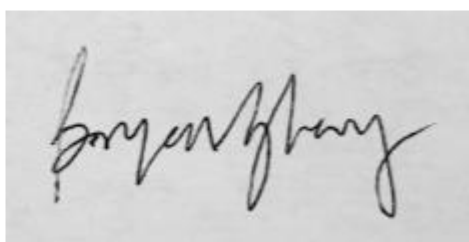
The University of British Columbia

Mini Project 2

ELEC 301 – Electronic Circuits



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Contents

Part 1

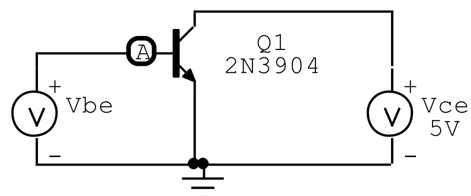
a) 2N3904 datasheet lookup

The datasheet values for the 2N3904 transistor at $V_{CE} = 10V, I_C = 1mA, f = 1kHz$, and $T = 1kHz$ are shown below.

Symbol	Description	Minimum	Maximum
$h_{fe} = \beta$	DC Current Gain	100	400
$h_{ie} = r_\pi$	Input Impedance	1.0 kΩ	10 kΩ
$h_{oe} = 1/r_0$	Output Admittance	1.0 µmhos	40 µmhos

b) 2N3904 characteristics

Here is the circuit used to obtain the graph of I_b vs V_{BE}. I set $V_{CE} = 5V$ and then sweep V_{BE} from 0 to 0.7V in 0.01V increments.



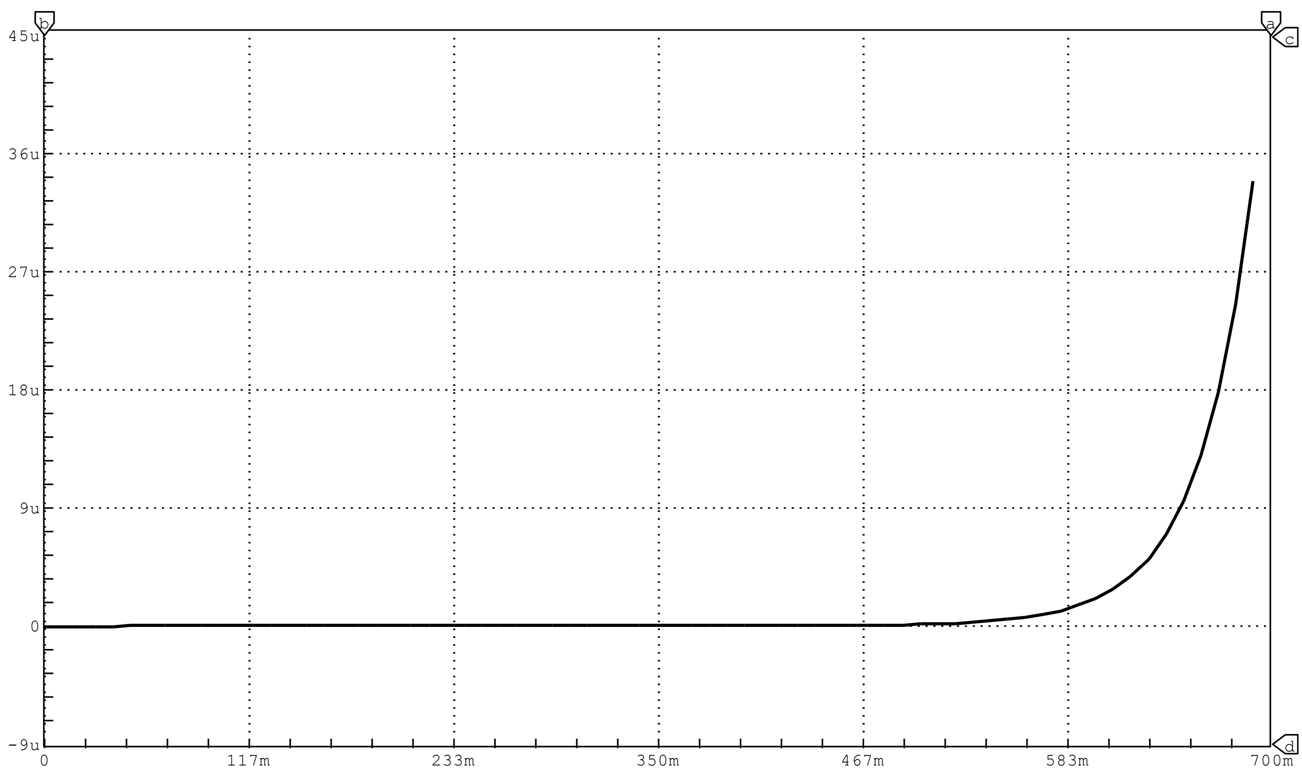
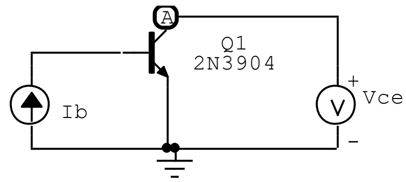


Figure 1: I_B vs V_{BE} graph

To find I_C vs V_{CE} with I_B as the varying parameter the circuit below is simulated. V_{CE} is swept from 0-6V in 20mV increments and I_B is swept from 1-10µA in 0.5µA increments.



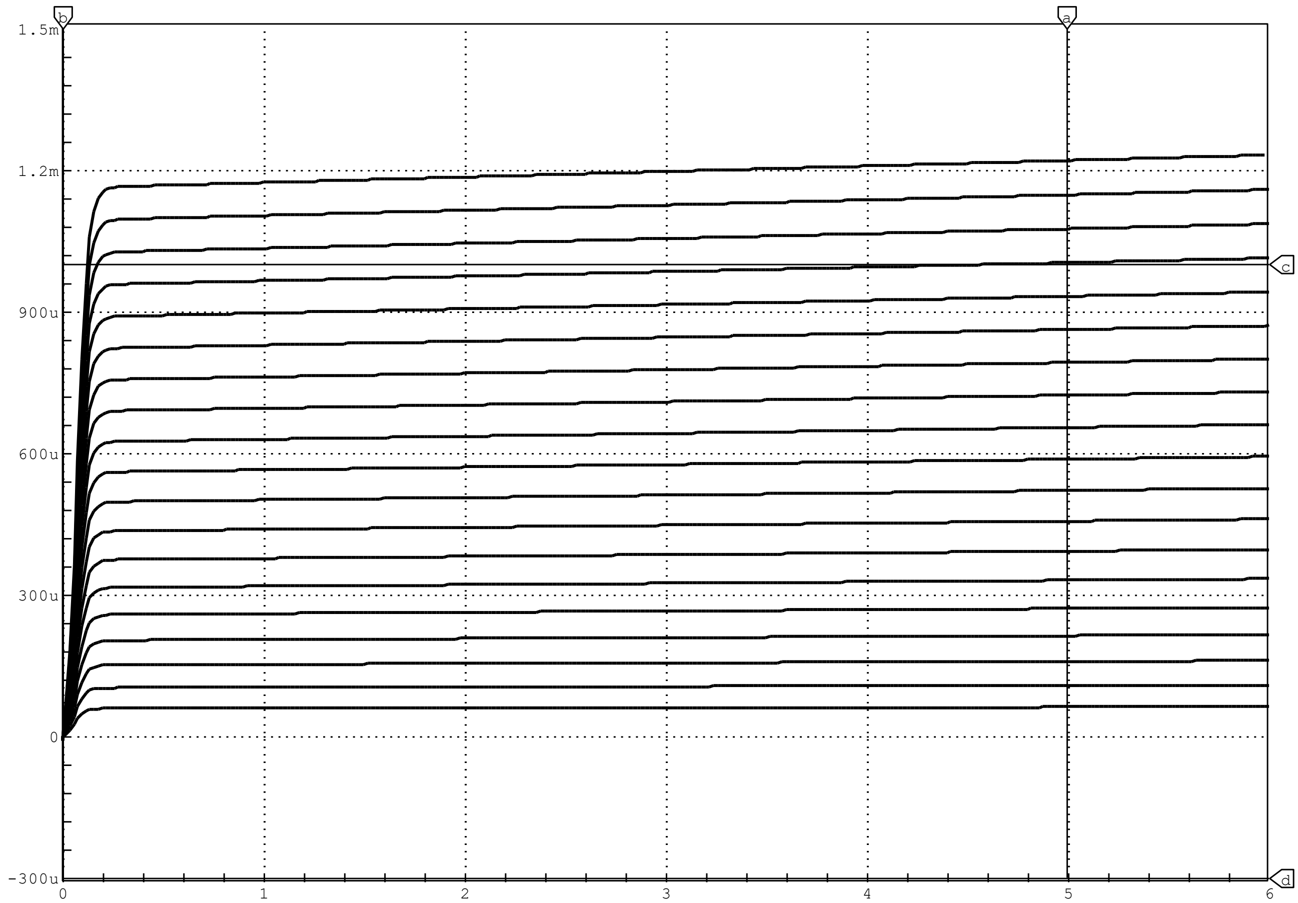


Figure 2: I_C vs V_{CE} with varying I_B

Each line represents a different characteristic, with the bottom line being when I_B is 1 µA and the top line when I_B is 10 µA. The 'a' cursor is set to the value of V_{CE}=5V and the 'c' cursor is set to the value of I_C = 1mA. The intersection of the 2 cursors falls on the 3rd line from the top, so therefore

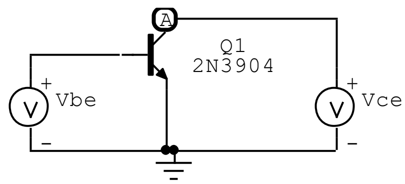
$$I_B = 10 - 3 \cdot 0.5\mu A = \underline{8.5\mu A}.$$

$$\xrightarrow{yields} \beta = \frac{I_C}{I_B} = \frac{1mA}{8.5\mu A} = \boxed{118}$$

$$g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = \boxed{0.04S}$$

$$r_\pi = \frac{\beta}{g_m} = \boxed{2950\Omega}$$

Finally, we can find I_C vs V_{CE} with varying V_{BE} by simulating the below circuit. V_{CE} is the primary and is swept from 0-6V in 20mV increments, and V_{BE} is the secondary swept from 0.55-0.70V in 0.01V increments.



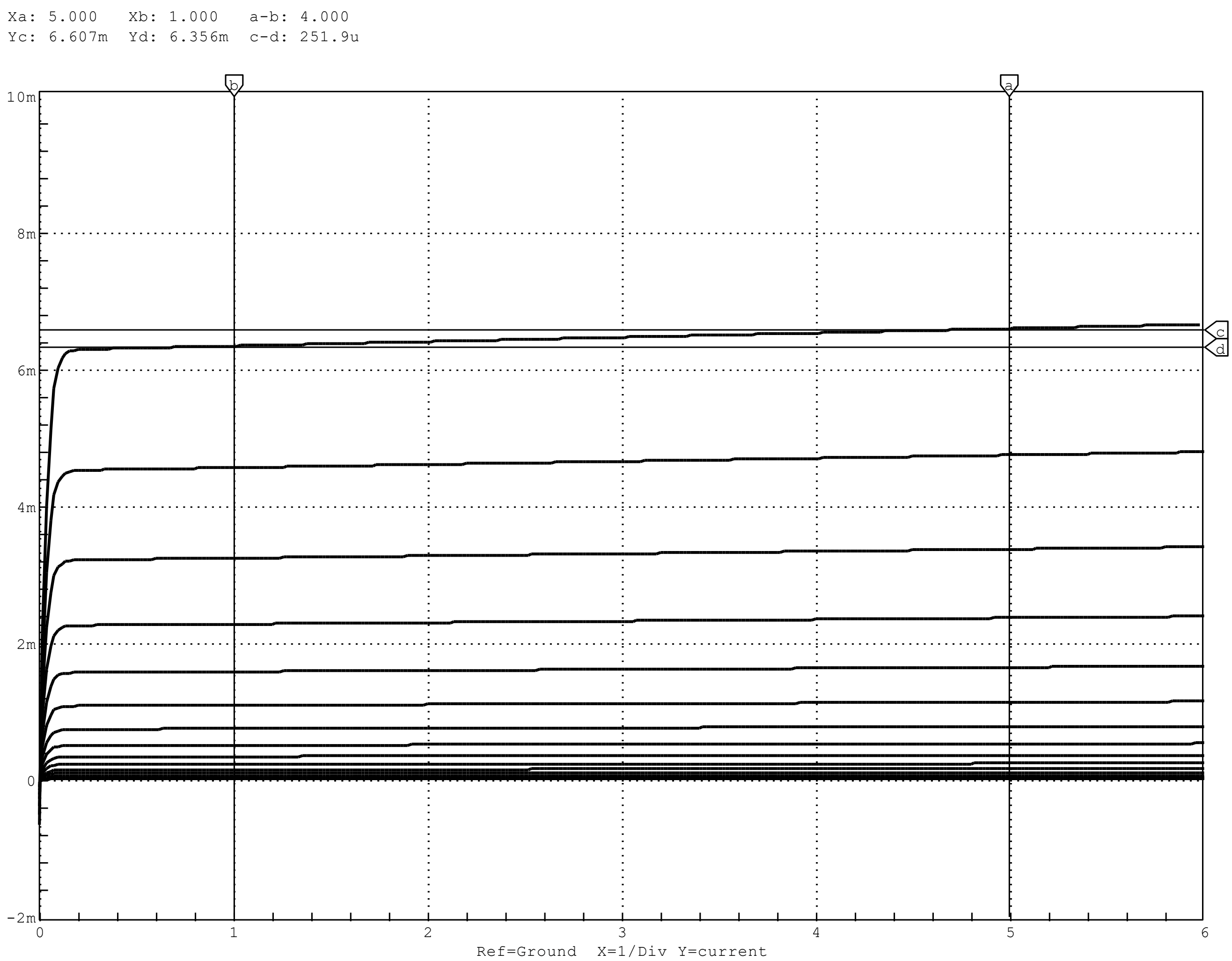


Figure 3: I_C vs V_{CE} with varying V_{BE}

Observe that at I_C=1mA at the intersected curve corresponds to $\underline{V_{BE} = 0.65V}$. The slope of the top curve can be calculated as $m = \frac{c-d}{a-b}$ where a, b, c, d are the cursor positions.

$$m = \frac{c-d}{a-b} = \frac{251.9 \cdot 10^{-6}A}{4V} = 6.30 \cdot 10^{-5}S$$

An equation of the line can be found using point-slope form $y - y_1 = m(x - x_1)$. The X_b, Y_d point is selected but any of the two points may be used.

$$I_C - 6.356 \cdot 10^{-3} = 6.30 \cdot 10^{-5}(V_{CE} - 1)$$

Now the early voltage can be found at the x-intercept when I_C=0:

$$-6.356 \cdot 10^{-3} = 6.30 \cdot 10^{-5}(V_A - 1) \xrightarrow{yields} V_A = |-100| = 100V$$

$$r_0 = \frac{V_A}{I_C} = \frac{100}{1mA} = \boxed{100k\Omega}$$

Comparing Measured value to datasheet values

The measured values of β, r_π, and $1/r_0$ all fall in between the minimum and maximum value found in the data sheet for the *2N3904* transistor.

c) Biasing

Biassing from measured plot (i)

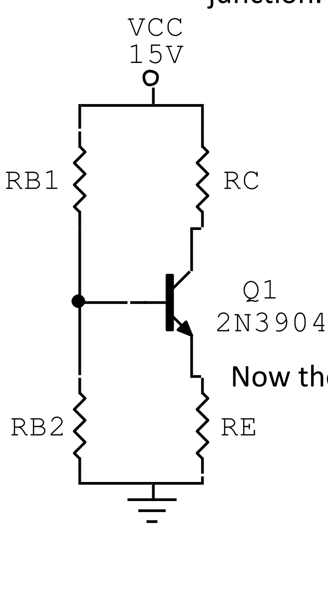
The measured parameters from the curves are $\beta = 118$ and V_{BE} = 0.65V.

In addition, V_{CC} = 15V, I_C = 1mA, V_{CE} < 4V, R_E=R_C/2. The other currents may be determined as follows:

$$I_B = \frac{I_C}{\beta} = \frac{1mA}{118} = 8.47\mu A$$

$$I_E = I_B + I_C = 8.47\mu A + 1mA = 1.0084mA$$

Next R_C and R_E can be determined by doing KVL from V_{CC} to ground across the collector-emitter junction. V_{CE} can be set to 3V since it is less than 4V.



$$V_{CC} = I_C R_C + I_E R_E + V_{CE} = I_C R_C + \frac{1}{2} I_E R_C + V_{CE}$$

$$\xrightarrow{yields} R_C = \frac{V_{CC} - V_{CE}}{I_C + \frac{1}{2} I_E} = \frac{15 - 3}{1mA + \frac{1}{2} \cdot 1.0084mA} = 7978\Omega$$

$$R_E = \frac{R_C}{2} = 3989\Omega$$

Now the voltage of the emitter, collector, and base can be calculated.

$$V_E = I_E R_E = 1.0084mA \cdot 3989\Omega = 4.022V$$

$$V_C = V_E + V_{CE} = 4.022V + 3V = 7.022V$$

$$V_B = V_E + V_{BE} = 4.012V + 0.65V = 4.662V$$

The following 2 equations can be used to determine the values of R_{B1} and R_{B2}.

$$KCL: \frac{V_{CC} - V_B}{R_{B1}} = I_B + \frac{V_B}{R_{B2}}$$

$$KVL: V_{CC}\left(\frac{R_{B2}}{R_{B1} + R_{B2}}\right) - I_B(R_{B1}||R_{B2}) - V_B = 0$$

These equations do not provide a unique solution, so I arbitrarily chose R_{B1}=10kΩ which gives R_{B2}=4.55 kΩ.

R_C	R_E	R_{B1}	R_{B2}
7978Ω	3989Ω	10kΩ	4.55kΩ

Here are the results of the simulation for the d.c operating point for the *2N3904*.

I_C	I_B	I_E	V_B	V_C	V_E
998.6μA	8.590 μA	1.007mA	4.664V	7.034V	4.017V

Biassing using the 1/3 rule (ii)

I will use the first version of the 1/3 rule which states that:

$$V_B = \frac{1}{3}V_{CC} = 5V, V_C = \frac{2}{3}V_{CC} = 10V, I_1 = \frac{I_E}{\sqrt{\beta}}$$

Using $\beta = 118$ and V_{BE} = 0.65V we find that $V_E = V_B - V_{BE} = 4.35V$

Subsequently the currents are calculated

$$I_B = \frac{I_C}{\beta} = \frac{1mA}{118} = 8.47\mu\text{A}$$

$$I_E = I_B + I_C = 8.47\mu A + 1mA = 1.0084mA$$

$$I_1 = \frac{I_E}{\sqrt{\beta}} = \frac{1.0084mA}{\sqrt{118}} = 92.83\mu A$$

$$I_2 = I_1 - I_B = 92.83\mu A - 8.47\mu A = 84.36\mu A$$

Finally, the resistances are calculated

$$R_C = \frac{V_{CC} - V_C}{I_C} = 5k\Omega$$

$$R_E = \frac{V_E}{I_E} = \frac{4.35V}{1.0084mA} = 4.314k\Omega$$

$$R_{B1} = \frac{V_{CC} - V_B}{I_1} = \frac{10V}{92.83\mu A} = 107.72k\Omega$$

$$R_{B2} = \frac{V_B}{I_2} = \frac{5V}{84.36\mu A} = 59.27k\Omega$$

The d.c operating point values of the biased circuit using the 1/3 rule is shown below.

I_C	I_B	I_E	V_B	V_C	V_E
1.001mA	8.431μA	1.010mA	5.002V	9.994V	4.356V

Using standard resistors (iii)

Replace the resistances calculated using the 1/3 rule with standard resistors.

$$R_C = 5.1k\Omega, R_E = 4.3k\Omega, R_{B1} = 110k\Omega, R_{B2} = 62k\Omega$$

I_C	I_B	I_E	V_B	V_C	V_E
1.020mA	8.575μA	1.028mA	5.067V	9.801V	4.420V

Every method biases the circuit correctly however using the 1/3 rule is much faster and still provides accurate results while allowing versatility when selecting the resistances.

d) *2N2222A* and *2N4401* d.c operating points (iv)

Using the same standard resistance values, we replace the *2N3904* with the *2N2222A* and *2N4401* and measure their d.c operating points.

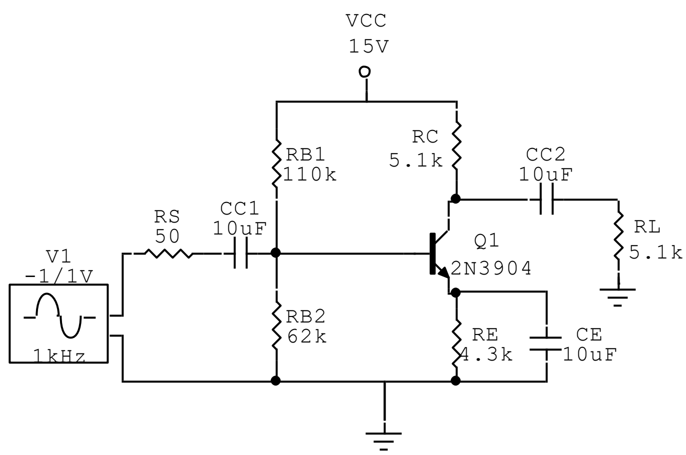
	I_C	I_B	I_E	V_B	V_C	V_E
2N3904	1.020mA	8.575μA	1.028mA	5.067V	9.801V	4.420V
2N222A	1.055mA	6.285μA	1.061mA	5.158V	9.629V	4.556V
2N4401	1.035mA	6.971μA	1.042mA	5.131V	9.731V	4.472V

The BJTs are still biased properly in the active region. Therefore the 1/3 rule is a valid method of biasing BJTs even with different β values.

Part 2

a) *2N3904 & 2N4401* Common Emitter Amplifier

Here is the biased common emitter amplifier using the *2N3904*.

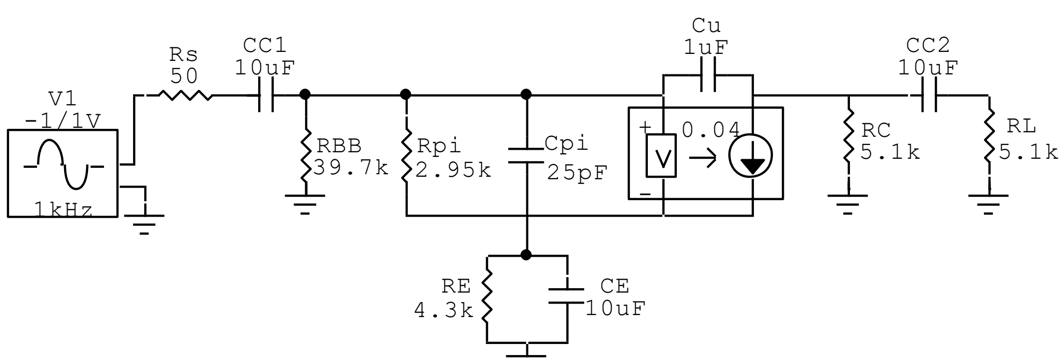


The magnitude and phase(degrees) bode plots are included in the appendix simulated from 1mHz to 100GHz. Calculate C_π and C_μ using the d.c operating point g_m=0.04S and V_{CB} = 5V and the SPICE model parameters of the *2N3904*.

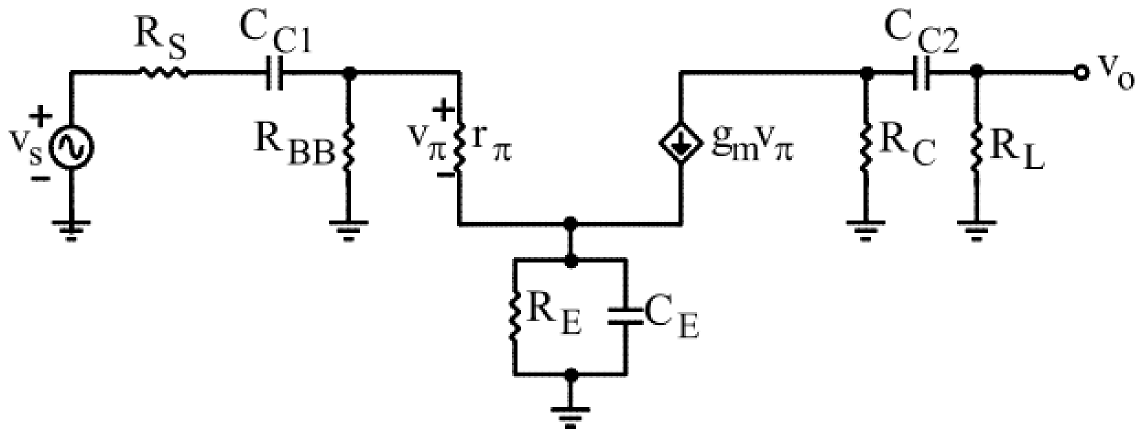
$$C_\pi = 2 \cdot CJE + TF \cdot g_m = 2 \cdot 4.5pF + 400ps \cdot 0.04 = 25pF$$

$$C_\mu = \frac{CJC}{\left(1 + \frac{V_B}{VJC}\right)^{MJC}} = \frac{3.5pF}{(1 + \frac{5}{0.75})^{0.330}} \approx 2pF$$

The complete small-signal model is created for the *2N3904*. Recall r_π = 2950Ω and β=118 from part 1.



Applying Miller's theorem and Thevenin equivalent for the CE amplifier like in the course notes can yield the zeros and poles. There are two coupling capacitors so it is known that there will be 2 low frequency zeros at zero. This is the Low Frequency Small-Signal Model.



$$f_{Lz1} = f_{Lz2} = 0\ Hz$$

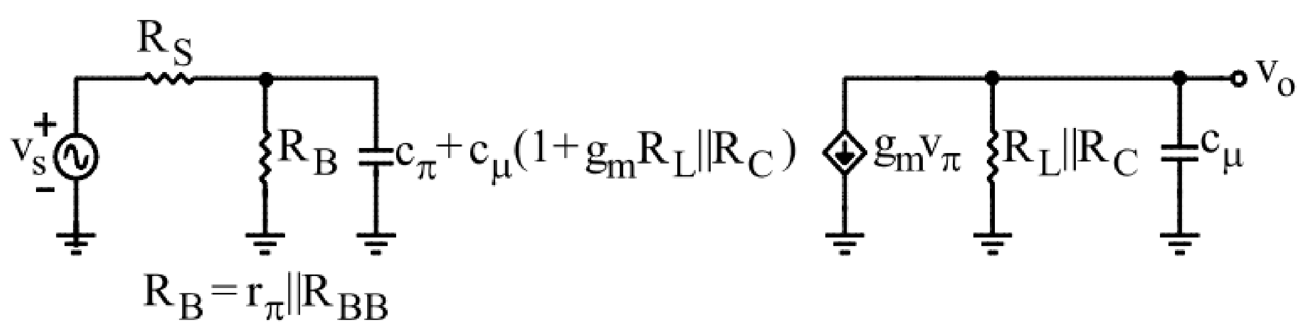
$$f_{Lz3} = \frac{1}{2\pi R_E C_E} = 3.70\ Hz$$

$$f_{Lp2} = \frac{1}{2\pi(R_C + R_L)C_{C2}} = 1.56\ Hz$$

$$f_{Lp1} = \frac{1}{2\pi\big(R_s + R_{BB}||(r_\pi + (1+\beta)R_E)\big)C_{C1}} = 432\ mHz$$

$$f_{Lp3} = \frac{1}{2\pi C_E\left(\left(\frac{r_\pi + R_{BB}||R_S}{1+\beta}\right)||R_E\right)} = 635\ Hz$$

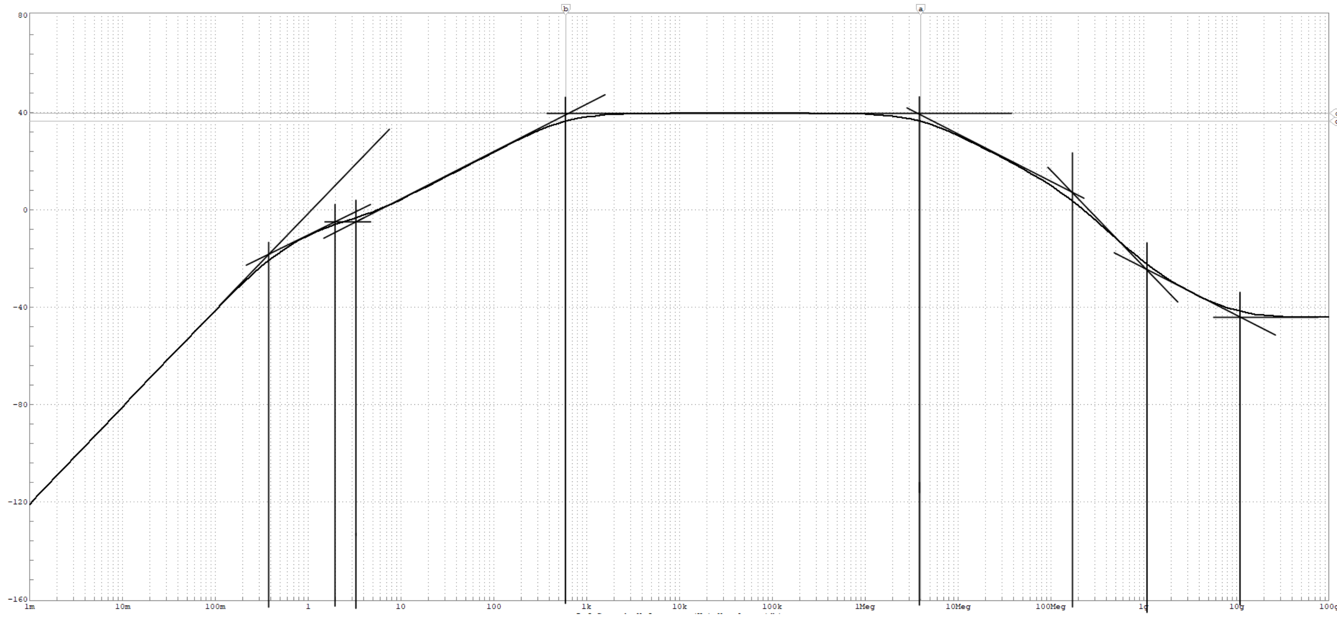
This is the High Frequency Small-Signal Model.



$$f_{Hp1} = \frac{1}{2\pi((R_{BB}||r_\pi)||R_S)(c_\pi + g_m \cdot R_L||R_C)} = 15.5\ MHz$$

$$f_{Hp2} = \frac{1}{2\pi(R_C||R_L)c_\mu} = 34.9\ MHz$$

Here are the locations of the poles and zeros estimated using linear approximation.



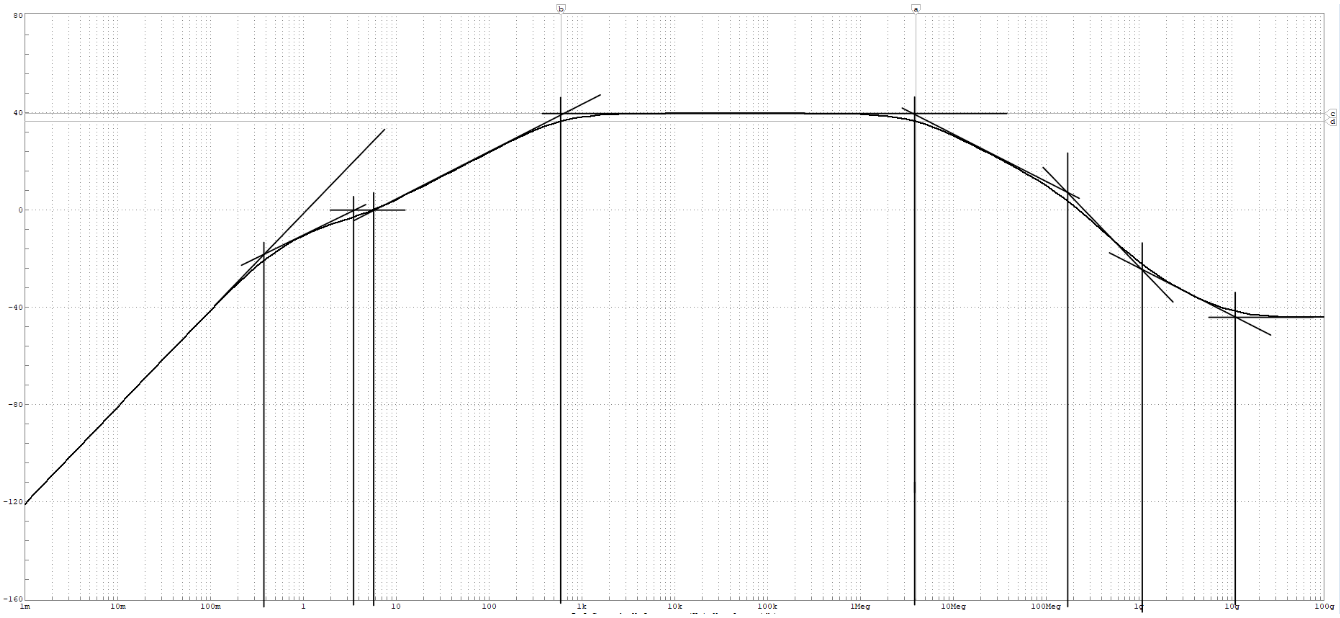
This table summarizes the calculated and graphically measured locations of the poles and zeros in Hz.

2N3904	f_{Lz1}	f_{Lz2}	f_{Lp1}	f_{Lp2}	f_{Lz3}	f_{Lp3}	f_{Hp1}	f_{Hp2}	f_{Hz1}
Calculated	0	0	0.432	1.56	3.70	635	15.5M	34.9M	∞
Measured	0	0	0.400	2.2	4	600	10M	600M	5G
% error	0	0	8%	29.1%	7.5%	5.83%	55%	94.1%	

The graphically measured values are quite like the calculated values other than the high frequency poles. There was also a high frequency zero in the simulated result.

Now replace the *2N3904* with the *2N4401*. The magnitude and phase bode plots simulated from 1mHz to 100GHz for the *2N4401* are included in the appendix. Recalculate the location of the poles and zeros the same way as done before, except with new parameters for the parasitic capacitances of the *2N4401*, and then recalculate β and r_π. β = 148, r_π = 3586Ω. C_π=67.28pF, C_μ=5.2pF.

Then, graphically measure the poles/zeros with linear approximation and compare with the calculated.



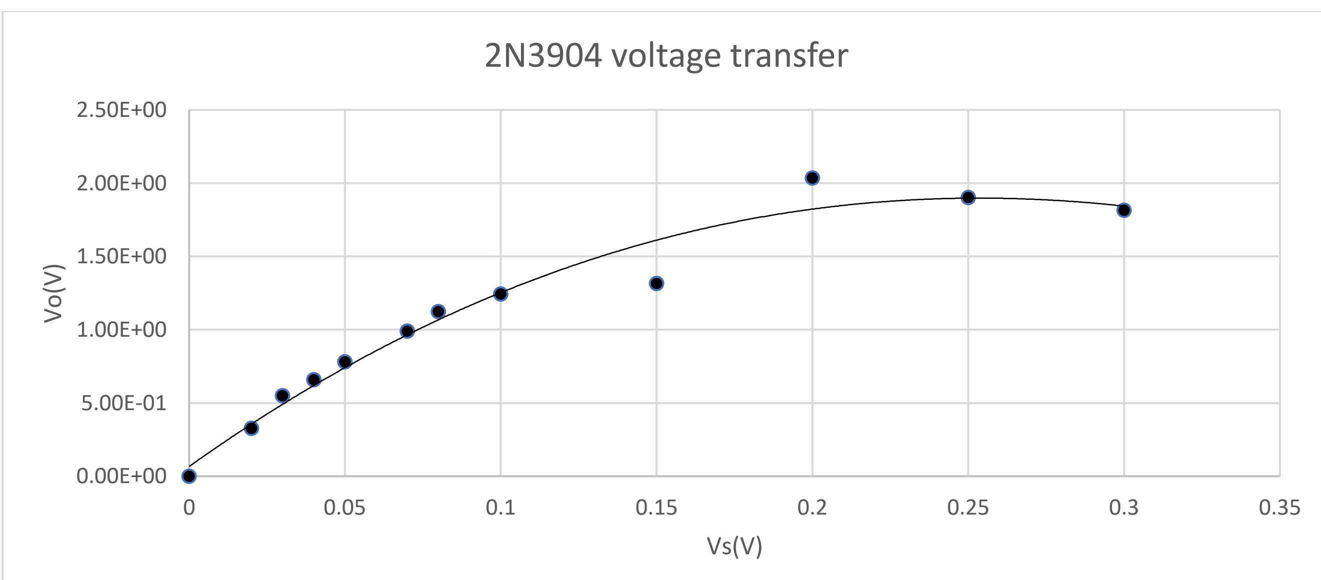
Here are the calculated and graphically measured frequencies in Hz for the 2N4401.

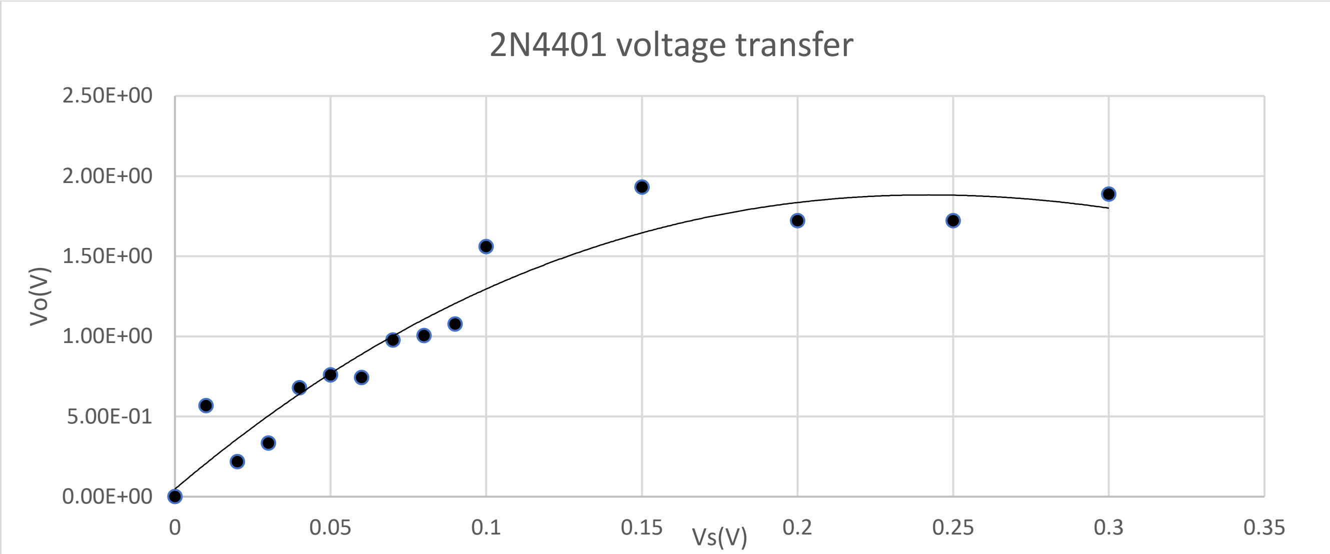
2N4401	f_{Lz1}	f_{Lz2}	f_{Lp1}	f_{Lp2}	f_{Lz3}	f_{Lp3}	f_{Hp1}	f_{Hp2}	f_{Hz1}	f_{Hz2}
Calculated	0	0	0.426	1.56	3.70	655	5.19M	11.9M	∞	∞
Measured	0	0	0.390	2	3.40	600	4M	190M	1G	10G
% error	0	0	9.23%	22%	8.82%	9.17%	29.8%	93.7%		

Again, the graphically measured values are quite like the calculated values other then the high frequency poles. There are also two a high frequency zero in the simulated result.

b) Midband Voltage Transfer Curve

A midband frequency of 100kHz is selected for this test. The input voltage source amplitude is varied from 0-0.3V.

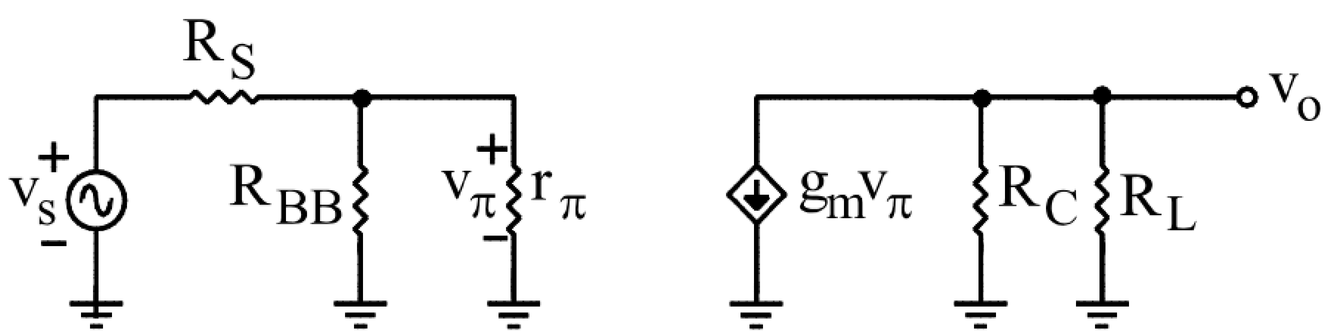




The non-linear behavior starts to happen around <u>0.1V</u> for both transistors.

c) <u>Midband Input Impedance</u>

Here is the circuit at midband. C_E will be shorted, and so the emitter will be grounded.



The input impedance for the *2N3904* can be <u>calculated</u> as $Z_{in} = R_{BB}||r_\pi = \boxed{2745\Omega}$

The input impedance for the *2N4401* is $Z_{in} = R_{BB}||r_\pi = \boxed{3289\Omega}$

To measure the input impedance set the AC source to 100kHz with 1V amplitude and then use the AC multimeter to measure the input current and base voltage.

$$Z_{in} = \frac{V_B}{I_{in}} = \frac{6.12mV}{1.755\mu A} = \boxed{3487\Omega}\ (2N3904)$$

$$Z_{in} = \frac{V_B}{I_{in}} = \frac{6.14mV}{1.379\mu A} = \boxed{4453\Omega}\ (2N4401)$$

d) <u>Midband Output Impedance</u>

At the midband the impedance seen at the output impedance is simply R_C. A 10mV, 10kHz source is used.

$$Z_{out} = R_C = \boxed{5.1k\Omega}$$

The output impedance is measured by

$$Z_{out} = \frac{V_o}{I_{out}} = \frac{570.1mV}{111.8\mu A} = \boxed{5.1k\Omega}\ (2N3904)$$

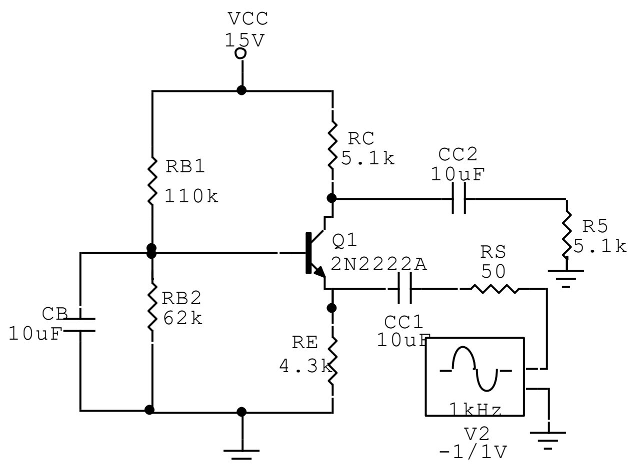
$$Z_{out} = \frac{V_o}{I_{out}} = \frac{592.4mV}{116.2\mu A} = \boxed{5.1k\Omega}\ (2N4401)$$

e) Transistor selection

The *2N3904* has a larger bandwidth than the *2N4401* with other characteristics remaining similar. For an amplifier a wider bandwidth gives the best performance, so the *2N3904* should be selected.

Part 3

a) 2N2222A Common Base Amplifier poles & zeros



Calculate c_π=75.7pF and c_μ=7.76pF with the new circuit parameters. The d.c operating point calculated in part 1 for the *2N2222A* can be used to calculate $\beta = 168$, $g_m = 0.0422$, and $r_\pi = 3981\Omega$. There are 2 zeros at zero due to the coupling capacitors. We find the locations of the remaining poles/zeros using formulas taught in the class.

$$f_{Lz1} = f_{Lz2} = 0\ Hz$$

$$f_{Lz3} = \frac{1}{2\pi R_{BB} C_B} = 0.401\ Hz$$

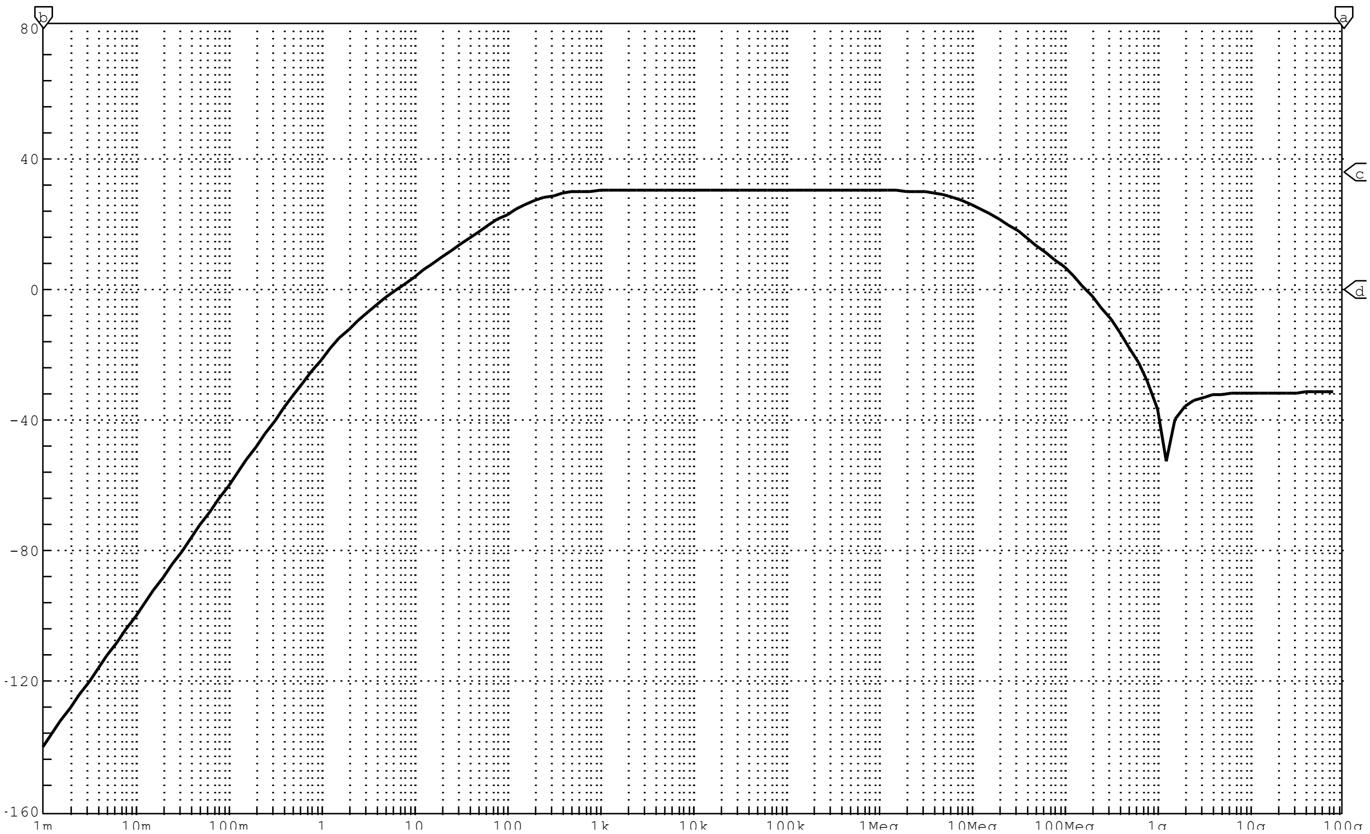
$$f_{Lp1} = \frac{1}{2\pi(R_{BB}||(r_\pi + (1+\beta)R_E))C_B} = 0.423\ Hz$$

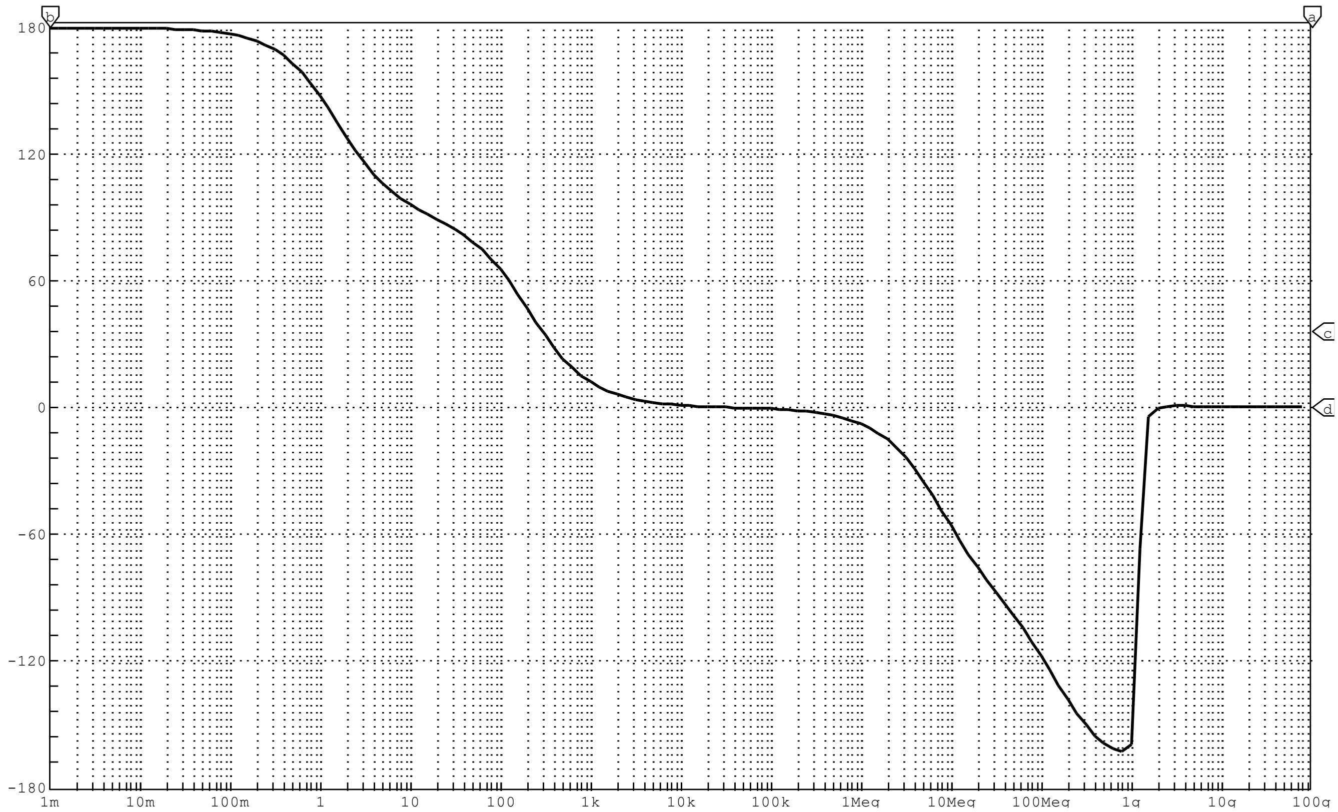
$$f_{Lp2} = \frac{1}{2\pi(R_C + R_L)C_{C2}} = 1.56\ Hz$$

$$f_{Lp3} = \frac{1}{2\pi\left(\frac{r_\pi}{1+\beta}||R_E + R_S\right)C_{C1}} = 217\ Hz$$

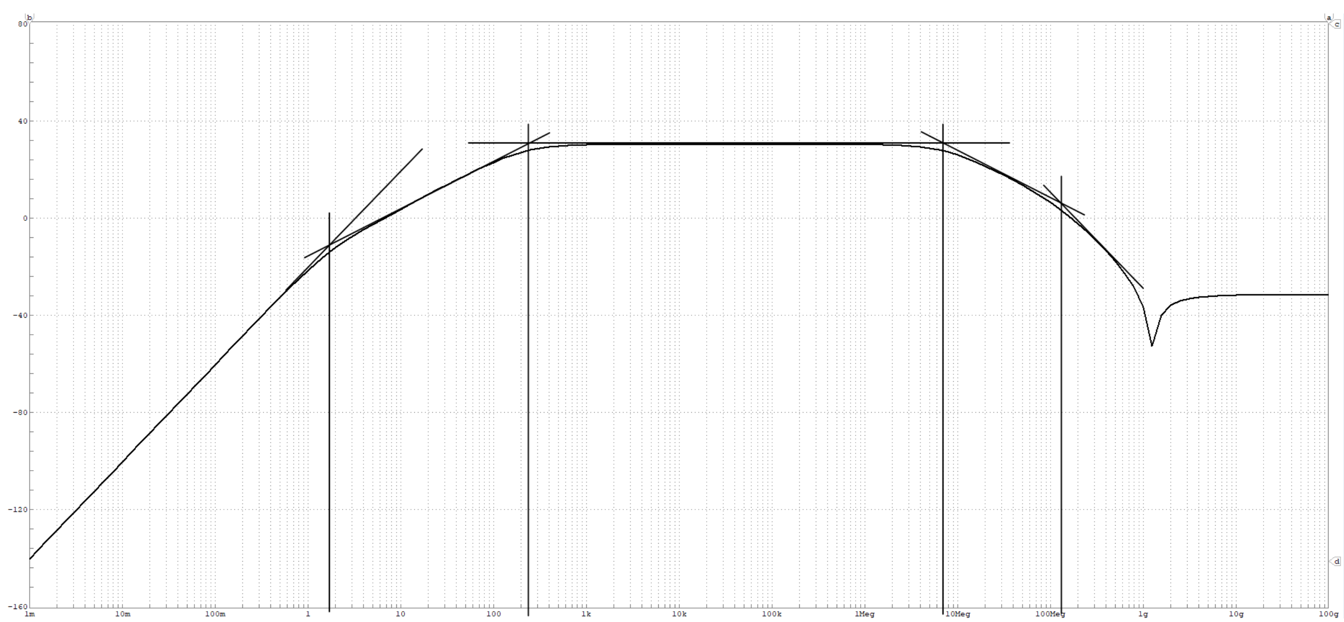
$$f_{Hp1} = \frac{1}{2\pi(R_C||R_L)c_\mu} = 8.04\ MHz$$

$$f_{Hp2} = \frac{1}{2\pi\left(\frac{r_\pi}{1+\beta}||R_E||R_S\right)c_\pi} = 132\ MHz$$





Approximate the locations using linear approximation. There must be a low frequency pole and zero that occur in the same location (as shown in the calculations), these are marked in the table by *.

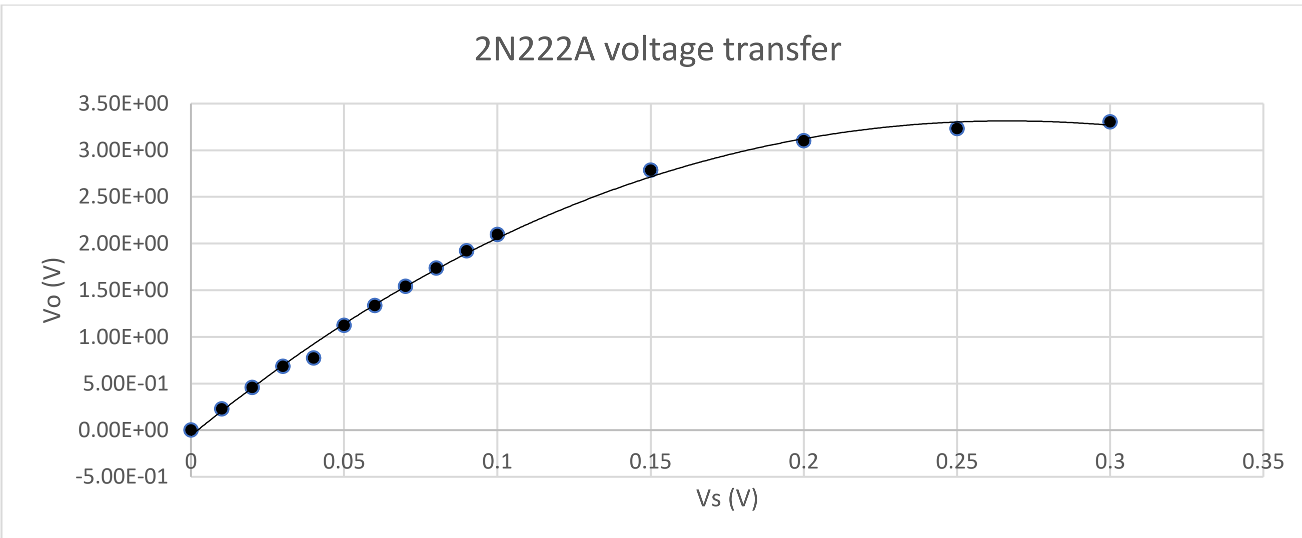


Here are the calculated and approximated values for the locations of the poles in Hz. The cusp at ~1GHz may be caused by multiple zeros or a complex pole.

2N2222A	f_{Lz1}	f_{Lz2}	f_{Lz3}	f_{Lp1}	f_{Lp2}	f_{Lp3}	f_{Hp1}	f_{Hp2}
Calculated	0	0	0.401	0.423	1.56	217	8.04M	132M
Measured	0	0	0.401*	0.423*	1.80	220	8M	130M
% error	0	0	0	0	13.3%	1.36%	0.5%	1.54%

b) Voltage Transfer Curve

Use a 1kHz source and vary the amplitude. It starts to become non-linear at around V_s = 0.1V.



c) Midband Input Impedance

Calculate the input impedance as $Z_{in} = R_E || \frac{1}{1+\beta} r_\pi = \boxed{23.4\Omega}$

To measure the input impedance, short the source resistance and apply a source with 10mV amplitude and 100kHz frequency. Use the AC RMS multimeter to measure the emitter voltage and input current.

$$Z_{in} = \frac{V_E}{I_{in}} = \frac{1.011mV}{40.09\mu A} = \boxed{25.2\Omega}$$

d) Midband Output Impedance

The output impedance is simply $Z_{out} = R_C = \boxed{5.1k\Omega}$

$$Z_{out} = \frac{V_C}{I_{in}} = \frac{70.36mV}{13.97\mu A} = \boxed{5.04k\Omega}$$

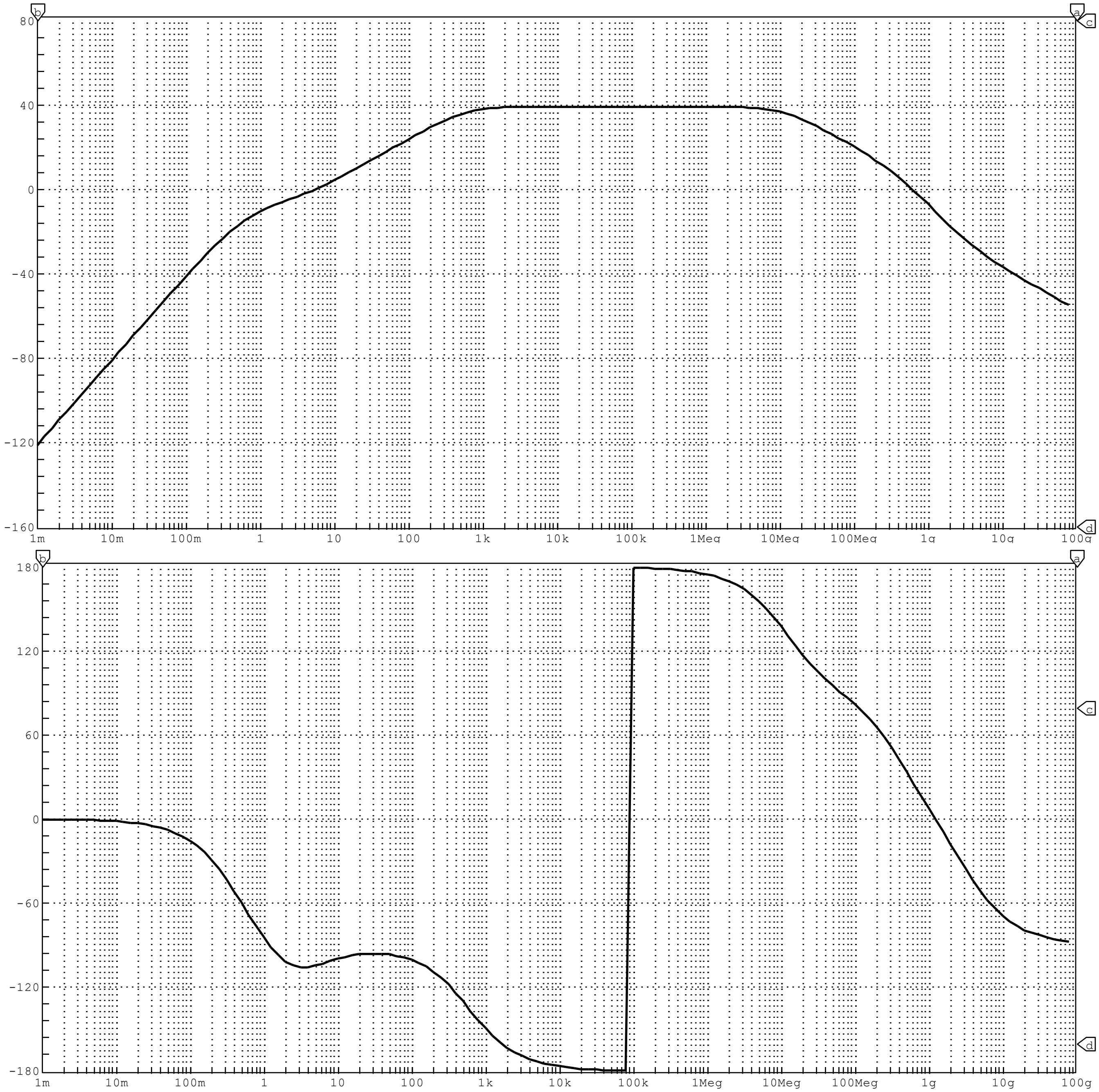
References

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 2a:

2N3904 magnitude/phase bode plot:



2N4401 magnitude/phase bode plot: