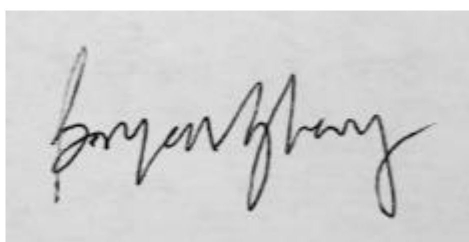
The University of British Columbia

Mini Project 3

ELEC 301 – Electronic Circuits



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11-16-2022

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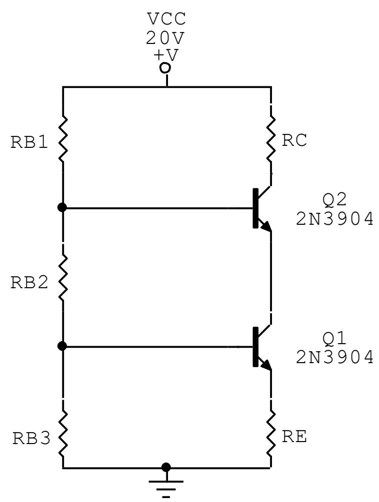
Part 1 The Cascode Amplifier

A. DC operating point



Looking at the CircuitMaker SPICE model, the *2N3904* β is found to be 300 (ideal maximum forward beta). Assume that V_T=0.025V and V_{BE}=0.7V. The cascode amplifier in d.c mode is shown to the left. Use the ¼ rule to bias the cascode amplifier.

$$V_{C2} = \frac{3}{4}V_{CC} = 15V \qquad V_{E2} = V_{C1} = \frac{1}{2}V_{CC} = 10V$$

$$V_{E1} = \frac{1}{4}V_{CC} = 5V \qquad V_{B1} = V_{E1} + V_{BE} = 5.7V$$

$$V_{B2} = V_{E2} + V_{BE} = 10.7V$$

<u>At midband the value of R_{out}=R_C=2.5kΩ±250Ω</u>. Set R_C to the closest standard value of 2.4kΩ and compute all currents.

$$I_{C2} = \frac{V_{CC}-V_{C2}}{R_C} = 2.083mA \qquad I_{B2} = \frac{I_{C2}}{\beta} = 6.944\mu A \qquad I_{E2} = I_{C1} = (1+\beta)\cdot I_{B2} = 2.09mA$$

$$I_{B1} = \frac{I_{C1}}{\beta} = 6.968\mu A \qquad I_{E1} = (1+\beta)\cdot I_{B1} = 2.097mA \qquad I_1 = \frac{I_{E1}}{\sqrt{\beta}} = 121.1\mu A$$

$$I_2 = I_1 - I_{B2} = 114.1\mu A \qquad I_3 = I_2 - I_{B1} = 107.2\mu A$$

Now, calculate the resistances and small signal parameters g_m and r_π

$$R_{B1} = \frac{V_{CC}-V_{B2}}{I_1} = 76.8k\Omega \qquad R_{B2} = \frac{V_{B2}-V_{B1}}{I_2} = 43.8k\Omega \qquad R_{B3} = \frac{V_{B1}}{I_3} = 53.2k\Omega \qquad R_E = \frac{V_{E1}}{I_{E1}} = 2.4k\Omega$$

$$g_{m1} = \frac{I_{C1}}{V_T} = 0.08S \qquad r_{\pi1} = \frac{\beta}{g_{m1}} = 3.6k\Omega \qquad g_{m2} = \frac{I_{C2}}{V_T} = 0.08S \qquad r_{\pi2} = \frac{\beta}{g_{m2}} = 3.6k\Omega$$

<u>R_{in} should be at least 5kΩ</u>. Currently $R_{in} = R_{B2}||R_{B3}||r_{\pi_1} = 3.12k\Omega$. It is necessary to add a resistor of at least R_1 = 5-3.12=1.88kΩ at the input. Here are the standard values chosen for the resistors.

R_C	R_{B1}	R_{B2}	R_{B3}	R_E	R_1
2.4 kΩ	75 kΩ	43 kΩ	51 kΩ	2.4 kΩ	2kΩ

<u>The low-f cut-in f_L is specified to be at most 500 Hz</u>. Calculate the low 3dB frequency point for the cascode amplifier using short circuit time constants. $R_{BB} = R_{B2}||R_{B3} = 24k\Omega, R_L = 50k\Omega$

$$\tau_{C_E}^{sc} = C_E\left(R_E||\frac{r_\pi + R_{BB}||(R_s+R_1)}{1+\beta}\right) = 18.1C_E \xrightarrow{yields} \omega_{Lp1} = \frac{1}{\tau_{C_E}^{sc}} = \frac{1}{18.1C_E}$$

$$\tau_{C_{C2}}^{sc} = C_{C2}(R_C + R_L) = 52.4k\cdot C_{C2} \xrightarrow{yields} \omega_{Lp2} = \frac{1}{\tau_{C_{C2}}^{sc}} = \frac{1}{52.4k\cdot C_{C2}}$$

$$\tau_{C_{C1}}^{sc} = C_{C1}(R_s + R_1 + R_{BB}||r_\pi) = 5.17k\cdot C_{C1} \xrightarrow{yields} \omega_{Lp3} = \frac{1}{\tau_{C_{C1}}^{sc}} = \frac{1}{5.17k\cdot C_{C1}}$$

Notice that $\tau_{C_E}^{sc} \ll \tau_{C_{C1}}^{sc}$ so do the open circuit time constant for C_{C1} instead.

$$\tau_{C_{C1}}^{oc} = C_{C1}\big(R_s + R_1 + (R_{BB}||(r_\pi + (1+\beta)R_E))\big) = 24.7k \cdot C_{C1} \xrightarrow{yields} \omega_{Lp3} = \frac{1}{\tau_{C_{C1}}^{sc}} = \frac{1}{24.7k \cdot C_{C1}}$$

$$\omega_{Lz} = \frac{1}{R_E C_E} = \frac{1}{2.4k \cdot C_E}$$

Notice that ω_{LP1} is the dominant pole so ignore the other ones when calculating the 3dB frequency. C_B is a large capacitor, so it does not need to be considered. Assume $C_E = C_{C1} = C_{C2}$.

$$\omega_{L3dB} = \sqrt{\omega_{Lp1}^2 - 2\omega_{Lz}^2} = \sqrt{\left(\frac{1}{17.8C_E}\right)^2 - 2\left(\frac{1}{2.4k \cdot C_E}\right)^2} = 2\pi f_L = 1000\pi/s$$

$$\xrightarrow{yields} C_E = C_{C1} = C_{C2} = 17.6\mu F$$

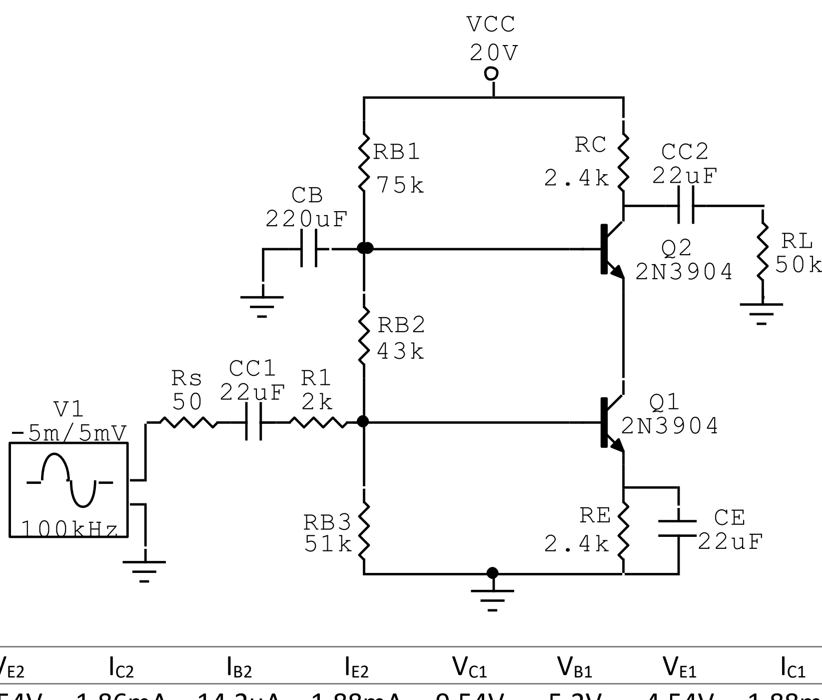
Calculate the <u>midband gain $|A_V| > 50$</u> as specified for the cascode amplifier.

$$A_v = \frac{V_o}{V_{\pi2}} \cdot \frac{V_{\pi2}}{V_{\pi1}} \cdot \frac{V_{\pi1}}{V_s} = -g_m(R_C||R_L) \cdot 1 \cdot \frac{R_{B2}||R_{B3}||r_\pi}{R_{B2}||R_{B3}||r_\pi + R_s + R_1} = -115$$

The midband voltage gain meets the specification. The standard values for the capacitors are selected.

C_E	C_{C1}	C_{C2}
22µF	22µF	22µF

Finally, the full circuit can be constructed and the d.c operating point is simulated.



V_{C2}	V_{B2}	V_{E2}	I_{C2}	I_{B2}	I_{E2}	V_{C1}	V_{B1}	V_{E1}	I_{C1}	I_{B1}	I_{E1}
15.5V	10.2V	9.54V	1.86mA	14.2µA	1.88mA	9.54V	5.2V	4.54V	1.88mA	14.4µA	1.89mA

B. Bode plots and estimated 3dB locations

f_{L3dB} may be approximated using the dominant pole ω_{Lp1}. Use C_E=22µF

$$\omega_{Lp1} = \frac{1}{18.1 \cdot C_E} = 3.139k\ {rad}/{s} \xrightarrow{yields} f_{Lp1} = f_{L3dB} = \frac{\omega_{Lp1}}{2\pi} = \boxed{500Hz}$$

Apply miller's theorem and then calculate the high 3dB frequency. $V_{CB}=V_{C2}-V_{B2}=V_{C1}-V_{B1}=4.3V$.

$$c_\pi = 2 \cdot CJE + TF \cdot g_m = 42.4pF \qquad c_\mu = \frac{CJC}{\left(1+\frac{V_{CB}}{VJC}\right)^{MJC}} = 1.87pF$$

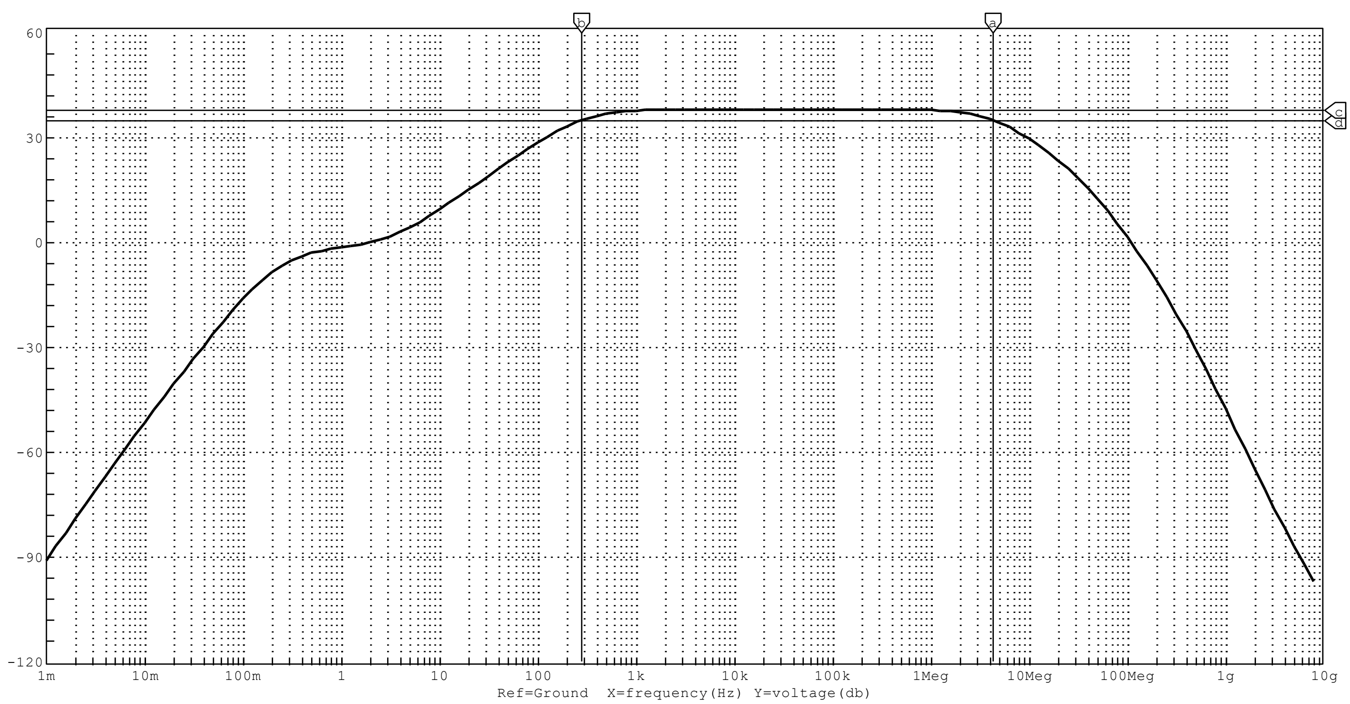
$$\omega_{Hp1} = \frac{1}{(c_\pi + 2c_\mu)(R_{BB}||r_\pi||(R_1 + R_s))} = 17.5M\ {rad}/{s}$$

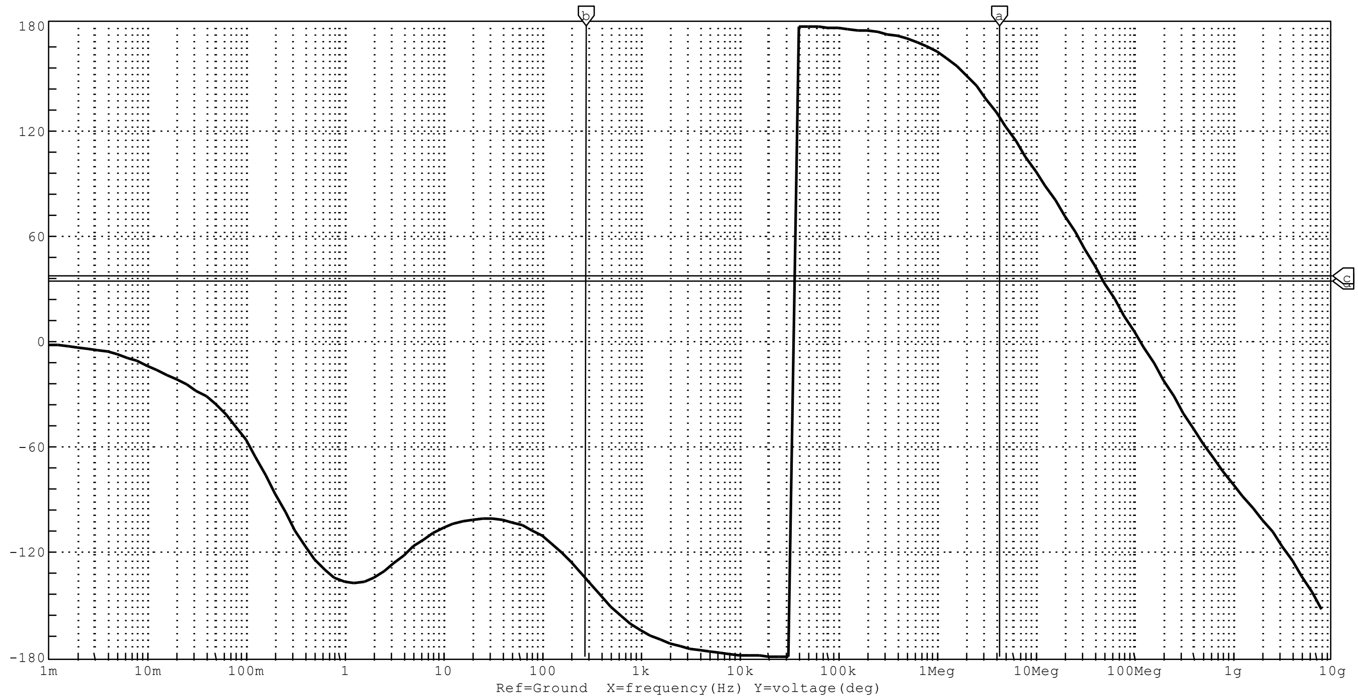
$$\omega_{Hp2} = \frac{1}{(c_\pi + 2c_\mu)\left(\frac{r_\pi}{1+\beta}\right)} = 1.81G\ {rad}/{s}$$

$$\omega_{Hp3} = \frac{1}{(c_\mu)(R_C||R_L)} = 234.1M\ {rad}/{s}$$

Notice the dominant high frequency pole is ω_{Hp1} so the high 3dB point can be approximated using that.

$$f_{H3dB} = \frac{\omega_{Hp1}}{2\pi} = \boxed{2.79MHz}$$

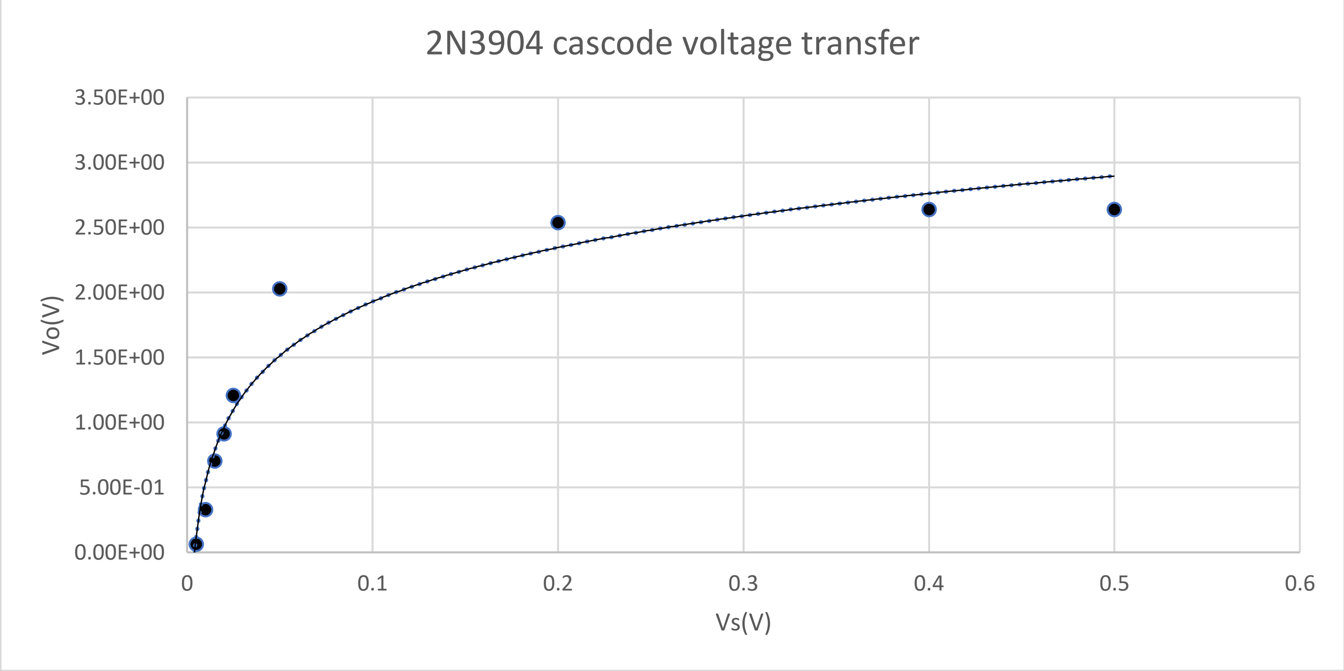




	f_{L3dB}	f_{H3dB}
calculated	500Hz	2.79MHz
simulated	275.4Hz	4.223MHz

C. Voltage Transfer curve

Set the source to the midband frequency of 100kHz. Vary the source amplitude from 0-0.5V.



The input voltage reaches about 0.025V before becoming non-linear.

D. Input/Output Impedance measurement

Set the source to the midband frequency of 10kHz with an amplitude of 5mV. The input impedance can be calculated as $R_{in} = R_{BB}||r_\pi + R_1 = 5.12k\Omega$.

To measure the input and output impedance remove the source resistor and short the load resistor. Use the AC RMS multimeter and probe the voltage & current directly at the source to measure R_{in}.

$$R_{in} = \frac{V_{rms}}{I_{rms}} = \frac{3.104mV}{584.2nA} = 5.313k\Omega$$

The output impedance at midband is simply computed R_C=2.4kΩ. To measure the output impedance use an AC multimeter to probe V_{C2} and I_{C2} with R_L shorted.

$$R_{out} = \frac{V_{C2}}{I_{C2}} = \frac{49.91\mu V}{20.80nA} = 2.4k\Omega$$

Discussion

The simulated results of the cascode amplifier meet the required specifications:

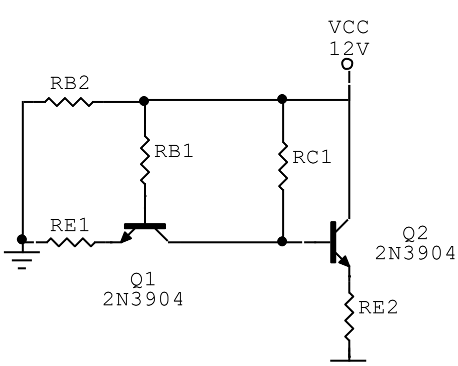
- R_{out} @ midband is within 2.5 kΩ ± 250Ω
- R_{in} > 5 kΩ @ midband
- $|A_v|$ > 50 @ midband
- f_{L3dB} < 500Hz

However, the calculated and simulated 3dB points are significantly off. The calculated value of R_1 =2kΩ was different from the actual required value of 3.3kΩ in simulation. I believe these inaccuracies could be caused by the fact that the beta used in the calculation was the *ideal* forward maximum beta but in simulation, it may have been significantly different. Nonetheless a cascode amplifier that meets the specifications is designed.

Part 2 Cascaded Amplifiers

Design the repeater so that R_{in} & R_{out} are 50±5Ω and the low frequency 3dB point is less than 1kHz.

A. Biasing



Here is the circuit at d.c. Use the 1/3 rule to bias.

$V_{E1} = \frac{V_{CC}}{3} = 4V \qquad V_{B1} = V_{E1} + V_{BE} = 4.7V$

$V_{C2} = V_{CC} = 12V \qquad V_{C1} = V_{B2} = \frac{2}{3}V_{CC} = 8V$

$V_{E2} = V_{B2} - V_{BE} = 7.3V \qquad \beta = 300$

At the midband the input impedance is found to be

$$R_{in} = \frac{r_\pi}{1+\beta}||R_{E1} = \left(\frac{\beta}{1+\beta}\frac{V_T}{I_{C1}}\right)||\frac{V_{E1}}{I_{E1}} = \frac{V_T}{I_{E1}}||\frac{V_{E1}}{I_{E1}} = \frac{V_T}{I_{E1}}$$

$50 = \frac{25mV}{I_{E1}} \xrightarrow{yields} I_{E1} = I_{C1} = 500\mu A$ $\quad I_{B1} = \frac{I_{C1}}{\beta} = 1.67\mu A$ $\quad I_1 = 0.1 I_{E1} = 50\mu A$

$R_{B1} = \frac{V_{CC}-V_{B1}}{I_1} = \underline{146k\Omega}$ $\quad I_3 = I_1 - I_{B1} = 48.3\mu A$ $\quad R_{B2} = \frac{V_{B1}}{I_3} = \underline{97.2k\Omega}$

$$R_{out} = R_{E2}||\frac{r_{\pi 2}+R_{C1}}{1+\beta} = R_{E2}||\left(\frac{R_{C1}}{1+\beta}+\frac{V_T \cdot R_{E2}}{V_{E2}}\right) = R_{E2}||\left(\frac{V_{CC}-V_{C1}}{(1+\beta)I_{C1}+\frac{V_{E2}}{R_{E2}}}+\frac{V_T \cdot R_{E2}}{V_{E2}}\right)$$

$$50 = R_{E2}||\left(\frac{V_{CC}-V_{C1}}{(1+\beta)I_{C1}+\frac{V_{E2}}{R_{E2}}}+\frac{V_T \cdot R_{E2}}{V_{E2}}\right) \xrightarrow{yields} R_{E2} = \underline{7k\Omega}$$

$I_{E2} = \frac{V_{E2}}{R_{E2}} = 1.043mA$ $\quad I_{B2} = \frac{I_{E2}}{1+\beta} = 3.47\mu A$ $\quad I_{C2} = \beta I_{B2} = 1.040mA$

$$I_2 = I_{C1} + I_{B2} = 503\mu A$$

$R_{C1} = \frac{V_{CC}-V_{C1}}{I_{C2}} = \underline{3.85k\Omega}$ $\quad R_{E1} = \frac{V_{E1}}{I_{E1}} = \underline{8k\Omega}$ $\quad R_{BB} = R_{B1}||R_{B2} = 58.4k\Omega$

$g_{m1} = \frac{I_{C1}}{V_T} = 20mS$ $\quad r_{\pi 1} = \frac{\beta}{g_{m1}} = 15k\Omega$ $\quad g_{m2} = \frac{I_{C2}}{V_T} = 41.6mS$ $\quad r_{\pi 2} = \frac{\beta}{g_{m2}} = 7.2k\Omega$

Compute the f_{L3dB} using the open and short circuit time constants.

$$\tau_{C_{C1}}^{sc} = \left(\frac{r_{\pi 1}}{1+\beta}||R_{E1}\right)C_{C1} = 49.5C_{C1}$$

$$\tau_{C_B}^{sc} = (R_{BB}||r_{\pi 1})C_B = 11.9 \cdot 10^3 C_B$$

Notice $\tau_{C_{C1}}^{sc} \ll \tau_{C_B}^{sc}$ so the open circuit time constant for C_B must be computed.

$$\tau_{C_B}^{oc} = (R_{BB}||(r_{\pi 1} + (1+\beta)R_{E1}))C_B = 57 \cdot 10^3 C_B$$

$$\tau_{C_{C2}}^{sc} = \left(R_{E2}||\frac{r_{\pi 2}+R_{C1}}{1+\beta}\right)C_{C2} = 36.6C_{C2}$$

Assume C = C_{C1} = C_{C2} and that they determine the low frequency cut-in. Assume C_B is small and places a pole at least 1 decade away.

$$1000 \cdot 2\pi \, {}^{rad}/_{s} = \sqrt{\left(\frac{1}{\tau_{C_{C1}}^{sc}}\right)^2 + \left(\frac{1}{\tau_{C_{C2}}^{sc}}\right)^2} = \sqrt{\left(\frac{1}{49.5C}\right)^2 + \left(\frac{1}{36.6C}\right)^2} \xrightarrow{yields} C_{C1} = C_{C2} = \underline{5.4\mu F}$$

$\omega_{Lp1} = \frac{1}{49.5 \cdot 5.4\mu F} = 3.734k \, {}^{rad}/_{s}$ $\qquad \omega_{Lp2} = \frac{1}{36.6 \cdot 5.4\mu F} = 5.059k \, {}^{rad}/_{s}$

$$\omega_{L3dB} = \sqrt{\omega_{Lp1}^2 + \omega_{Lp2}^2} = 6.29k\, {}^{rad}/_{s} = 1.0006kHz$$

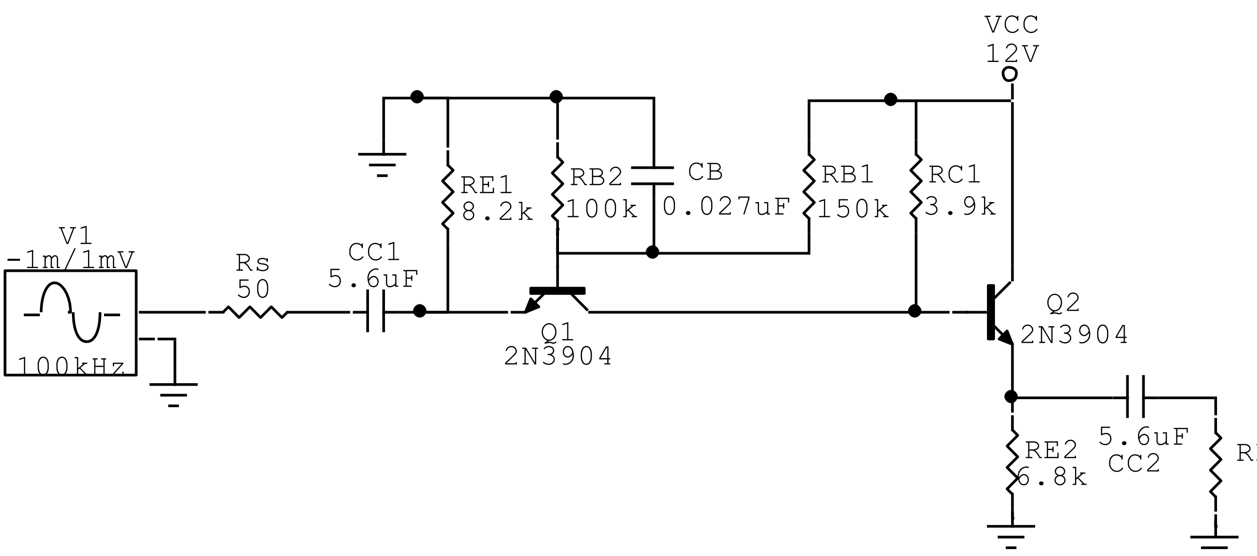
The pole associated with C_B should be placed at least 1 decade below the 3dB point.

$$\omega_{Lp3} = \frac{1}{57 \cdot 10^3 C_B} = \frac{6.29k}{10} \xrightarrow{yields} C_B = \underline{27.9nF}$$

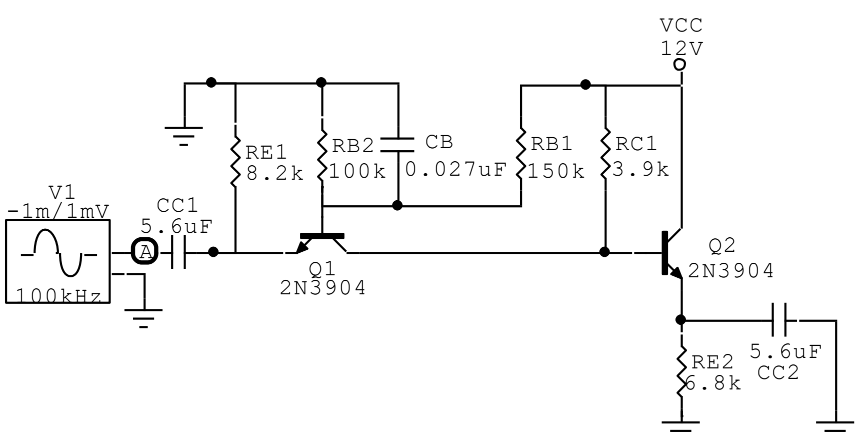
Here are the standard values of the resistors and capacitors that will be used in the simulation.

R_{E1}	R_{C1}	R_{B1}	R_{B2}	R_{E2}	C_{C1}	C_B	C_{C2}
8.2kΩ	3.9kΩ	150kΩ	100kΩ	6.8kΩ	5.6µF	.027µF	5.6µF

The full cascaded amplifier is shown below.

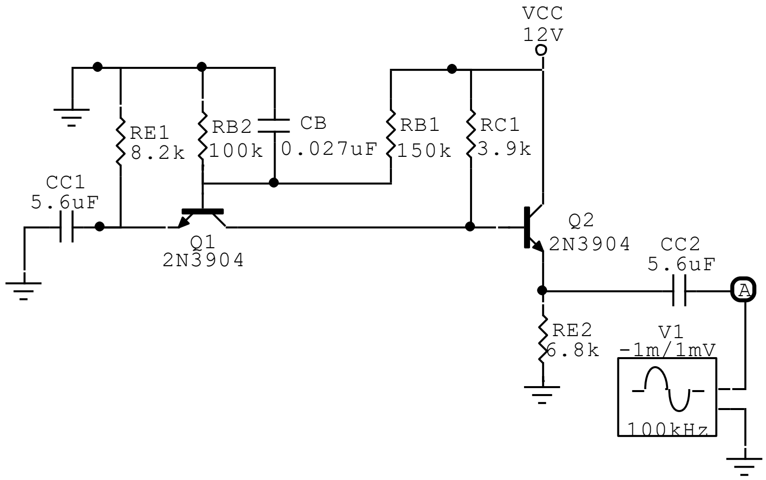


B. Measuring Input/Output Impedance & Midband Gain



To measure the input impedance, remove the source resistor, short the load resistor, and use a 1mV source with the midband frequency of 100kHz. Use an AC multimeter to measure the RMS voltage and current at the source node 'A'.

$$R_{in} = \frac{V_{rms}}{I_{rms}} = \frac{702.6\mu V}{12.86\mu A} = \underline{54.63\Omega}$$

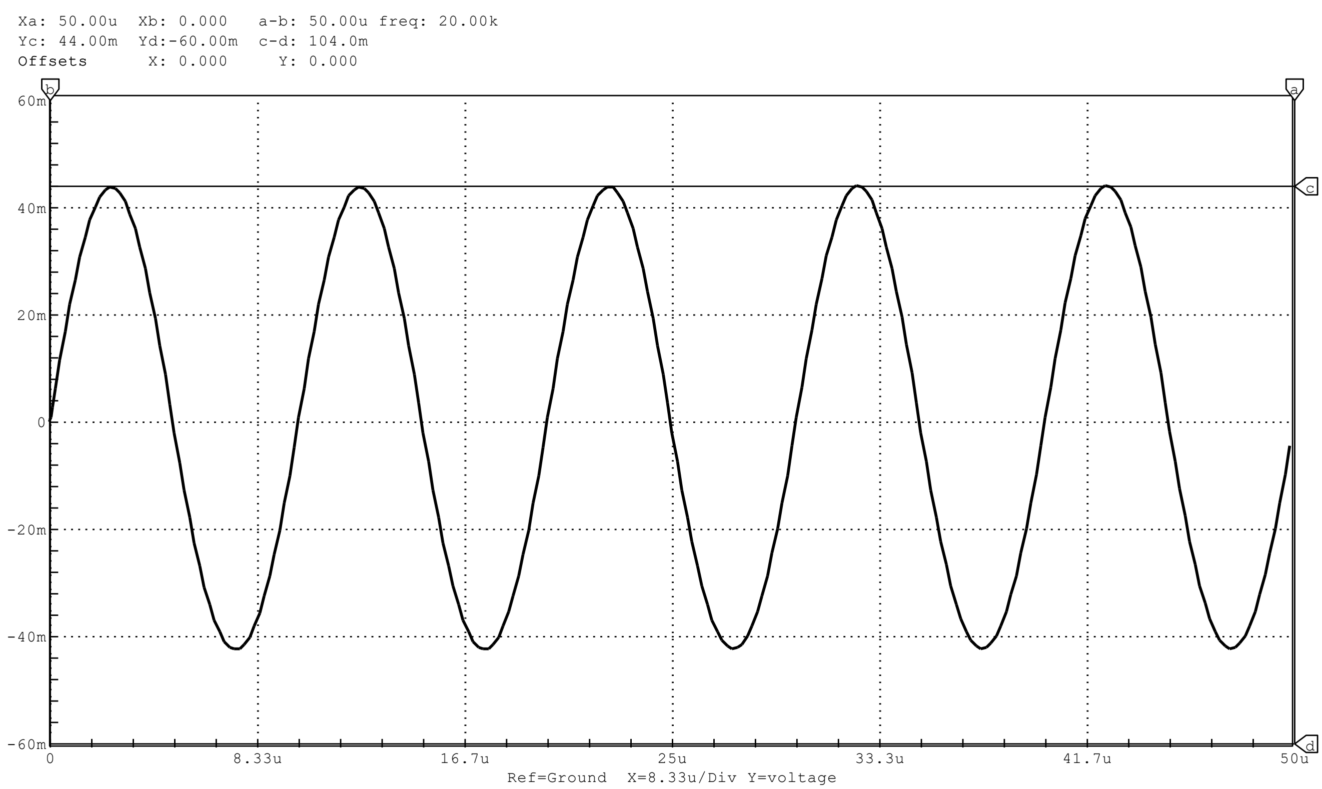


To measure the output impedance, move the source to the output node and ground C_{C1}. Then measure the RMS voltage and current at the node 'A' like before.

$$R_{out} = \frac{V_{rms}}{I_{rms}} = \frac{706.2\mu V}{12.89\mu A} = \underline{54.79\Omega}$$

Both the input and output impedance is within 45-50Ω, the specification is met.

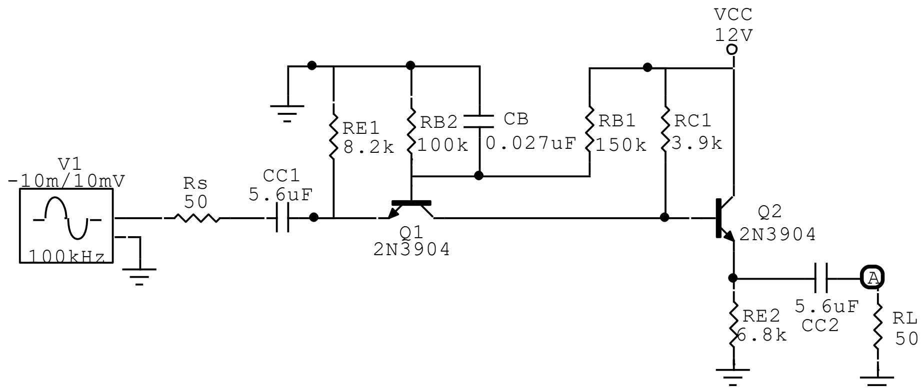
To measure the midband gain A_M place the source back to the input side (like shown in the complete circuit of part A but with the <u>load open circuited with a large resistance</u>) and then observe the transient response to find the peak voltage at the output node 'A'.

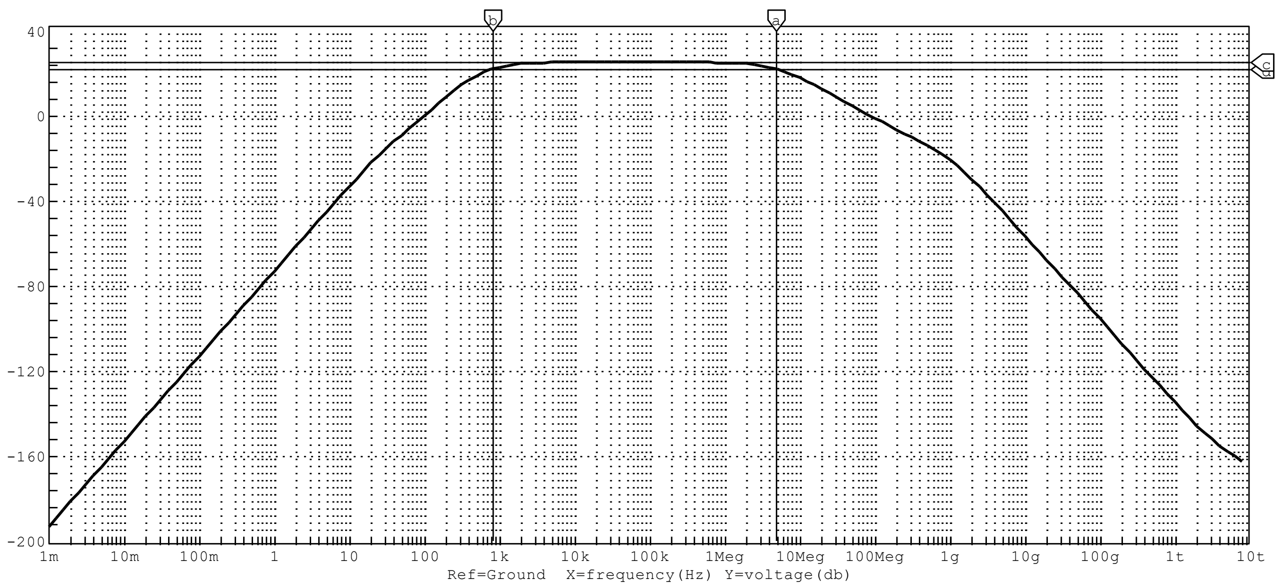


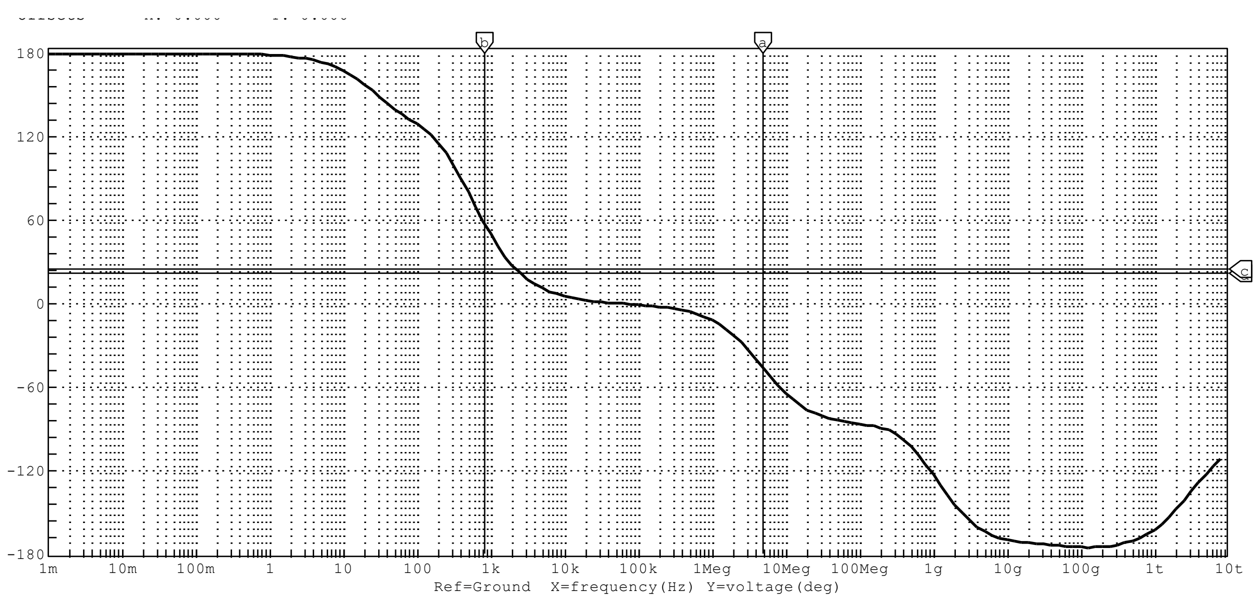
$$|A_M| = \frac{44mV}{1mV} = \underline{44}$$

C. Bode Plots

Add a 50Ω source and load resistance, the simulated circuit and its magnitude & phase bode plots are shown below.







f_{L3dB}	f_{H3dB}
832.4Hz	4.802MHz

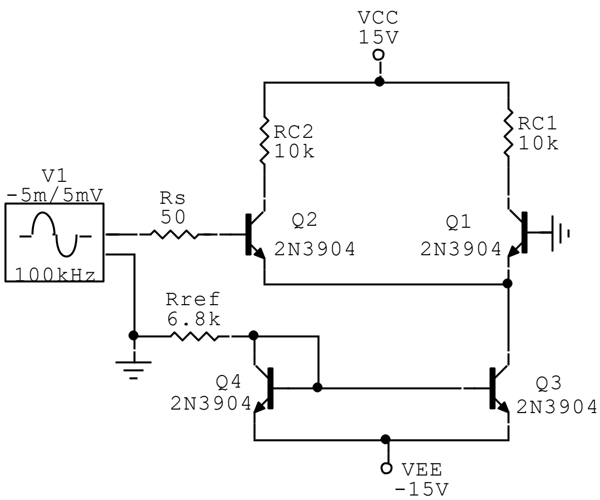
Discussion

The simulated results of the cascaded amplifier meet the required specifications:

- R_{in} & R_{out} @ midband is within 50Ω ± 5Ω
- The low frequency cut-in is below 1kHz

Part 3 Cascaded Amplifiers

A. Bode plots

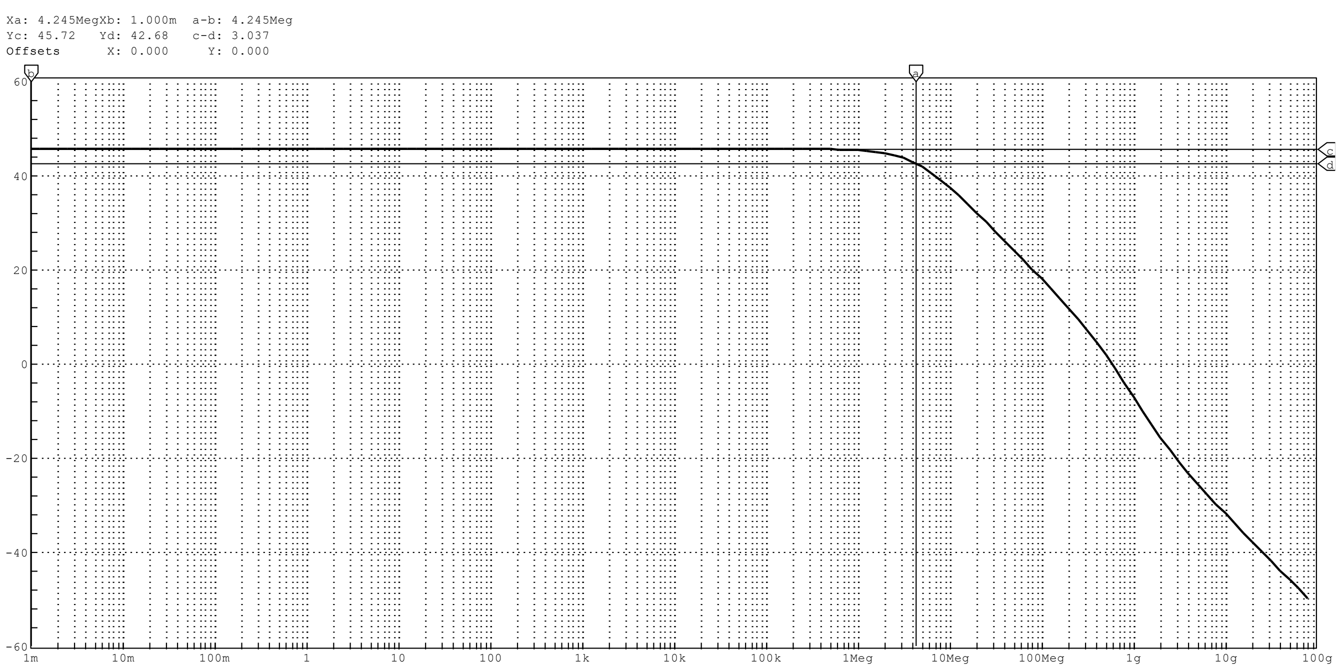


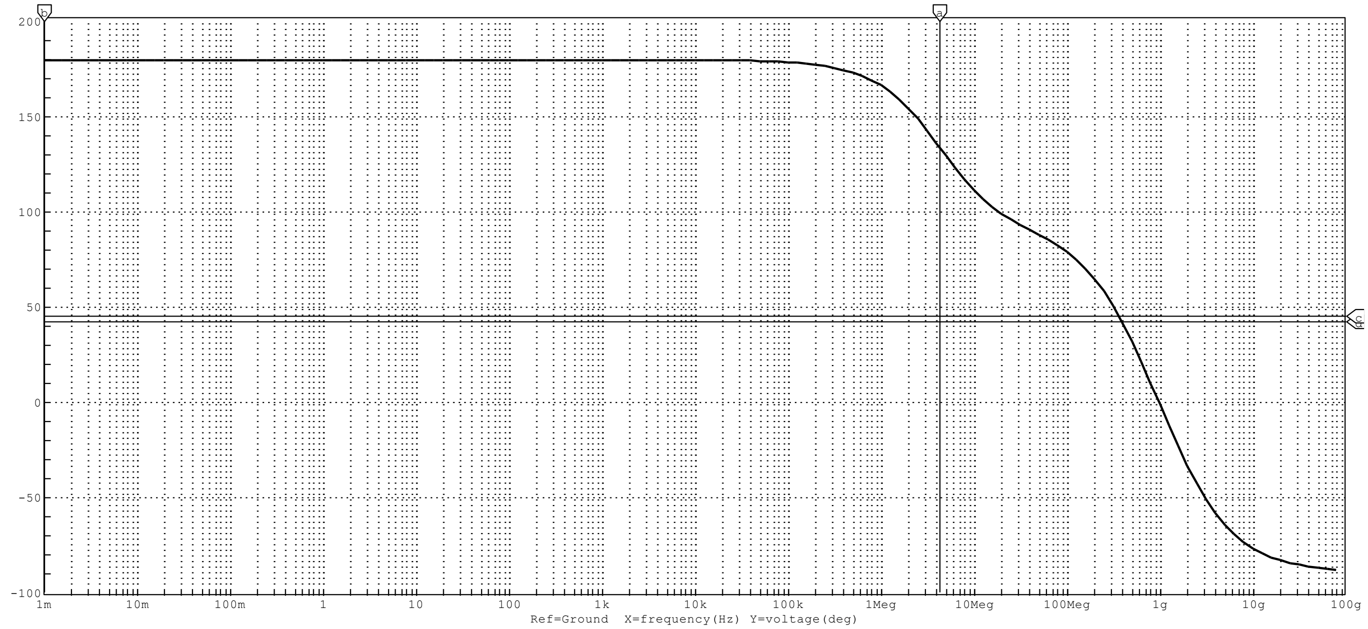
Find the reference resistance. The current source should produce 2mA because the two emitter currents are specified to be 1mA.

$$\frac{1}{2} I_o = I_{E1} = I_{E2} = 1mA$$

$$I_o = \frac{I_{REF}}{1 + \frac{2}{\beta}} = 2mA \xrightarrow{yields} I_{REF} = 2.01mA$$

$$I_{REF} = \frac{0 - (V_{EE} + V_{BE})}{R_{Ref}} \xrightarrow{yields} R_{REF} = 7.1k\Omega$$





B. Calculating differential gain and f_{H3dB}

Compute the high frequency 3dB point using open and short circuit time constants. V_{CB} is measured to be approximately 3.3V at the d.c operating point.

$$g_m = \frac{\alpha I_o}{2V_T} = 40mS$$

$$c_\pi = 2 \cdot CJE + TF \cdot g_m = 25pF \qquad c_\mu = \frac{CJC}{\left(1+\frac{V_{CB}}{VJC}\right)^{MJC}} = 1.9pF \qquad r_\pi = \frac{\beta}{g_m} = 7.53k\Omega$$

$$|A_d| = \frac{-2g_m R_C r_\pi}{R_S + 2r_\pi} = \underline{397\, {}^{V}\!/_{V}}$$

$$\omega_{Hp2} = \frac{1}{\frac{C_\mu}{2} \cdot 2R_C} = 52.54M\, {}^{rad}\!/_{s}$$

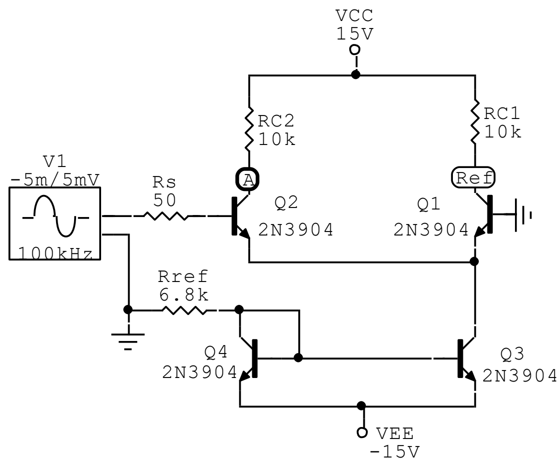
The other pole is non-dominant so the 3dB point may be approximated by ω_{Hp2}

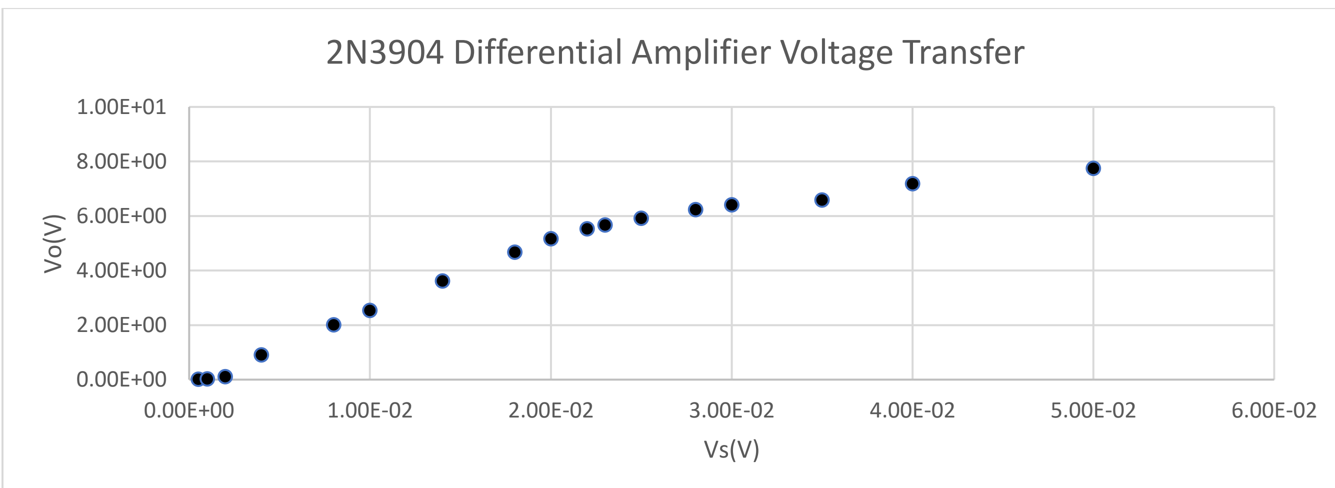
$$f_{H3dB} = \frac{\omega_{Hp2}}{2\pi} = 8.36MHz$$

	f_{H3dB}
Simulated (part A)	4.245MHz
Calculated (part B)	8.36MHz

C. Voltage Transfer curve

Choose a midband frequency of 100kHz and vary the peak amplitude of the source from 0.5mV to 50mV. Measure the output at the node ‘A’ with respect to ‘Ref’. Non-linear behavior starts happening at around 25mV.





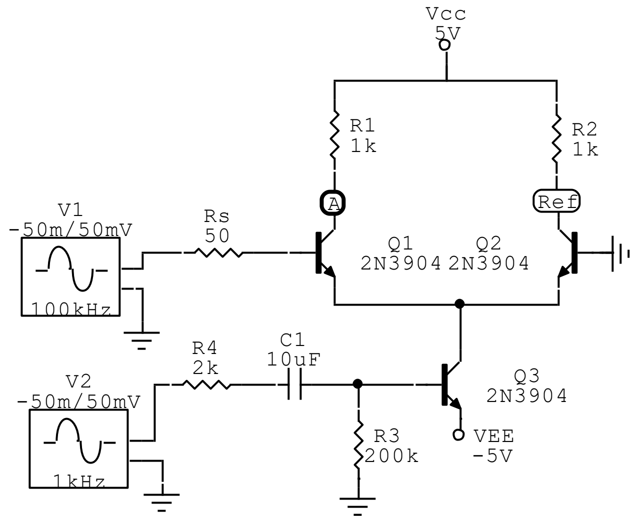
Discussion

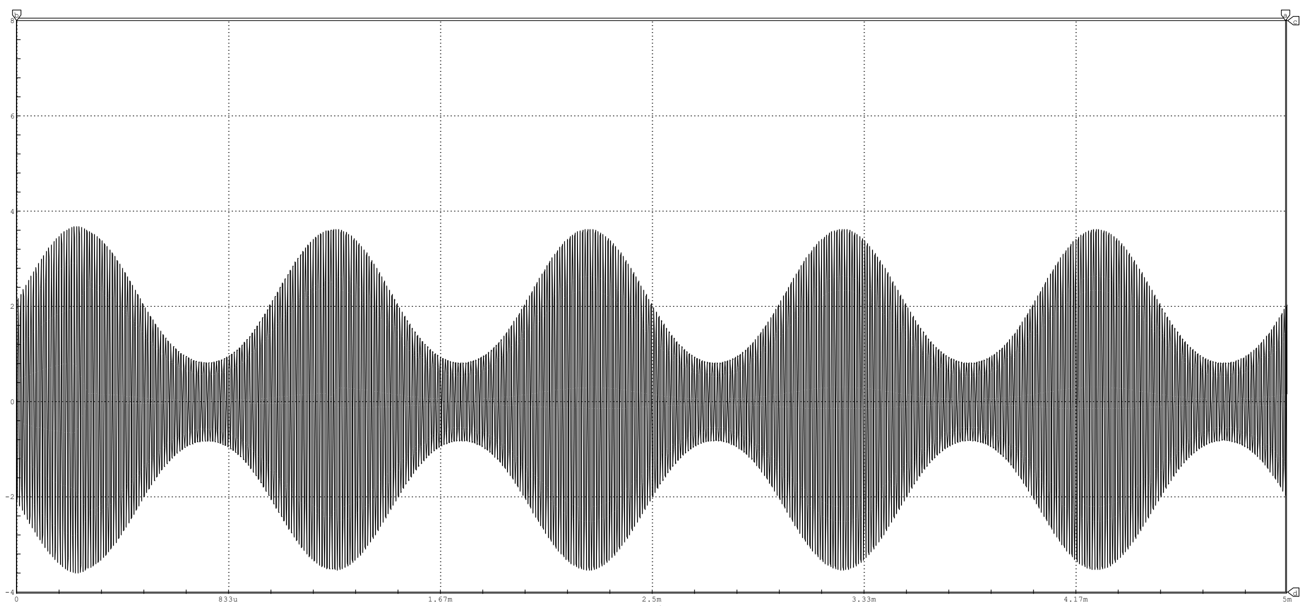
The high frequency cut-off points calculated and simulated are substantially different, this could again be due to the β of 300.

Part 4 Cascaded Amplifiers

A. Differential Output

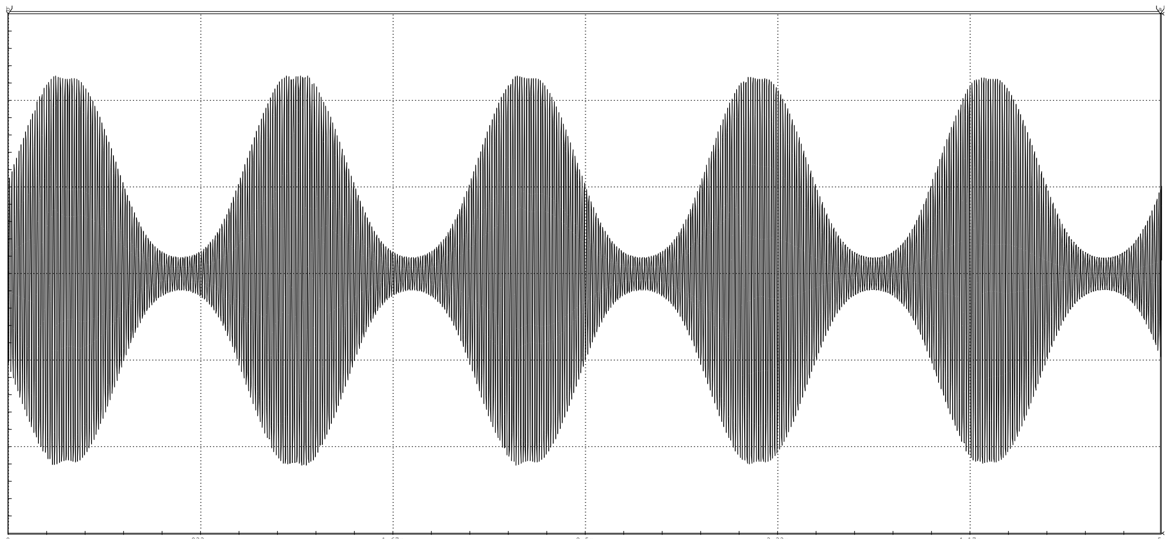
The simulated circuit and its differential output is shown below.





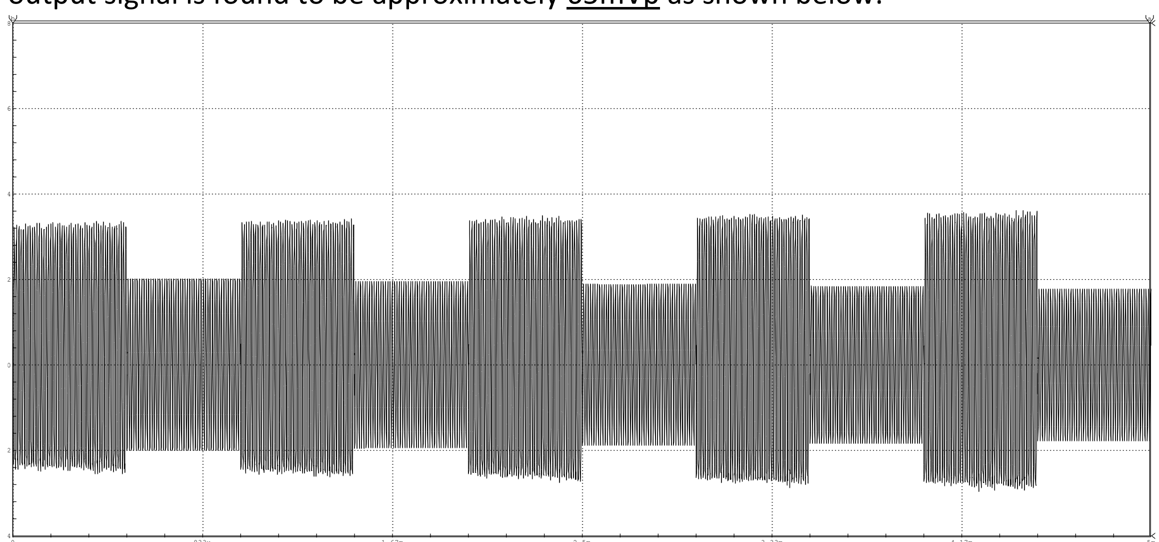
B. Sine wave Saturation

Refer to the appendix for the plots of varying the input signal sine wave between 10mVp – 100mVp. Notice that distortion happens somewhere between 75mVp-85mVp. After testing some values between this range notice the largest input signal that results in an undistorted output signal is found to be 80mVp as shown below.



C. Square wave Saturation

Refer to the appendix for the plots of varying the input signal square between 10mVp – 100mVp. Notice that distortion happens somewhere between 60mVp-70mVp. After testing some values between this range notice the largest input signal that results in an undistorted output signal is found to be approximately 65mVp as shown below.



Discussion

The AM signal works by multiplying the signals together in the time domain (or convoluting them in the frequency domain). The modulated signal will consist of the two frequencies of the carrier and input, so the receiver can reconstruct the input signal by filtering for that specific frequency.

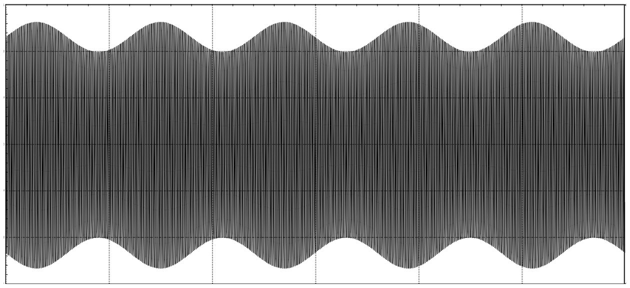
References

1. ELEC 301 Course Notes
2. A. Sedra and K. Smith, "Microelectronic Circuits,"5 th (or higher) Ed., Oxford University Press, New York
3. CircuitMaker™ User's Manual
4. 2N3904 datasheet [https://datasheetspdf.com/pdf-file/1114626/Motorola/2N3904/1]
5. Standard Resistor and Capacitor Values

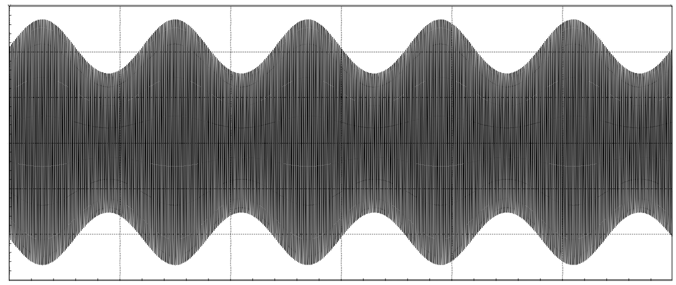
Appendix

Part 4B: Varying the input voltage using a sin wave from 10mVp – 100mVp

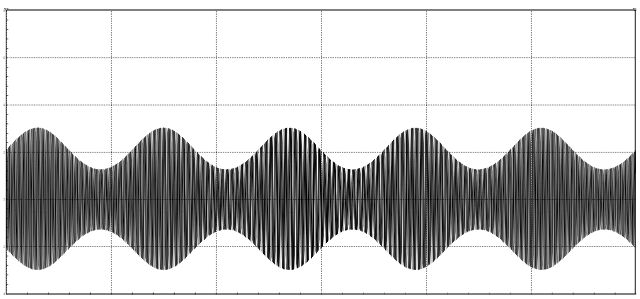
10mVp:



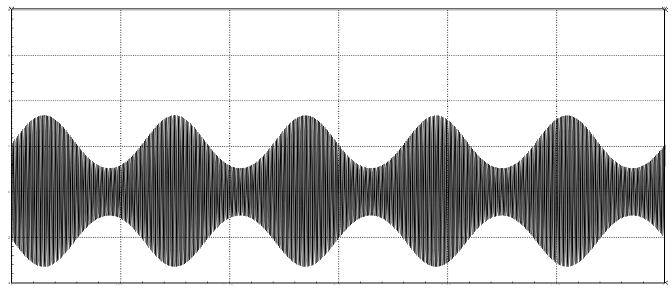
20mVp:



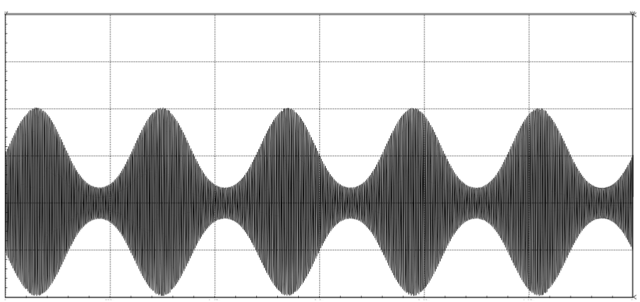
30mVp:



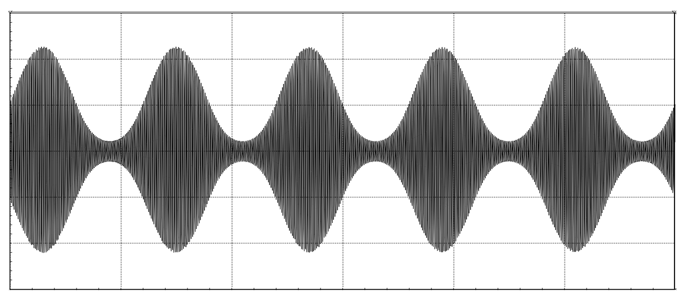
40mVp:



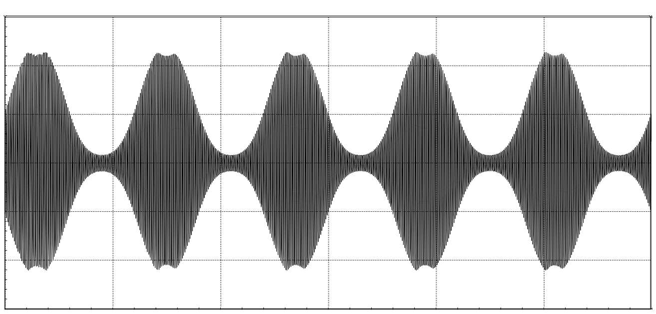
60mVp:



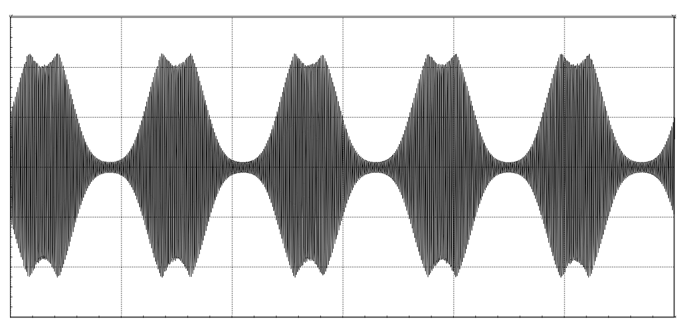
75mVp:



85mVp:

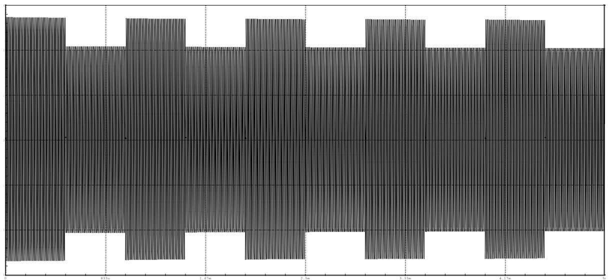


100mVp:

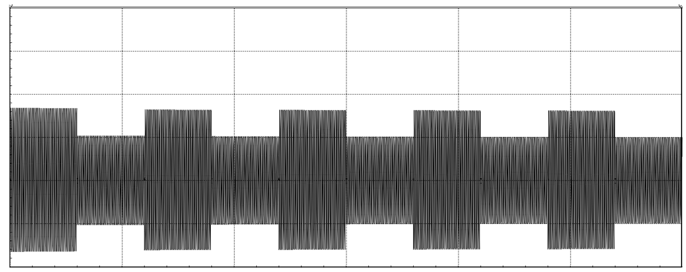


Part 4C: Varying the input voltage using a square wave from 10mVp – 100mVp

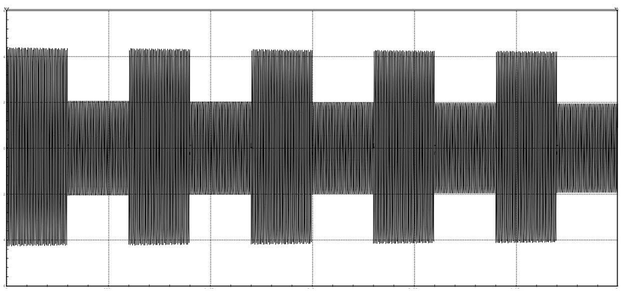
10mVp:



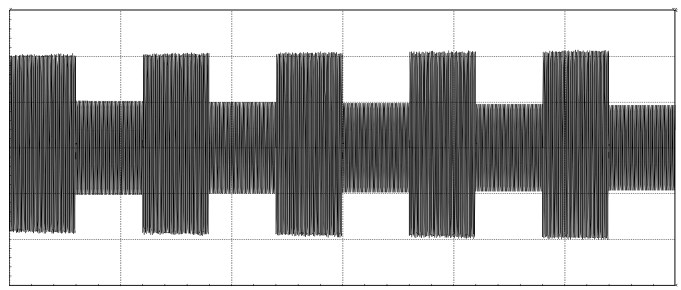
20mVp:



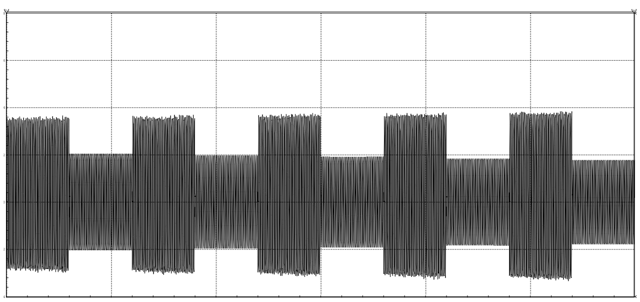
35mVp:



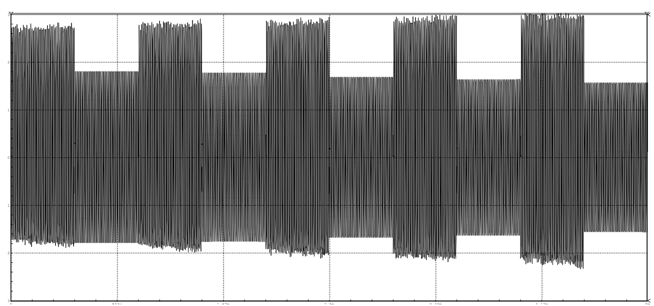
50mVp:



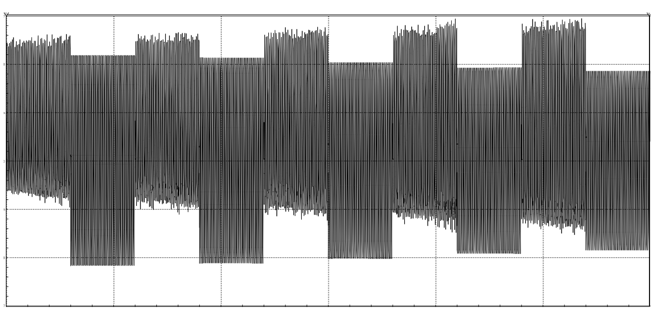
60mVp:



70mVp:



85mVp:



100mVp: