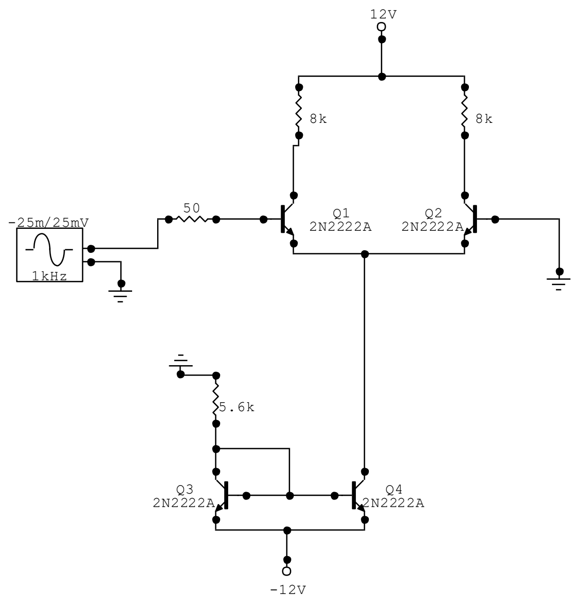
$$R_{REF} = \frac{0-(-12+0.7)}{I_{REF}} = \frac{11.3V}{2mA} = 5.650\ k\Omega$$



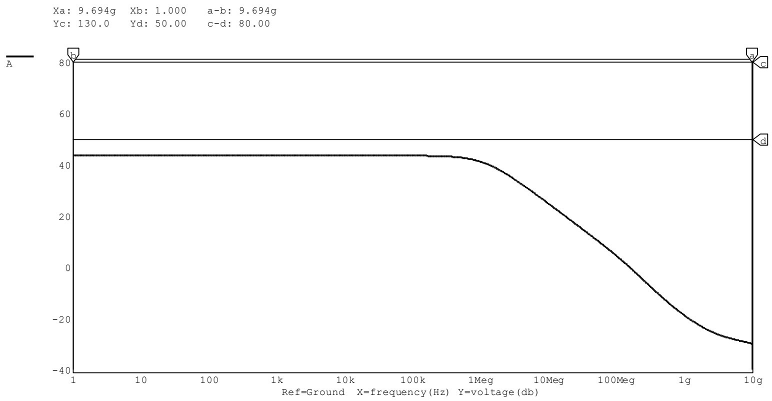
Circuit 7: The Current Mirror

A. **<u>Differential, small signal input</u>**

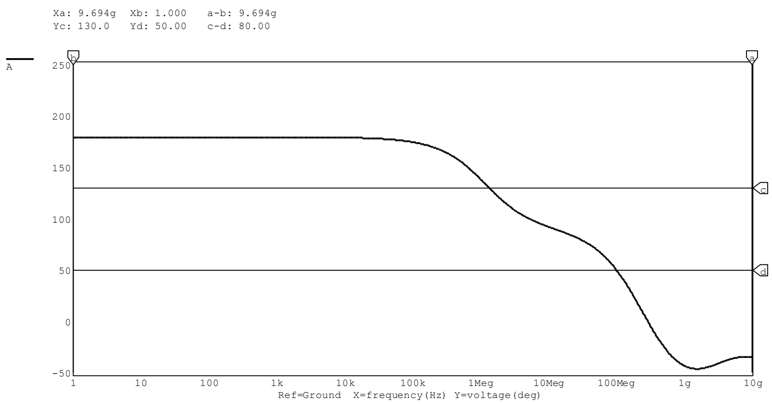
After "wiring up" the circuit and using standard resistor for $R_{REF} = 5.6\ k\Omega$



Circuit 8: Differential Amplifier



Plot 6: Amplitude Bode plot for differential amplifer

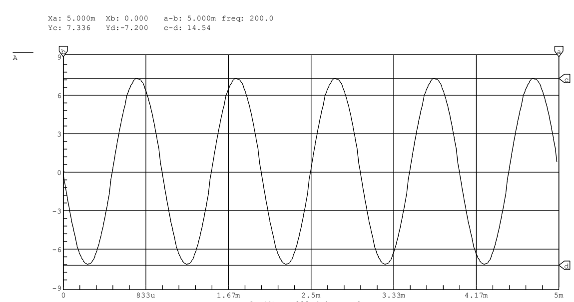


Plot 7: Phase Bode plot for differential amplifier

$$f_{H3dB} = 1.173\ MHz$$

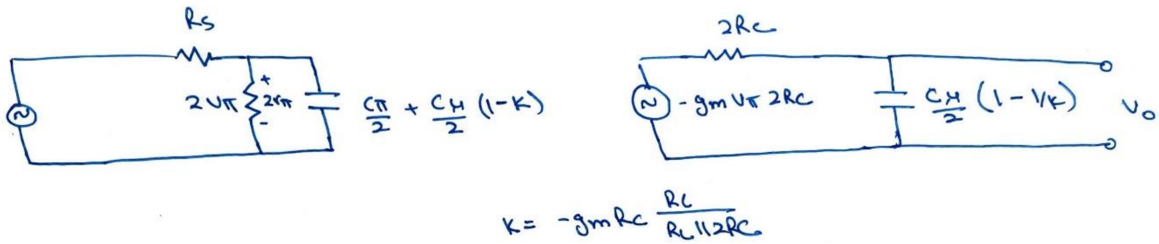
Using Transient Analysis and analyzing V_{PP}

$$|A_M| = 306.55\ V/V$$



Plot 8:Transient Analysis of Differential Amplifer

B. **Calculated Values**



Circuit 9: Differential amplifier small signal model

$r_\pi = 8.2\ k$

$g_m = 0.020\ s$

$C_\pi = 74.1\ pF$

$C_\mu = 8.27\ pF$

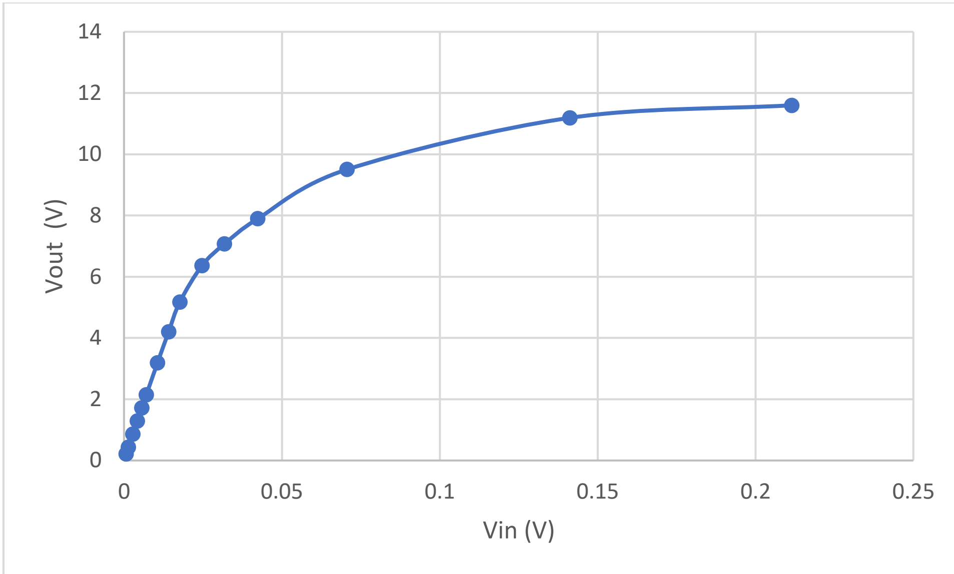
$$\omega_{HP1} = \frac{1}{\left[\frac{c_\pi}{2} + \frac{c_\mu}{2}(1-k)\right]2r_\pi \| R_S}$$

$f_{H3dB} = 1.1MHz$

$$\omega_{HP2} = \frac{1}{\frac{c_\mu}{2}\left(1-\frac{1}{k}\right) R_L \| 2R_C}$$

C. **Maximum input signal at Midband Frequency**

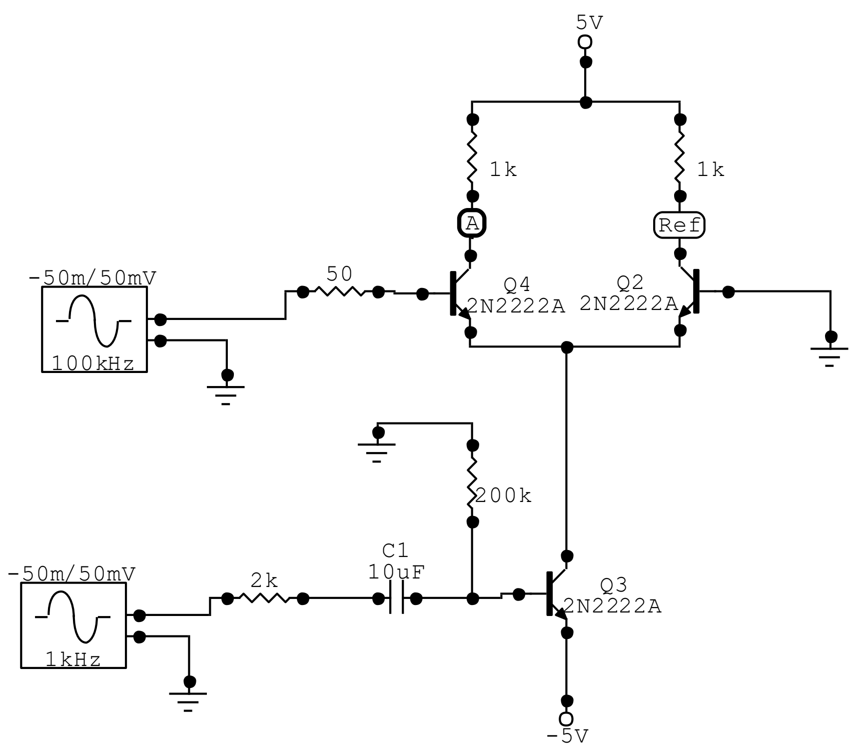
We picked 100kHz as "mid band" frequency and then after applying small differential signal to amplifier from -1mV/1mV to -300mV/300mV, it started becoming linear around $-25mV/25mV$



Plot 9: Amplitude Response at Midband Frequency for Differential Amplifier

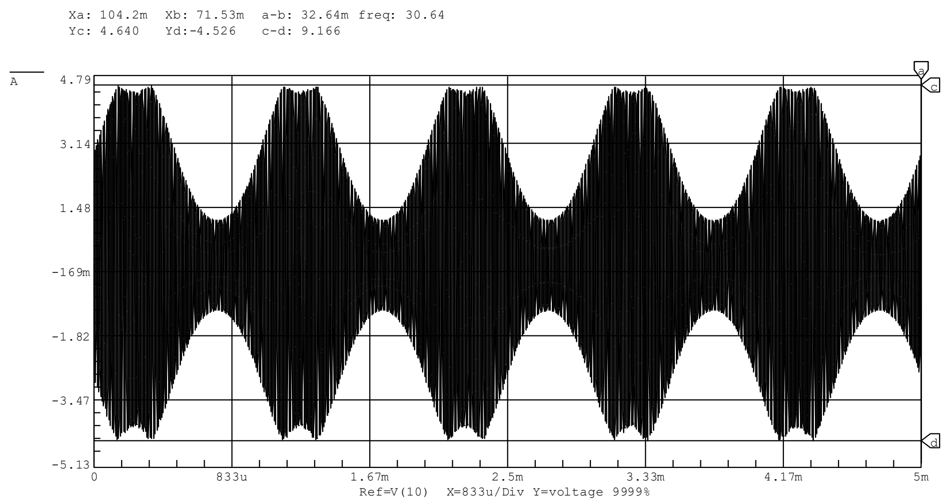
Part 4: AM Modular

A. **Modular Output**



Circuit 10:AM modulator

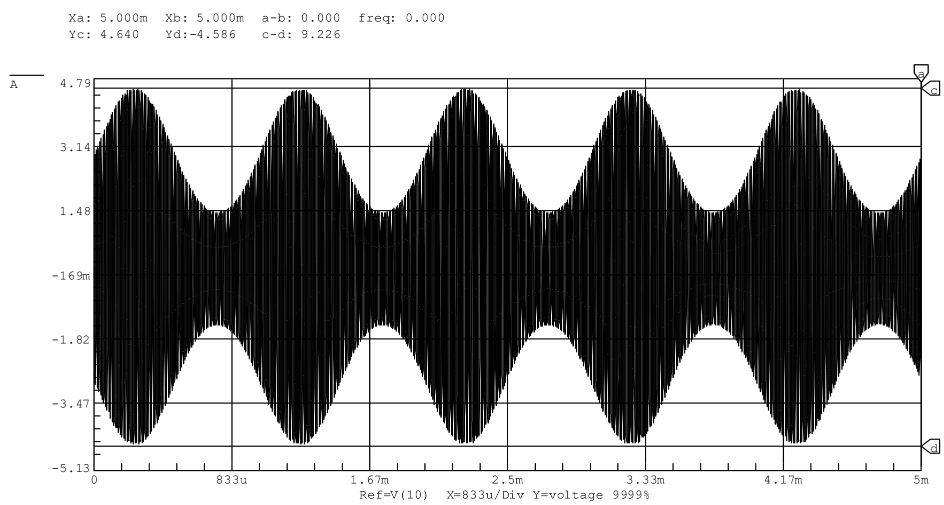
We observed the following plot when 50mV_P, 1kHz sine wave is applied to input of Modulator.



Plot 10: Transient Analysis for output of AM modulator.

B. <u>**Undistorted output signal**</u>

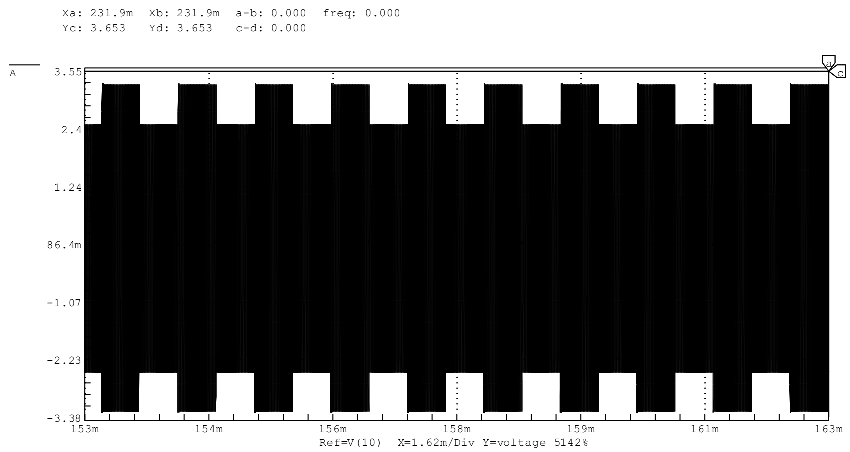
Varying the input signal from $10mV_P$ to $100mV_P$, the output signal started to get distorted shortly after $-40mV/40mV$ amplitude.



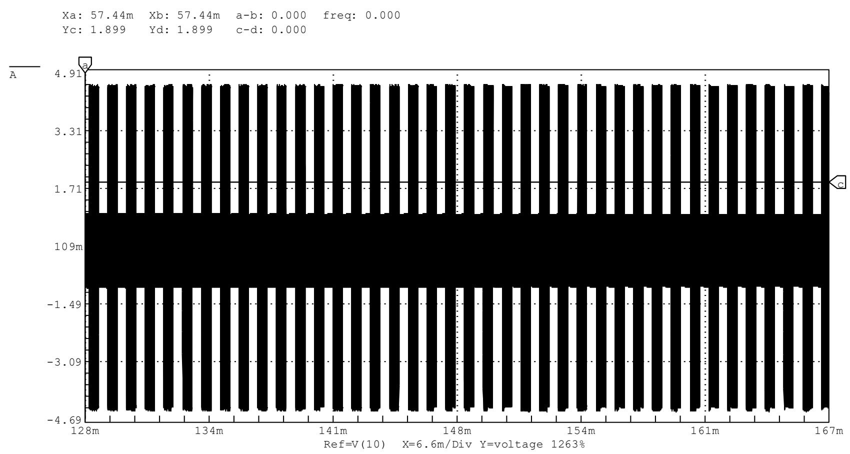
Even at $-45mV/45mV$ clipping of signal was noticed.

C. <u>Square Wave Signal</u>

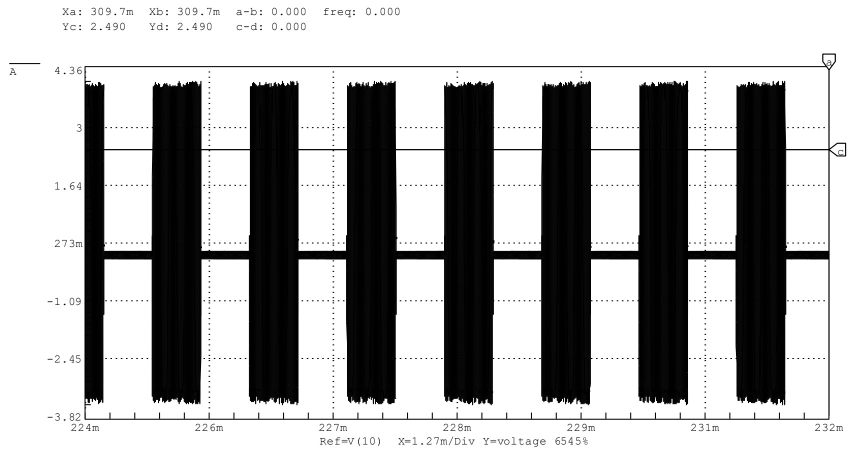
On increasing the input Amplitude of square wave from $10mV_P$ to $100mV_P$, the output signal started to get less distorted.



Plot 11: Square wave with -10mV/10mV amplitude



Plot 12: square wave with -50mV/50mV amplitude



Plot 13: Sqaure wave with -100mV/100mV amplitude

Conclusion

In this study, we investigated the construction and biasing of different types of amplifiers such as the Cascode, cascaded, and differential amplifiers. Our findings showed that the Cascode amplifier combines the benefits of both common-emitter and common-base amplifiers by having a large input impedance for a high gain, and also avoiding the Miller effect at high frequencies. We were able to apply the 1/4 rule to properly bias the circuit and make adjustments to meet specific requirements.

Moreover, we discovered the various applications of the cascaded amplifier, particularly as a signal repeater in transfer systems. We gained an understanding of the differential amplifier, its model, and the proper way to bias it. We also learned about modulation and how to implement it using the differential amplifier.

References

1.ELEC 301 Course Notes.

2. 2N2222A Datasheet https://www.st.com/resource/en/datasheet/cd00003223.pdf

3. 2N2222A Datasheet Plots https://web.mit.edu/6.101/www/reference/2N2222A.pdf

4. 2N3904 Datasheet https://www.onsemi.com/pdf/datasheet/2n3903-d.pdf

5. 2N4401 Datasheet https://www.onsemi.com/pdf/datasheet/2n4401-d.pdf

6. Mini Project 2

7. Mini Project 1

8. *CircuitMaker*