ELEC 301: Electronic Circuits

Mini Project 3: Multi-Transistor Amplifiers

Isabelle André

12521589

UNIVERSITY OF BRITISH COLUMBIA

Vancouver

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1. Introduction

This project report describes the characteristics of several multi-transistor amplifiers and circuits. More specifically, we explore amplifiers such as cascode amplifiers, cascaded amplifiers, differential amplifiers, and AM modulators with computer based circuit simulation tools. In Part 1, we obtain the small signal parameters for a cascode amplifier and analyze the circuit in an AC simulation. In Part 2, we obtain design values for cascaded amplifier resistors, measure the midband, and find the low and high frequency cut offs of the Bode plot. In Part 3, a differential amplifier is designed using a 2N3904 transistor, followed by an AC analysis of the circuit. Lastly, Part 4 outlines the modeling of an AM modulator and observing its output signal in various states.

2. Objective

The objective of this mini project is to strengthen our understanding of computer based circuit simulation tools in the context of designing and solving several multi-transistor amplifiers and circuits.

3. Project

3.1 Part 1: Cascode Amplifier

This section consists in designing the cascode with 2N2222A transistors, and meeting the specifications in Table 3.1.

R_{out}	R_{in}	$\lvert A_V \rvert$	f_L	V_{CC}	R_S	R_L	C_B
2.5 kΩ	5 kΩ	50	500 Hz	18 V	50 Ω	50 kΩ	150 µF

Table 3.1: Cascode amplifier Specifications

We first calculate the resistor values needed to bias the circuit using the ¼ Rule as shown in Figure 3.1. It is assumed that $V_{BE} = 0.7\,V$ and $\beta = 167$. For Voltages:

$V_{C2} = \frac{3}{4}V_{CC} = 13.5\,V$ $\quad V_{C1} = V_{E2} = \frac{1}{2}V_{CC} = 9\,V$ $\quad V_{E1} = \frac{1}{4}V_{CC} = 4.5\,V$

$V_{B2} = V_{E2} + V_{BE} = 9.7\,V$ $\quad V_{B1} = V_{E1} + V_{BE} = 5.2\,V$

As $R_{out} = R_C$ must be in range $2.5\,k\Omega \pm 250\,\Omega$, we set it at a standard resistor value $R_C = 2.4\,k\Omega$. For Currents:

$I_{C2} = \frac{V_{CC} - V_{C2}}{R_C} = 1.875\,mA$, $I_{B2} = \frac{I_{C2}}{\beta} = 11.227\,\mu A$, $I_{E2} = I_{C1} = I_{C2} + I_{B2} = 1.886\,mA$

$I_{B1} = \frac{I_{C1}}{\beta} = 11.295\,\mu A$, $I_{E1} = I_{B1} + I_{C1} = 1.897\,mA$

Using the ¼ Rule for Currents to find currents through R_B resistors:

$I_1 = 0.1 I_{E1} = 189.7\ \mu A$, $I_2 = I_1 - I_{B2} = 178.473\ \mu A$, $I_3 = I_2 - I_{B1} = 167.178\ \mu A$

Using the above calculated voltages and currents, the resistances can now be calculated and approximated to their nearest standard values, as shown in Table 3.2.

$R_E = \frac{V_{E1}}{I_{E1}} = 2.372\ k\Omega$, $R_{B1} = \frac{V_{CC}-V_{B2}}{I_1} = 43.753\ k\Omega$, $R_{B2} = \frac{V_{B2}-V_{B1}}{I_2} = 25.213\ k\Omega$,

$R_{B3} = \frac{V_{B1}}{I_3} = 31.104\ k\Omega$

R_E	R_{B1}	R_{B2}	R_{B3}
$2.4\ k\Omega$	$43\ k\Omega$	$24\ k\Omega$	$30\ k\Omega$

Table 3.2: Standard Resistor Values

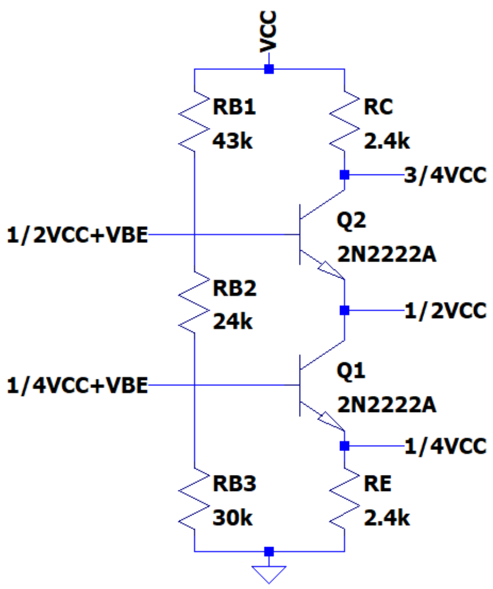


Figure 3.1: Cascode Biasing using ¼ Rule

Next, the small-signal parameters for the transistors can be solved:

$g_{m2} = \frac{I_{C2}}{V_T} = 0.075\ S$, $r_{\pi 2} = \frac{\beta}{g_{m2}} = 2.226\ k\Omega$, $g_{m1} = \frac{I_{C1}}{V_T} = 0.075\ S$,

$r_{\pi 1} = \frac{\beta}{g_{m1}} = 2.226\ k\Omega$

These small-signal parameters are used to create the low frequency model shown in Figure 3.2 to solve for the capacitances.

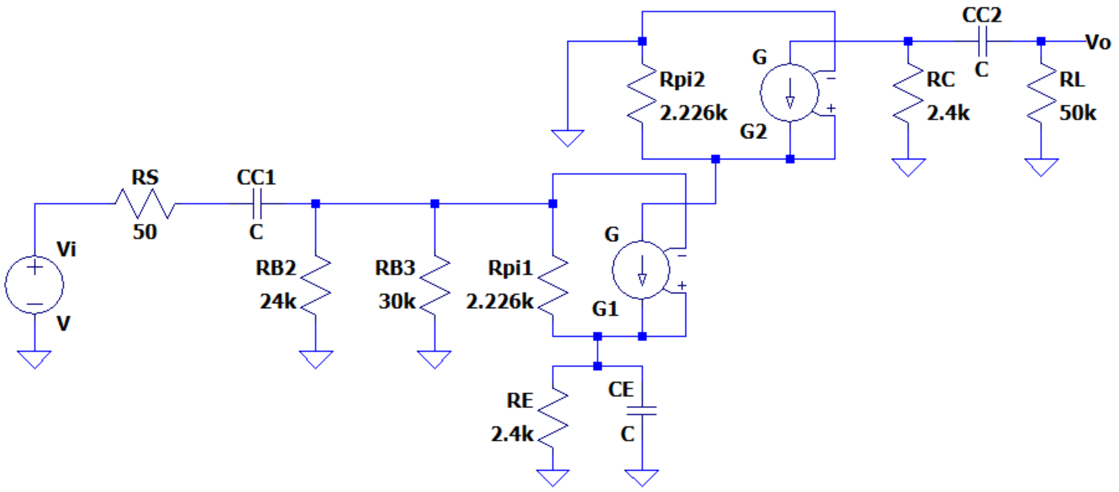


Figure 3.2: Cascode Low Frequency Small Signal Model

As C_{C1} will short first, we calculate C_{C1} with OCTC and C_E with SCTC:

$$\tau_{OC}^{CC1} = C_{C1}((R_S + (R_{B2}||R_{B3}||(r_{\pi1} + (1 + \beta)R_E))) = C_{C1}18.192k$$

$$\tau_{OC}^{CC2} = C_{C2}(R_C + R_L) = C_{C2}52.4k$$

$$\tau_{SC}^{CE} = C_E(\frac{1}{1+\beta}((R_S||R_{B2}||R_{B3}) + r_{\pi1})||R_E) = C_E34.39$$

At low frequencies, $\omega_{LP} = \frac{1}{34.39C_E}$ and $\omega_{LZ} = \frac{1}{R_E C_E}$, therefore we can calculate ω_{L3dB} and solve for C_E:

$$\omega_{L3dB} = 2\pi f_L = \sqrt{\omega_{LP}^2 - 2\omega_{LZ}^2} \quad C_E = 9.25\ \mu F$$

Therefore, using standard values: $C_E = C_{C1} = C_{C2} = 12\mu F$

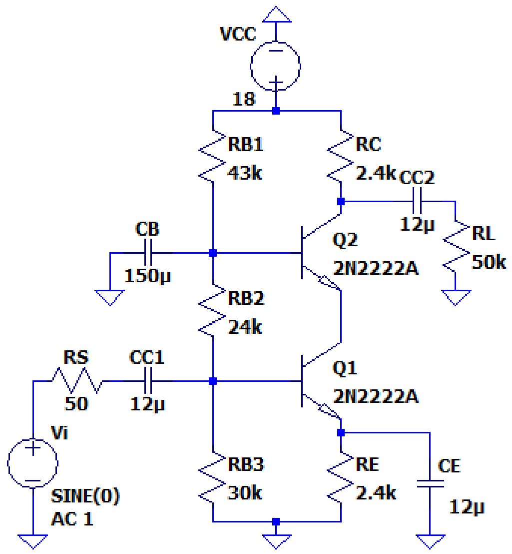


Figure 3.3: Biased Cascode Amplifier

A. DC Operating Point

The DC Operating Point is measured using the Biased Cascode Amplifier shown in Figure 3.3. The measured values are shown below in Table 3.3.

	VC	VB	VE	IC	IB	IE
Q1	9V	5.20V	4.58V	1.90mA	10.84μA	1.90mA
Q2	13.47V	9.62V	9V	1.887mA	10.78μA	1.90mA

Table 3.3 DC Operating Point of Q1 and Q2

B. Magnitude and Phase Bode Plots

The pole and zero locations are calculated as follows:

$$\omega_{LP1} = (C_{C1} 18.82k)^{-1} = 5.744\, rad/s$$

$$\omega_{LP2} = (C_E 34.38)^{-1} = 3.143\, krad/s$$

$$\omega_{LP3} = (C_{C2}(52.4k))^{-1} = 2.063\, rad/s$$

$$\omega_{LZ1} = \omega_{LZ3} = 0\, rad/s$$

$$\omega_{LZ2} = (C_E 2.4k)^{-1} = 45.045\, rad/s$$

$$\omega_{L3dB} = \sqrt{\omega_{LP1}^2 - 2\omega_{LZ1}^2 + \omega_{LP2}^2 - 2\omega_{LZ2}^2 + \omega_{LP3}^2 - 2\omega_{LZ3}^2} = 3.142\, krad/s = 500Hz$$

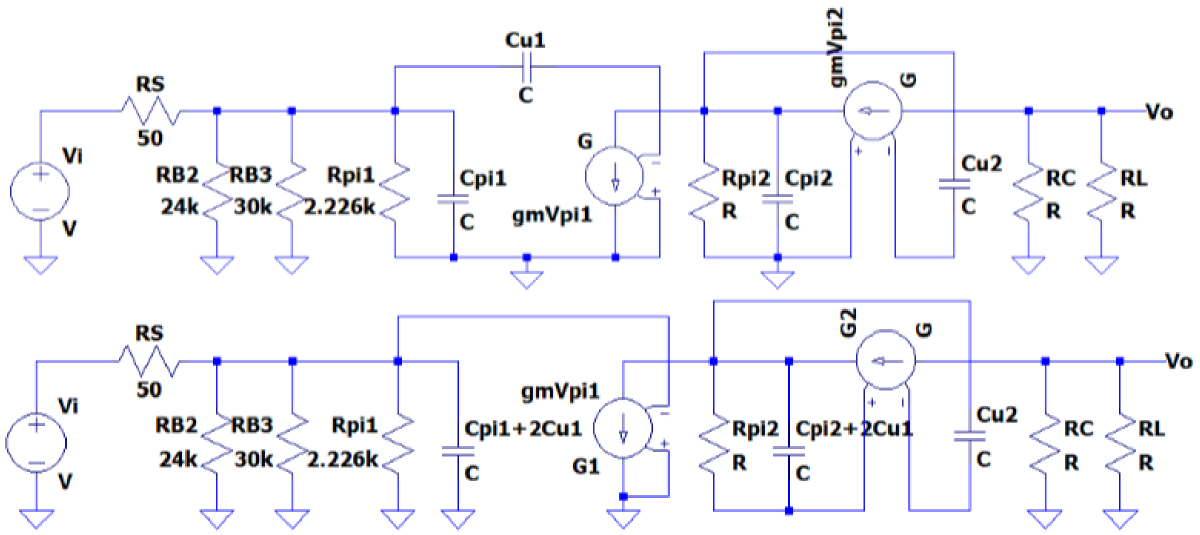


Figure 3.4: High Frequency Cascode Small Signal Model Before and After Miller

Using the SPICE model parameters, $C_{\pi1} = C_{\pi2} = 2\,CJE + TF * gm = 88.775pF$ and

$$C_{\mu1} = CJC((1 + \frac{V_{CB}}{VJC})^{MJC})^{-1} = 8.284\, pF,\ C_{\mu2} = 9.35\, pF$$

Using the Cascode's small signal model at high frequency in Figure 3.4, the high frequency poles are calculated as follows:

$\omega_{HP1} = ((C_{\pi1} + 2C_{\mu1})(R_S||R_{B2}||R_{B3}||r_{\pi1}))^{-1} = 194.832\ Mrad/s$

$\omega_{HP2} = ((C_{\pi2} + 2C_{\mu1})(\frac{r_{\pi2}}{1+\beta}))^{-1} = 703.089\ Mrad/s$

$\omega_{HP3} = (C_{\mu2}(R_C||R_L))^{-1} = 46.702\ Mrad/s$

$\omega_{H3dB} = (\tau_{HP1}^{\ 2} + \tau_{HP2}^{\ 2} + \tau_{HP3}^{\ 2})^{-1/2} = 45.321\ Mrad/s = 7.213\ MHz$

The following Magnitude and Phase Bode Plots were plotted as shown in Figure 3.5.

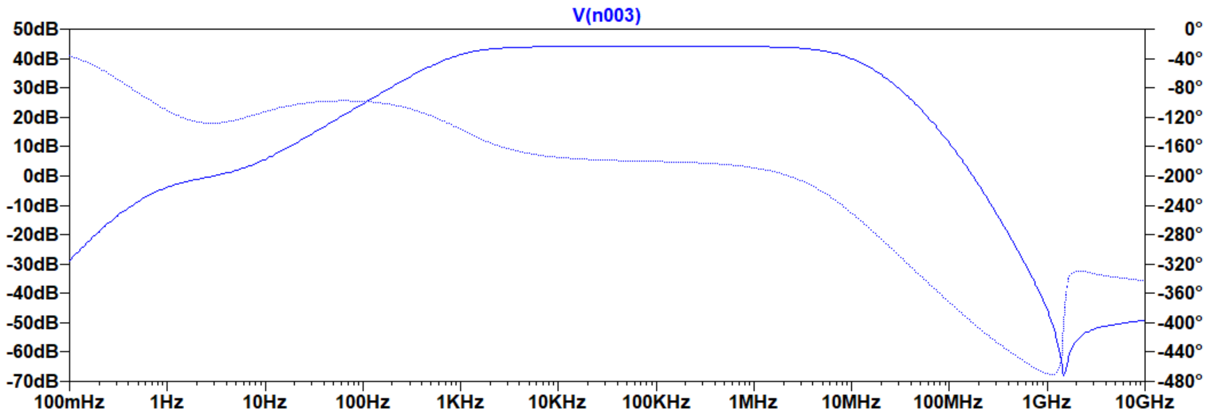


Figure 3.5: Magnitude and Phase Bode Plots of Cascode Amplifier

The measured 3dB points graphically determined are $\omega_{L3dB} = 523\ Hz$ and $\omega_{H3dB} = 7.8\ MHz$. The percent error for the low frequency pole is approximately 4.6%, and the percent error for the high frequency pole is 8.138%, with inconsistencies likely being due to Miller's theorem.

C. Saturating the Output Signal

The relationship between input and output voltage was plotted by conducting an amplitude sweep from 20 to 100mV at an arbitrary midband frequency of 20kHz, shown in Figure 3.6.

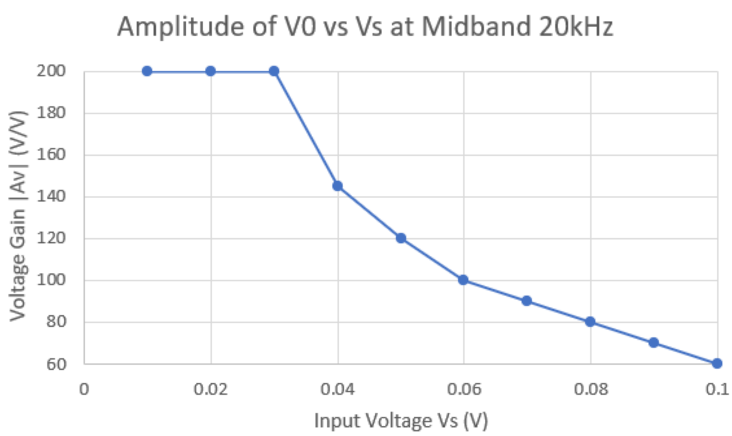


Figure 3.6: Amplitude of V0 vs Vs at 20kHz Midband

It is noted that the gain begins decreasing and becomes non-linear at ~30mV of input voltage, therefore remaining within our specified gain of $|A_V| \geq 50\ V/V$.

D. Input Impedance at Midband

An AC Sweep analysis was conducted on the input and output of the circuit to measure the impedance at midband frequency of 20kHz. As the initial measured input resistance was too low at approximately 1.9kΩ, a 3.3kΩ resistor was added in series with Rs, resulting in $R_{in} = 5.2\ k\Omega$, which meets the specified input impedance of $R_{in} \geq 5\ k\Omega$ as shown in Figure 3.7. R_{out} was found to be 2.289 kΩ which is also within specifications of $2.5 \pm 0.25\ k\Omega$.

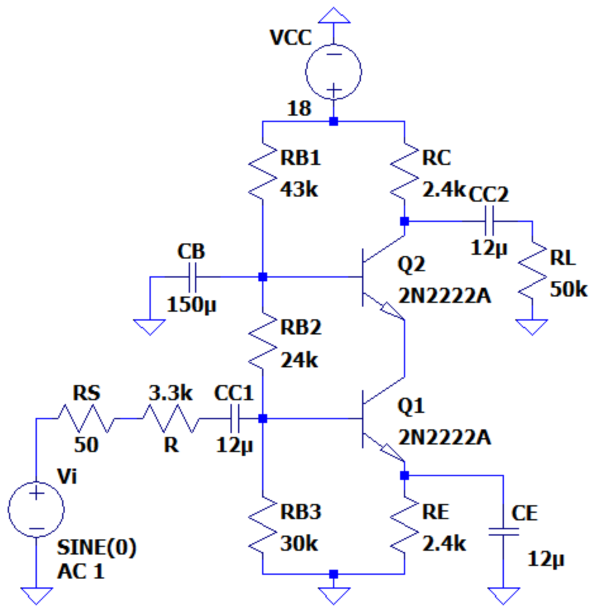


Figure 3.7: Cascode Amplifier With Designed Parameters

Discussion

In this section, we measured the DC operating point for a Cascode Amplifier, and modeled its high and low frequency small signal model. Using these models, the cut-in and cut-off frequencies were found as well as the midband gain. The output was then saturated as it was noted that the gain begins decreasing and becomes non-linear, and the resistances were adjusted such that input and output impedance were within specifications.

3.2 Part 2: Cascaded Amplifiers

A. Calculating Resistance Values

Using the ⅓ Rule, a Cascaded Amplifier is designed by calculating resistance values. The Midband circuit is shown in Figure 3.8.

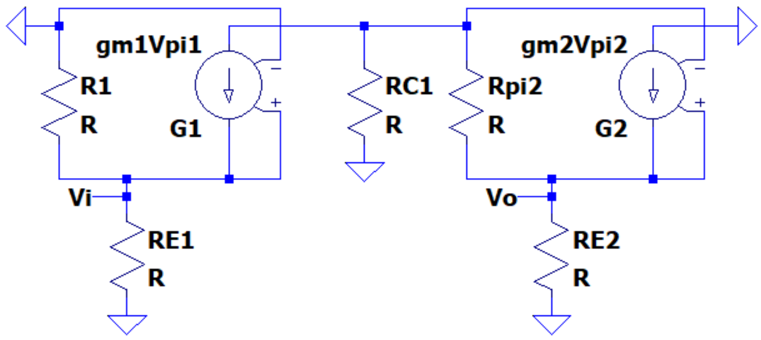


Figure 3.8: Cascaded Amplifier at Midband

Using the ⅓ Rule with $V_{CC} = 12V$, $V_{E1} = \frac{1}{3}V_{CC} = 4V$, $V_{B1} = V_{E1} + V_{BE1} = 4.7V$, $V_{C1} = V_{B2} = \frac{2}{3}V_{CC} = 8V$, $V_{E2} = V_{B2} - V_{BE2} = 7.3V$.

It is also known that $R_{in} = (\frac{r_{\pi 1}}{1+\beta})||R_{E1} = \frac{V_T}{I_{E1}} = 50\Omega$, therefore $I_{E1} = 0.5\ mA$ and $I_1 = 0.1I_{E1} = 50\ \mu A$. Then $I_{B1} = \frac{1}{1+\beta}I_{E1} = 2.976\ \mu A$, $I_2 = I_1 - I_{B1} = 47.024\ \mu A$, $I_{C1} = \beta I_{B1} = 0.496\ mA$

For resistances: $R_{E1} = \frac{V_{E1}}{I_{E1}} = 8\ k\Omega$, $R_{B1} = \frac{V_{CC}-V_{B1}}{I_1} = 146\ k\Omega$, $R_{B2} = \frac{V_{B1}}{I_2} = 99.948\ k\Omega$.

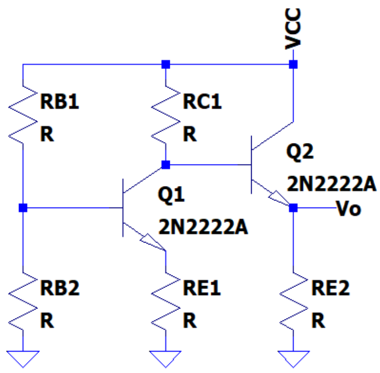


Figure 3.9: Cascaded Amplifier Circuit in DC

For the output impedance, $R_{out} = (\frac{r_{\pi 2}+R_{C1}}{1+\beta})||R_{E2} = 50\ \Omega$, and knowing that $R_{C1} = \frac{V_{CC}-V_{C1}}{I_3}$, $I_3 = I_{C1} + I_{B2}$, $I_{B2} = \frac{1}{1+\beta}I_{E2}$, and $I_{E2} = \frac{V_{E2}}{R_{E2}}$, we can solve for the following unknowns using the equations above: $R_{C1} = 7.6\ k\Omega$, $I_{E2} = 12.867\ mA$, $I_{B2} = \frac{I_{E2}}{1+\beta} = 76.589\ \mu A$, $R_{E2} = 1.75\ k\Omega$.

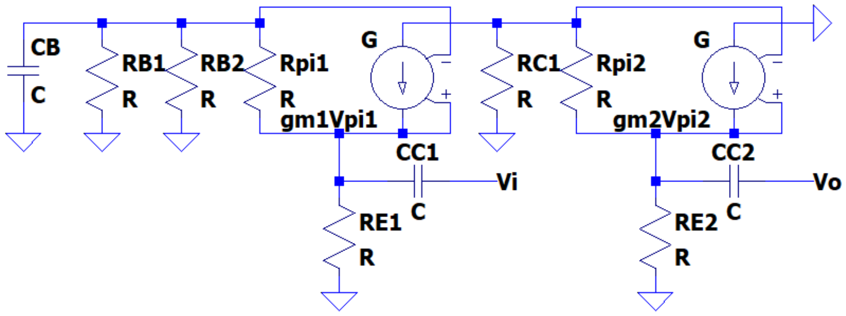


Figure 3.10: Cascaded Amplifier Low Frequency Small Signal Model

Next, we can solve for the capacitance using the SCTC and $\omega_{L3dB} = 1000Hz$.

$\omega_{LP3} = (R_{out}C_{C2})^{-1} = (49.995C_{C2})^{-1}\ rad/s$, $\tau_{OC}^{CC1} = R_{in}C_{C1} = 50C_{C1}\ s$

Since $C_{C1} = C_{C2}$, $1000 = \sqrt{\omega_{LP3}^{2} + \omega_{LP2}^{2}}$ and we solve for $C_{C1} = C_{C2} = 4.5\ \mu F$. Therefore, $\omega_{LP2} = \omega_{LP3} = 2.564\ krad/s$. C_B is designed as small as possible without changing the cut-in frequency, designing its pole to be at least one decade away from the cut-in: $\omega_{LP1} \leq \frac{\omega_{LP3}}{10} = 256.4\ rad/s$. Solving for the pole

$\omega_{LP1} = (C_B(R_{B1}||R_{B2}||(r_{\pi1} + (1 + \beta)R_{E1})))^{-1} = 439.933\ rad/s$ with $C_B = 33nF$.

B. Measuring Ri and Ro at Midband and Voltage Gain

The designed Cascode Amplifier circuit is built as shown in Figure 3.11.

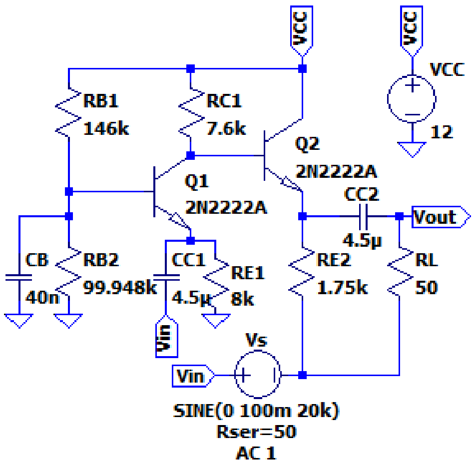


Figure 3.11 Designed Cascaded Amplifier Circuit

As the input and output impedances were measured to be too high for their specification of $50\ \pm\ 5\Omega$, R_{E1} and R_{E2} were decreased until the resistances reached without specification range, at $R_{E1} = 7.5\ k\Omega$, and $R_{E2} = 130\ \Omega$ resulting in $R_{in} = 51.7\ \Omega$ and $R_{out} = 51.1\ \Omega$. The midband gain is measured to be approximately $|A_M| = 135\ V/V$

C. Low Frequency Cut-In and High Frequency Cut-Off

Using the designed Cascaded circuit in Figure 3.11, a Bode plot was plotted as shown in Figure 3.12. Since the cut-in frequency was too far below specifications at 766 Hz, C_B was adjusted to 22nF such that the cut-in frequency is 947 Hz, with cut-out frequency at 1.3 MHz.

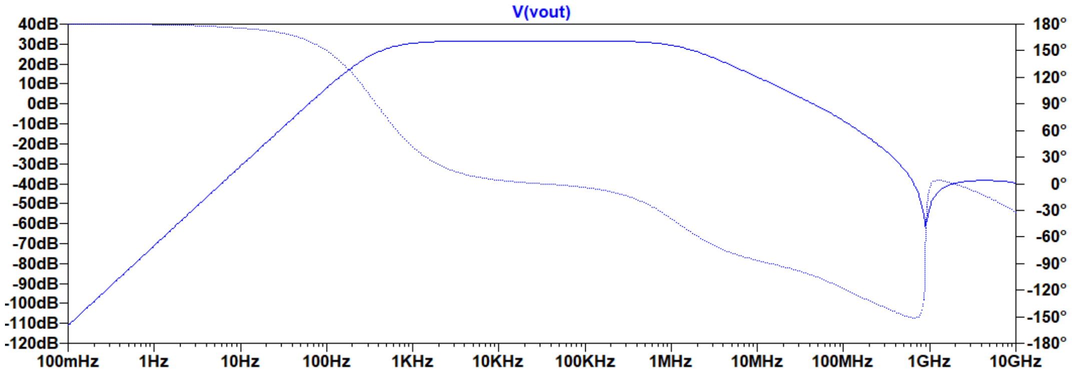


Figure 3.12: Cascaded Amplifier Magnitude and Phase Bode Plots

Discussion

This section consisted in constructing a Cascaded Amplifier using the ⅓ Rule to calculate its parameters and operating point. The input and output impedance were modeled and decreased as they were initially outside of their specified range. Similarly, C_B also needed to be adjusted to meet the cut-out frequency specification.

3.3 Part 3: Differential Amplifier

A. Bode Plots of Small Signal Input

Using a 12V source and $8k\Omega$ resistors, the circuit in Figure 3.13 can be constructed. Since $I_{E1} = I_{E2} = 1mA$ and $I_{REF} = I_{E1} + I_{E2} = 2mA$, R_{REF} is chosen to obtain a reference current near to the specifications. $I_{REF} = \frac{VCC-(VEE+VBE)}{RREF} = 1.941\ mA$ when $R_{REF} = 12\ k\Omega$. The resulting Phase and Magnitude Bode plot is shown in Figure 3.14.

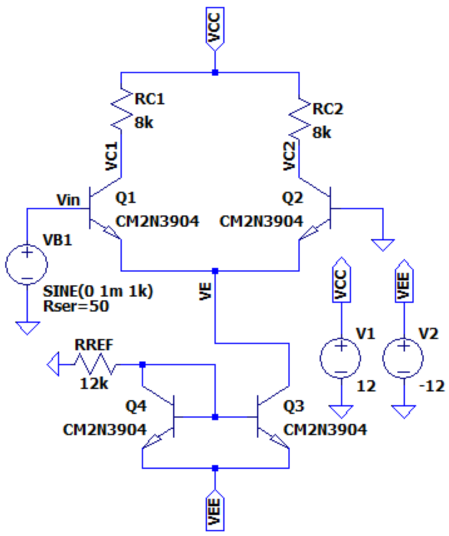


Figure 3.13: Differential Small Signal Model

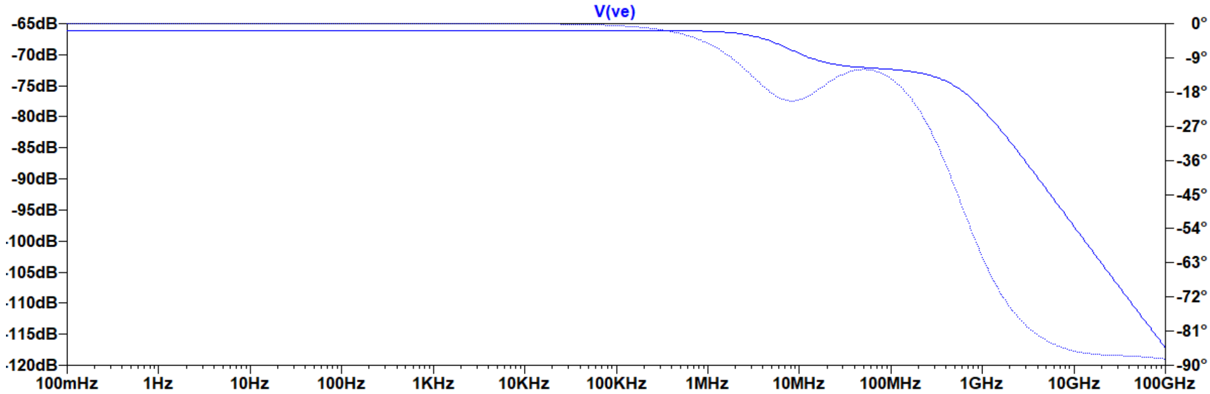


Figure 3.14: Differential Small Signal Model Magnitude and Phase Bode Plot

B. Differential Gain and High Frequency Cut-Off

By measuring the DC Operating point in LTSpice, we obtain the following parameters: $g_m = \frac{I_C}{V_T} = 0.04$, $r_{\pi1} = \frac{\beta}{g_m} = 3.875\, k\Omega$, $C_\mu = 23.3\, pF$, and $C_{\pi1} = C_{\pi2} = 1.9\, pF$. The differential gain and f_{H3dB} frequencies are calculated as follows:

$$|A_{diff}| = \frac{2gm\, Rc1\, r\pi1}{2r\pi1 + Rs} = 317.948\, V/V$$

$$\tau_{HP1} = (\frac{C\mu}{2} + \frac{C\pi}{2}) * 2 * r_{\pi1}||R_s = 9.808\, ns,\ \tau_{HP2} = C_\pi R_C = 15.2\, ns$$

$$f_{H3dB} = [\, 2\pi\sqrt{\tau_{HP1}^{\ 2} + \tau_{HP2}^{\ 2}}\,]^{-1} = 1.759\, MHz$$

Next, we compare our calculated values above to the values obtained by measurement, as shown in Table 3.3.

	Measured	**Calculated**	**Error**
$\lvert A_{diff}\rvert$	305.93 V/V	318 V/V	3.94 %
f_{H3dB}	7.905 MHz	8.8 MHz	11.32 %

Table 3.4: Measured and Calculated Cut-Off Frequency Values

The percentage error for the differential gain is minimal, however the error for the cut-off frequency is higher, which is to be expected due to the simplifications and assumptions in this section. Nonetheless, this provides an adequate estimate of the behavior of the circuit.

C. Saturation

Using the circuit in Figure 3.13, a small differential signal was applied to the amplifier (0.5 mV) before measuring the differential output voltage. This yields the diagram shown in Figure 3.15.

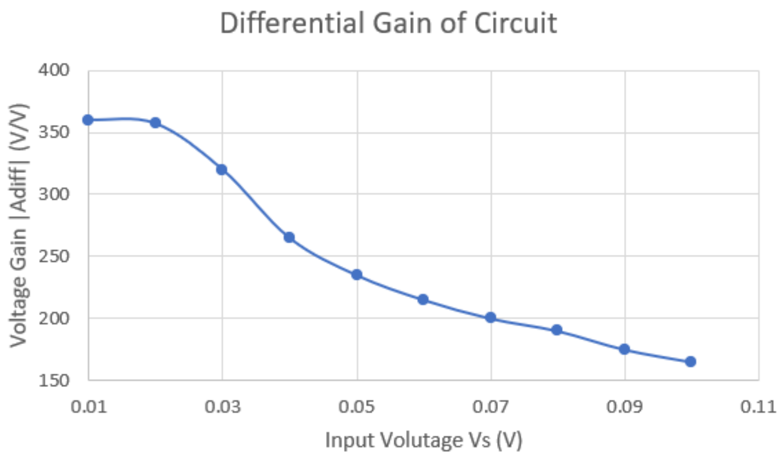


Figure 3.15: Differential Gain of Differential Amplifier

It is observed that the gain is no longer linear after the input voltage reaches 20 mV, as the amplifier saturates.

<u>Discussion</u>

Increasing the voltage will result in the gain eventually plateauing, amplifying a signal similarly to a gate circuit. While the calculated and measured differential gains were near each other, the high frequency cut-orr error was much higher likely due to the Miller effect and other simplifications. However an adequate estimate of the circuit is still provided.

3.4 Part 4: The AM Modulator

<u>A. Differential Output</u>

The output of the AM Modulator built in Figure 3.16 is shown in Figure 3.17, creating an amplitude modulated signal of a 100kHz sinusoidal with an amplitude oscillating at 1kHz. It is observed that the magnitude of the output and modulation is dependent on the input voltage's amplitude and frequency.

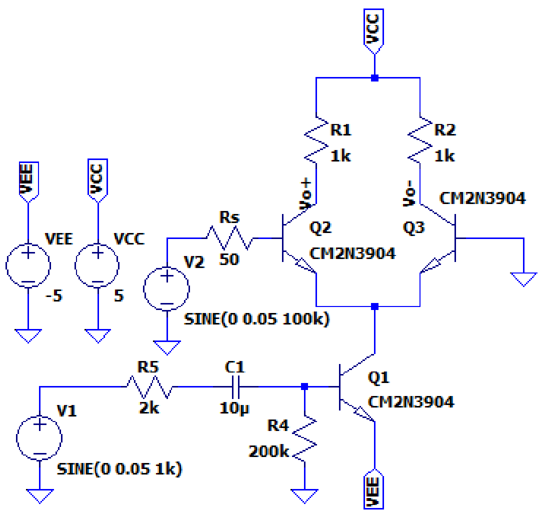


Figure 3.16: AM Modulator

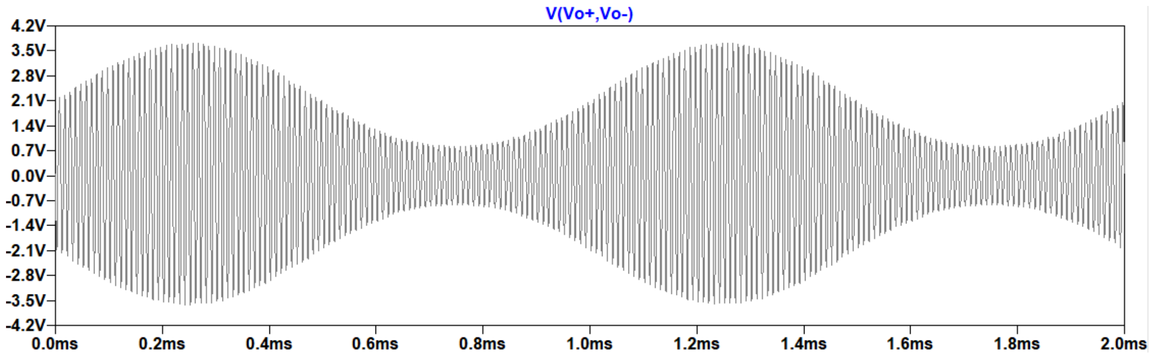


Figure 3.17: AM Modulation Differential Output

B. Input Signal Amplitude

To find the largest input signal resulting in an undistorted 1 kHz signal, the input signal amplitude was varied between 10 mV and 100 mV. At higher amplitudes, the output signal saturates, and as input amplitude increases, output amplitude increases as well. The output begins to distort as the input voltage reaches approximately 80-85 mA as shown in Figure 3.18.

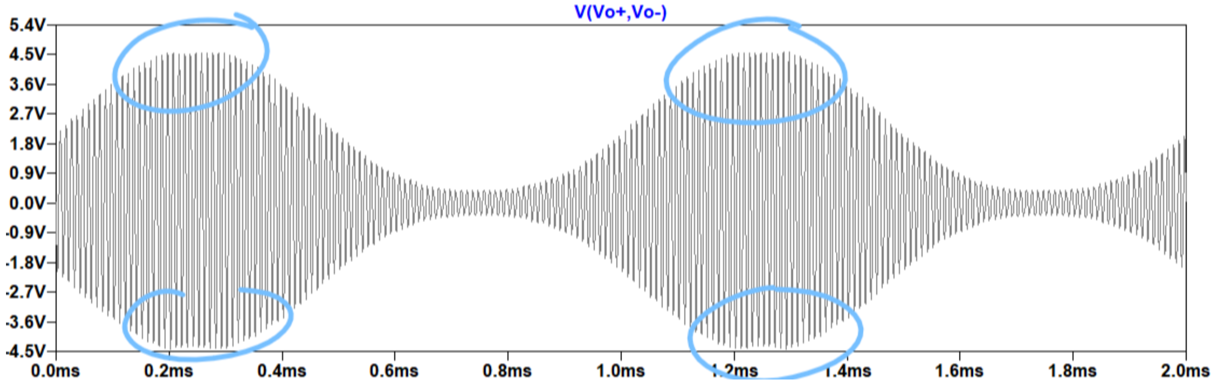
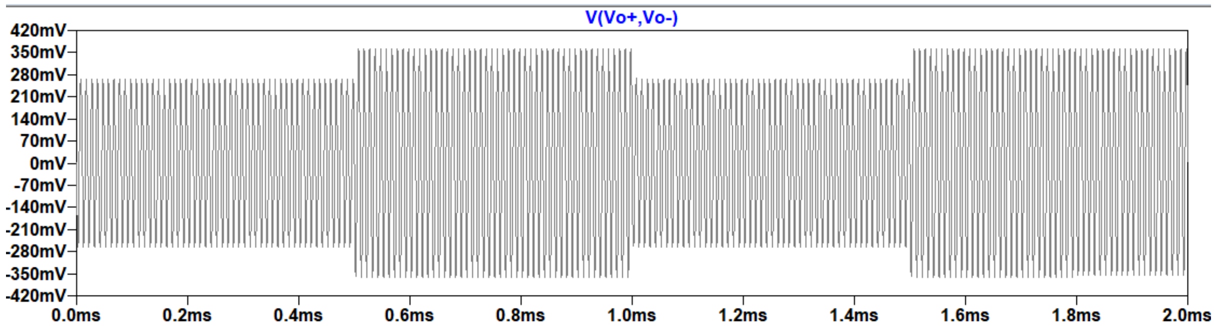


Figure 3.18: Saturation of AM Modulator

C. Square Wave Input

The input signal was changed to a square wave, and the -5V supply to -1.4V. Once again, the output amplitude increases with the input amplitude. In Figure 3.19, it is shown that as input voltage is increased, the difference between on and off cycles increases as well. Varying the input amplitude between 10 mV and 100 mV, it is found that the amplitude of the input signal resulting in the best on-off ratio of the carrier is approximately 60-70 mV.



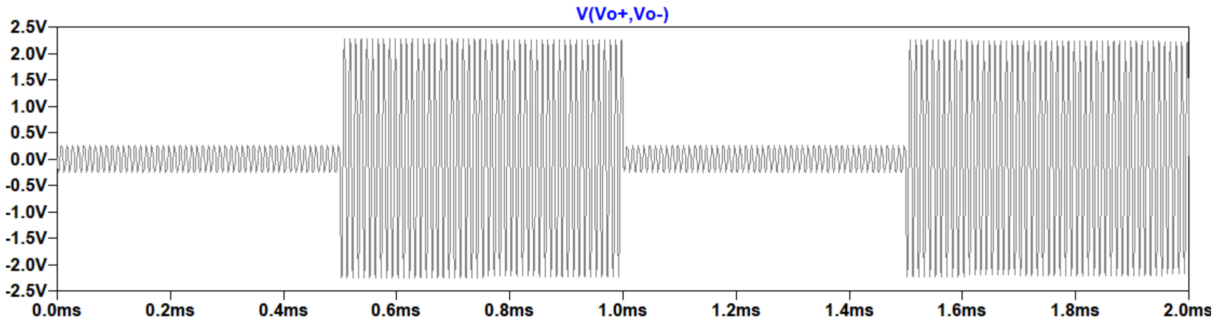


Figure 3.19: Differential Output of AM Modulator at 10mV (top) and 100mV (bottom)

Discussion

The multiplication of two waves results in amplitude modulation. It is noticed that at higher amplitudes, the output signal saturates, and as input amplitude increases, output amplitude increases as well. AM Modulators are widely used as the source dictates the gain of the carrier wave at the output voltage.

5. Conclusion

This project consisted in describing the characteristics of several multi-transistor amplifiers and circuits. Each Part of this project explores a different type of amplifier, including cascode amplifiers, cascaded amplifiers, differential amplifiers, and AM modulators. These amplifiers were designed and simulated with computer based circuit simulation tools. Part 1 consisted in creating a small signal model and calculating the parameters for a cascode amplifier. Part 2 explored how to design values for cascaded amplifiers, measuring the midband, and finding the cut-in and cut-off frequencies using a Bode plot. Part 3 consisted in designing a differential amplifier using 2N3904 transistors and observing the output signal saturating at high input signals, and finally Part 4 outlined the modeling of an AM modulator while observing its output signal in various states.

6. References

1. ELEC 301 Course Notes.
2. ELEC 301 Mini Project 3
3. A. Sedra and K. Smith, "Microelectronic Circuits," 5 th Ed., Oxford University Press, New York.
4. LTSpice™ User’s Manual.