Mini Project 2

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Task 1 a)

From the 2N3904 datasheet it can be found that $h_{fe} = \beta = 100\ to\ 400, h_{ie} = r_\pi = 1000\ to\ 10000, and\ \frac{1}{h_{oe}} = r_o = 10^6\ to\ 2.5 * 10^4$

Task 1 b i)

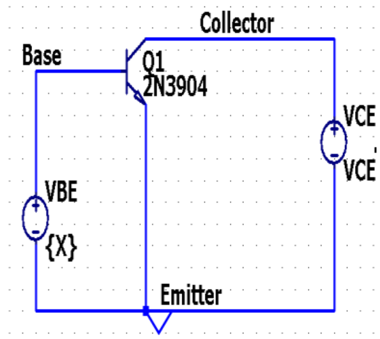

Figure 1: The circuit setup used for task 1b)

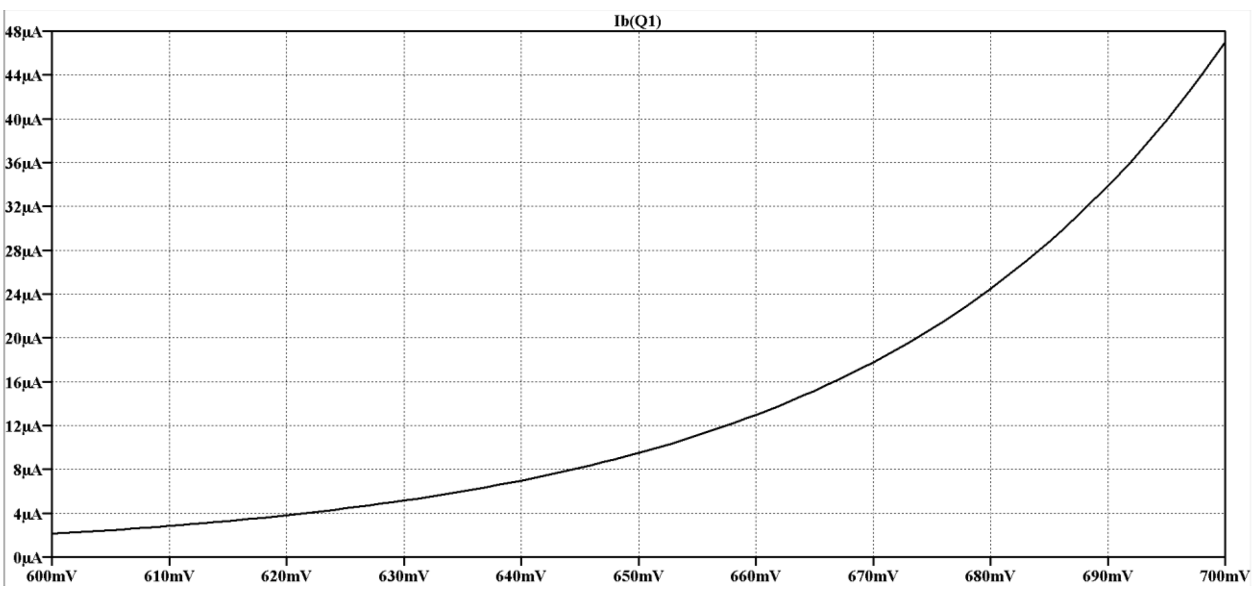

Figure 2: IB vs VBE with VCE=5V

Task 1 b ii)

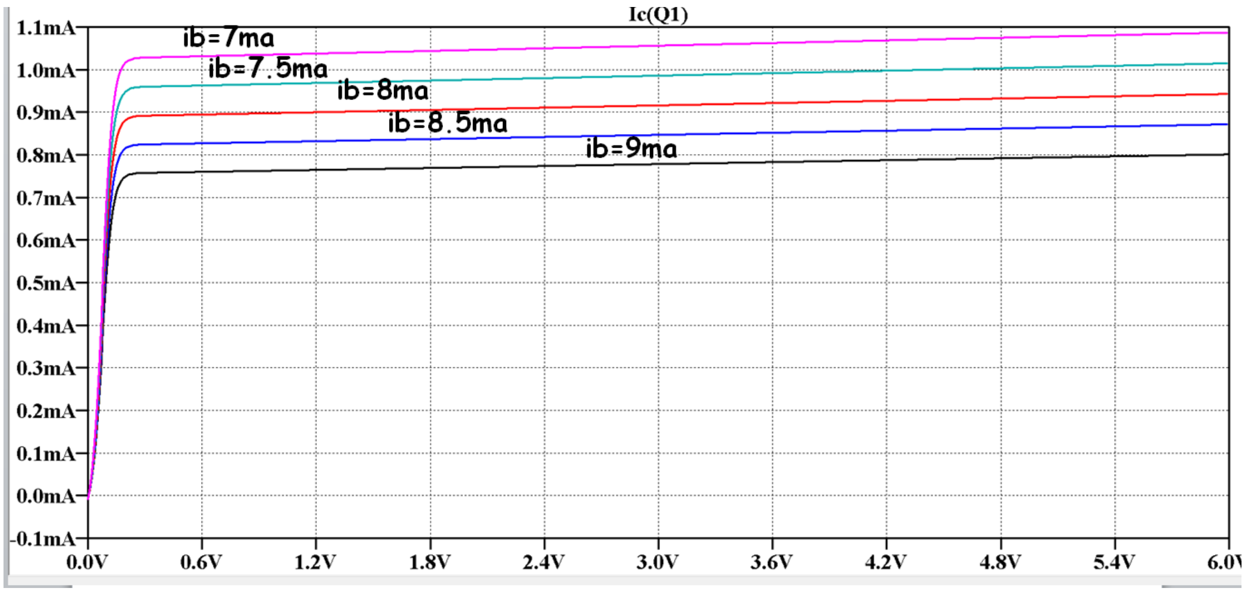

Figure 3: IC vs VCE with IB varying

From the graph with current being stepped in Figure 3, if VCE=5v then IC=1mA can be achieved if IB=8.5μA. As described in class, $\beta = \frac{\Delta ic}{\Delta ib}$ where Ib is small, so we step IB from $8\mu A$ to $9\mu A$. ltspice calculates the difference and we get $\frac{142.929*10^{-6}}{10^{-6}} = 142.929$

To find r_o at VCE=5v IB=1ma, one can look at rise over run of IC vs VCE, $r_o = \frac{VCE}{IC} = \left|\frac{\Delta VCE}{\Delta IC}\right|$

We can pick an increment of VCE from 4.9V to 5.1V and an increment of IC from 1.006mA to 1.004mA, $r_0 = \frac{5.101-4.901}{(1.006-1.004)*10^{-3}} = 10.3825K\Omega$

The early voltage can be estimated as $v_A \approx r_0 i_c = 1.03825 * 10^5 * 10^{-3} = 103.825\Omega$

Task 1 b iii)

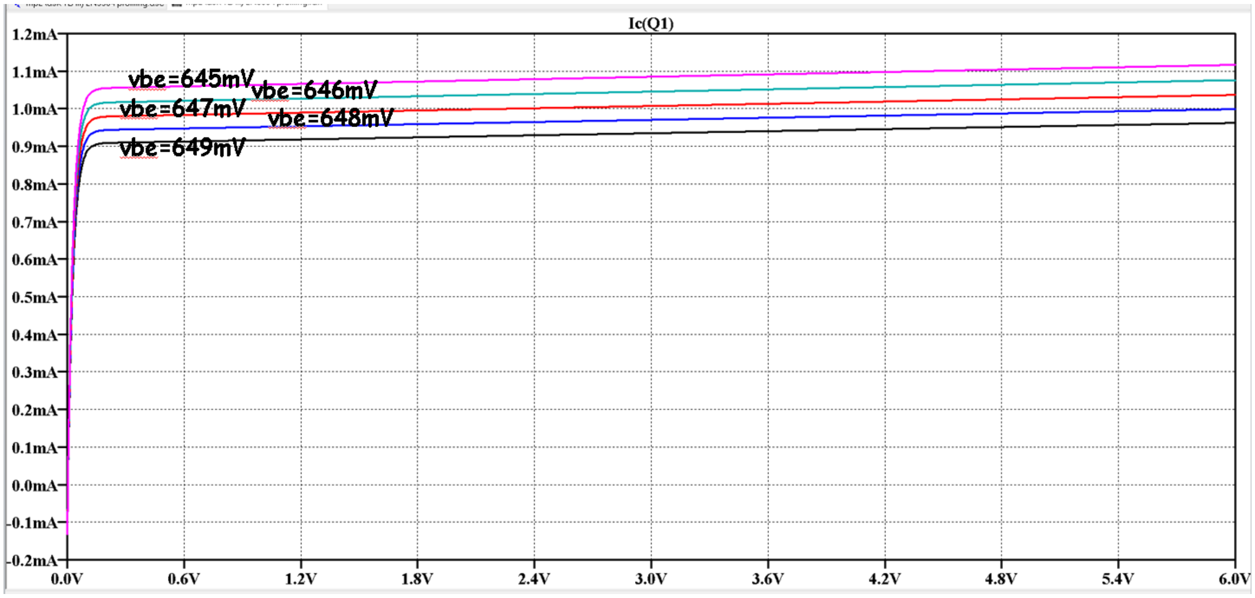

Figure 4: IC vs VCE with VBE varying

IC was found to be 1mA at VCE=5V if VBE=647mV. Since $v_\pi = v_{BE}$, $g_m = \frac{\Delta i_c}{\Delta v_{BE}}$ with VCE=5V and IC=1mA. We can look at the spot on the graph above and below VBE=647mV, so 646mV to 648mV will be the step increment. $g_m = \frac{(1065.8504-989.3489)*10^{-6}}{(648-646)*10^{-3}} = 3.8251 * 10^{-2}\ S$

r_π *can be calculated as* $\frac{\beta}{g_m}$ *so* $r_\pi = 3736.6326\Omega$

Task 1 c i)

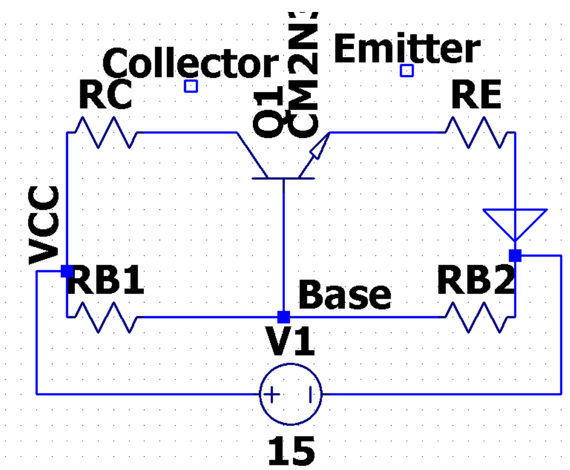

Figure 5: DC CE amplifier

It can be seen that $v_{cc} = i_c r_c + v_{ce} + i_e r_e. We\ know\ i_e = \left(\frac{1}{\beta} + 1\right) * i_c = \left(\frac{1}{142.929} + 1\right) * 10^{-3} = 1.007 * 10^{-3} A$, $i_b = \frac{i_c}{\beta} = \frac{10^{-3}}{142.929} = 6.996 * 10^{-6} A\ and\ we\ set\ r_e = \frac{r_c}{2}\ and\ v_e = 4$ so we can say $15 = 10^{-3} * r_c + 4 + \frac{r_c}{2} * 1.007 * 10^{-3}$ and $r_c = 7316.27$ and $r_e = 3658.14$, rb1 and rb2 can be semi arbitrarily chosen as $100kohm\ and\ 100kohm$ The DC operating point can be calculated with $v_c = 15 - i_c r_c = 15 - 3649.65 * 10^{-3} = 7.68373V$ $v_e = i_e r_e = 1.007 * 10^{-3} * 1.007 * 10^{-3} = 3.68373\ V.$ $v_{be} \approx 0.647V$ as determined in part b)

Task 1 c ii)

Using the second one third rule (LABEL CURRENTS IN DIAGRAM)
$v_c = \frac{2v_{cc}}{3} = 10V, v_e = \frac{v_{cc}}{3} = 5V, i_1 = \frac{i_e}{\sqrt{\beta}}, i_2 = i_1 - i_b, v_b = 15 - i_1 r_{b1} = i_2 r_{b2}$ which tells us that $r_{b1} = \frac{15 - v_b}{i_1} = \frac{15 - 5.647}{8.42302 * 10^{-5}} = 111041\ ohms\ \ and\ r_{b2} = \frac{v_b}{i_2} = \frac{5.647}{7.72337 * 10^{-5}} = 73115.7\ ohms$

$v_b = v_e + v_{be} = 5 + 0.647$ say that $V_{BE} = 0.647V$ so

VC can be calculated as $r_c = \frac{v_{cc} - v_c}{i_c} = \frac{15 - 10}{10^{-3}} = 5000ohms\ r_e = \frac{v_e}{i_e} = \frac{5}{1.007 * 10^{-3}} = 4965ohms$

Inserting these numbers into the LTSPICE simulation, the dc operating point was simulated as

PUT UNITS V/V AND A/A FOR GAIn Semens for gm

I_B	I_C	I_E	V_C	V_B	V_E
8.36330μA	986.771μA	995.134μA	10.0662V	5.58674V	4.94084V

Task 1 c iii)

The closest standard resistor values are $r_c = r_e = 5.1kohm, R_{B1} = 110Kohm, R_{B2} = 75Kohm$

The new operating point measured is

I_B	I_C	I_E	V_C	V_B	V_E
8.35950μA	984.270μA	992.629μA	9.98022V	5.70829V	5.06241V

Task 1 c iv)

The percent difference between values can be calculated as $\frac{|calculated - standard|}{calculated} * 100\%$

I_B error	I_C error	I_E error	V_C error	V_B error	V_E error
0.0454366%	0.253453%	0.251725%	0.854146%	2.17569%	2.46051%

It seems clear that the voltages have much larger errors than the currents do. While the currents have not changed too much, the differing resistors cause differing voltage drops from the currents and the node voltages see larger changes.

Task 1 d)

using the CM2N2222A

I_B	I_C	I_E	V_C	V_B	V_E
6.09102μA	1.01507mA	1.02117mA	9.82312V	5.80945V	5.20794V

Using the CM2N4401

I_B	I_C	I_E	V_C	V_B	V_E
6.80192μA	997.135mA	1.00394mA	9.91461V	5.77775V	5.12008V

There were some substantial differences between how the 3 transistors behaved. In particular, it seems like the CM2N3904 had significant divergence with its base current being much higher and collector and emitter currents being significantly lower.

Task 2 a)

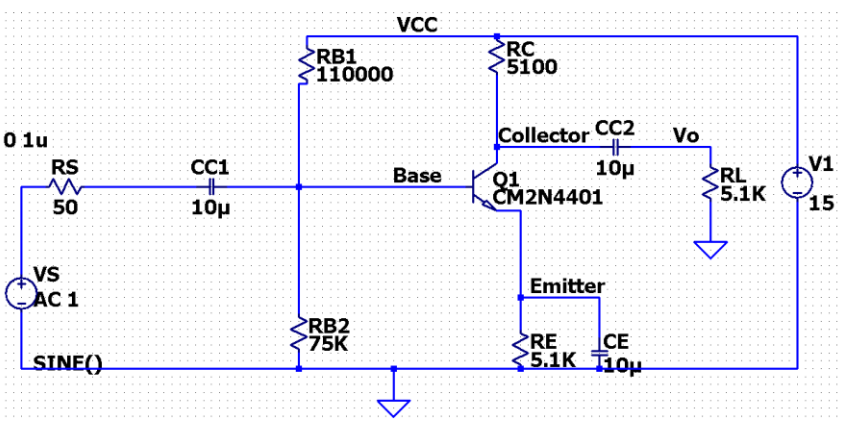

Figure 6: CE amplifier

As demonstrated in lecture 10, the poles and zeros of a common emitter amplifier can be approximated as

$\omega_{Hp1} \approx \omega_{Hp1} \approx \frac{1}{R_{BB}||r_\pi||R_s(c_\pi + c_\mu(1+g_m R_c||R_L))}$ and $\omega_{Hp2} \approx \frac{1}{R_C||R_L c_\mu}$

$\omega_{Lp2} \approx \frac{1}{(R_C+R_L)*C_{C2}}$ and $\omega_{Lp1} \approx \frac{1}{(R_s+R_{BB}||(r_\pi+(1+\beta)R_E))C_{C1}}$ and $\omega_{Lp3} \approx \frac{1}{\left(R_E|\frac{r_\pi+R_{BB}||R_S}{1+\beta}\right)C_E}$

Where $R_{BB} = R_{B1}||R_{B2}$=44694.6

$\omega_{Lz1} \approx \omega_{Lz2} \approx 0$ and $\omega_{Lz3} \approx \frac{1}{R_E C_E} =$. It is important to note that the high frequency response was derived using Miller's theorem which removes zeros so ω_{Hp1} and ω_{Hp2} are unknown

Sd $A_M = -g_m R_C||R_L \frac{R_{BB}||r_\pi}{R_{BB}||r_\pi + R_S}$. $c_\mu$and c_π can be calculated using the formulas $c_\pi \approx 2 * CJE + TF * g_m$ and $c_\mu = \frac{CJC}{\left(1+\frac{V_{CB}}{VJC}\right)^{MJC}}$. For the 3904, these parameters are $CJE = 4.5 * 10^{-12}, TF = 4 * 10^{-10}\ CJC = 3.6 * 10^{-12}, VJC = 0.75, MJC = 0.33, V_{CB} = 4.27193$ so $c_\pi =$and for the 4401 $CJE = 23.4 * 10^{-12}, TF = 512 * 10^{-12}. CJC = 10.2 * 10^{-12}, VJC = 0.75, MJC = 0.33, V_{CB} = 4.1368V$. From the 4401 datasheet it can be found that $\beta = 270\frac{A}{A}$ and $r_\pi = 8Kohm$ therefore $g_m = \frac{270}{8000} = 0.03375S$. Using previous values for the 3904 it can be found that $\beta = 142.929, r_\pi = 3736.6326, and\ g_m = 0.038251$ have already been calculated for the 3904.

For the 3904 it can be found that $c_\mu = 1.8688 * 10^{-12}F$ and $c_\pi = 2.43 * 10^{-11}F$

And thus $f_{Hp1} = \frac{\omega_{Hp1}}{2\pi} \approx \frac{1}{R_{BB}||r_\pi||R_s(c_\pi + c_\mu(1+g_m R_c||R_L))2\pi} = 15.271MHz$

And $f_{Hp2} = \frac{\omega_{Hp2}}{2\pi} = \frac{1}{R_C||R_L c_\mu 2\pi} = 33.399Mhz, f_{Lp2} = \frac{1}{2\pi(R_C+R_L)*C_{C2}} = 1.5603Hz\ f_{Lp1} = \frac{1}{2\pi(R_S+R_{BB}||(r_\pi+(1+\beta)R_E))C_{C1}} = 0.3785Hz$, $f_{Lp3} \approx \frac{1}{2\pi\left(R_E||\frac{r_\pi+R_{BB}||R_S}{1+\beta}\right)c_E} = 608.07Hz, \omega_{Lz3} = \frac{1}{2\pi R_E C_E} = 3.1207Hz$

For the 4401

$c_\pi = 2 * CJE + TF * g_m = 64.08pF\ c_\mu = 5.495pf\ f_{Hp1} = \frac{1}{R_{BB}||r_\pi||R_s(c_\pi + c_\mu(1+g_m R_c||R_L))2\pi} = 5.8673MHz\ f_{Hp2} = \frac{1}{R_C||R_L c_\mu 2\pi} = 11.358Mhz\ f_{Lp2} = \frac{1}{2\pi(R_C+R_L)*C_{C2}} = 1.5603$Hz, $f_{Lp1} = \frac{1}{(R_s+R_{BB}||(r_\pi+(1+\beta)R_E))C_{C1}} = 0.36834Hz, f_{Lp3} = \frac{1}{2\pi\left(R_E||\frac{r_\pi+R_{BB}||R_S}{1+\beta}\right)c_E} = 538.913Hz$, $f_{Lz3} = \frac{1}{2\pi R_E C_E} = 3.1207Hz$

The calculated pole and zero values for the 3904

f_{Lp1}	f_{Lp2}	f_{Lp3}	f_{Hp1}	f_{Hp2}	f_{Lz3}	f_{Hz1}
0.3785Hz	1.5603Hz	608.07Hz	15.271MHz	33.399MHz	3.1207Hz	N.A.

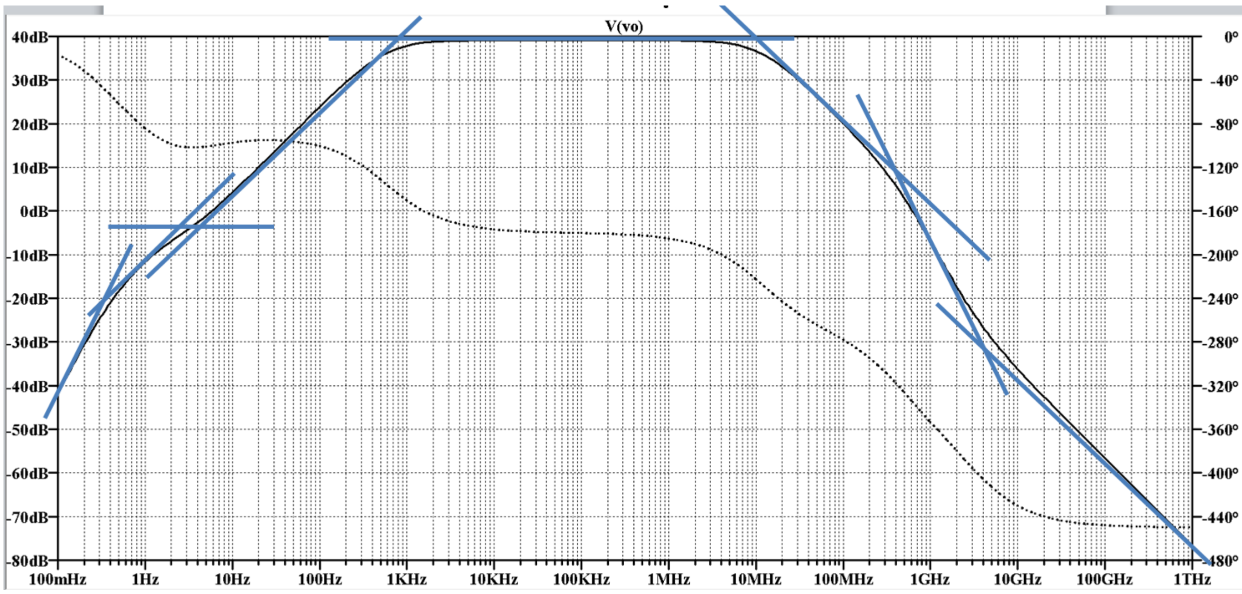

Figure 7: Bode plot of the 3904 CE amplifier

Graphically determining pole frequencies for the 3904

f_{Lp1}	f_{Lp2}	f_{Lp3}	f_{Hp1}	f_{Hp2}	f_{Lz3}	f_{Hz1}
0.35476Hz	4.349Hz	804.308Hz	10MHz	433.557MHz	2.444Hz	3.4673GHz

The calculated pole and zero values for the 4401

f_{Lp1}	f_{Lp2}	f_{Lp3}	f_{Hp1}	f_{Hp2}	f_{Lz3}	f_{Hz1}	f_{Hz2}
$0.36834Hz$	1.5603Hz	$538.913Hz$	$5.8673MHz$	$11.358Mhz$	$3.1207Hz$	N.A.	N.A.

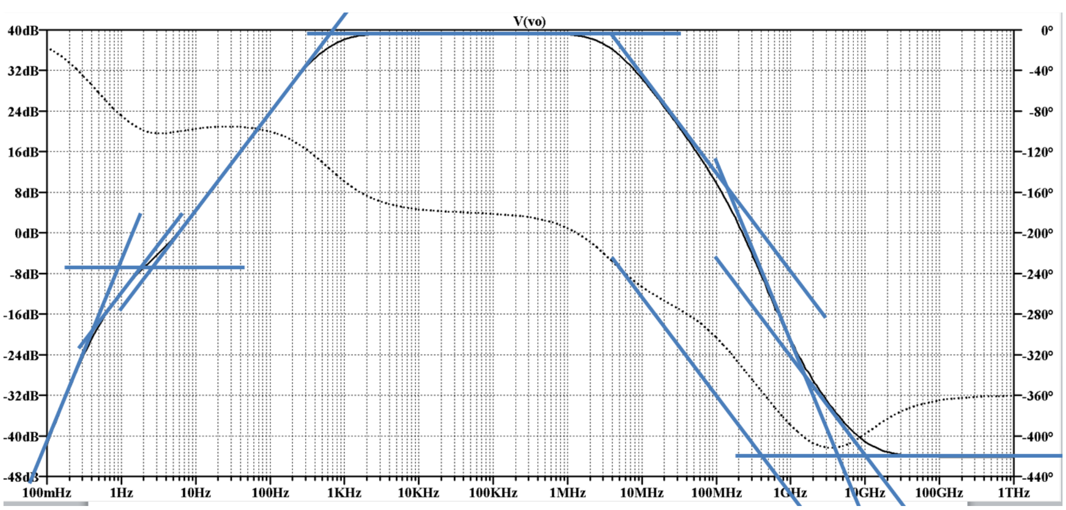

Figure 8: Bode plot of the 4401 CE amplifier

Graphically determining pole frequencies for 4401

f_{Lp1}	f_{Lp2}	f_{Lp3}	f_{Hp1}	f_{Hp2}	f_{Lz3}	f_{Hz1}	f_{Hz2}
0.455678	2.6671	687.76	3.8566MHz	135.751MHz	1.9935	1.34889GHz	10GHz

It seems that the open circuit short circuit time constant method is able to provide a decent approximation for most of the poles and zeros, but the second high frequency pole was consistently underestimated by over and order of magnitude. The approximation also fails to calculate the high frequency zero values.

Task 2 b)

The 3904 is in the midband at 100KHz, small nonlinearities began to be observed at 40mv. For the nonlinear signals, the positive peak was used as the positive and negative amplitude are different. The ratio of output to input voltage $\frac{V_0}{V_s}$ was plotted.

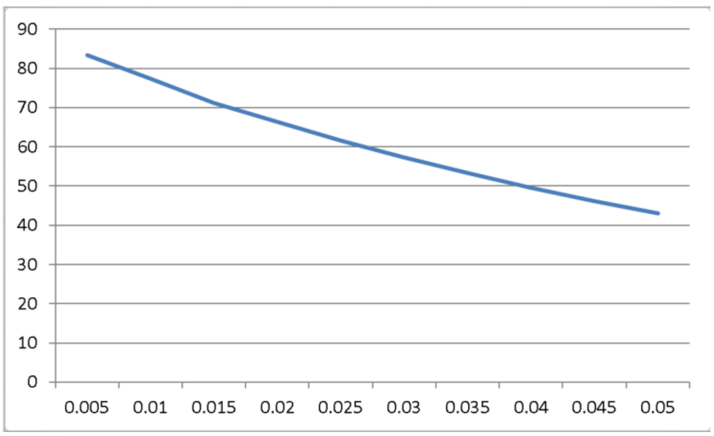

Figure 9: Plot of peak(Vo)/peak(Vs) as graph transitions to nonlinear for 3904

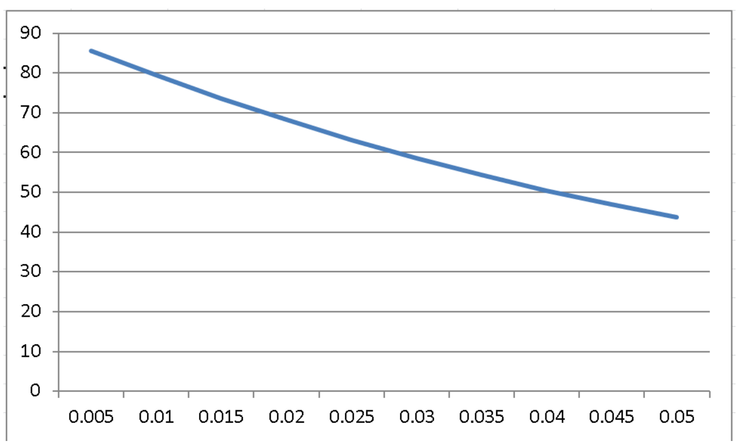

Figure 10: Peak Vo/Vs entering nonlinear region for 3904

It seems clear that the gain of the peak values will go down as the input voltage goes up. This corresponds to the peaks of the voltage waveforms getting cut-off, similar to a saturated OP AMP.

Task 2 c)

To measure the impedance at the midband of the 3904 CE amplifier with the 50Ω input resistor removed, the load was shorted and an AC sweep was performed at the input node.

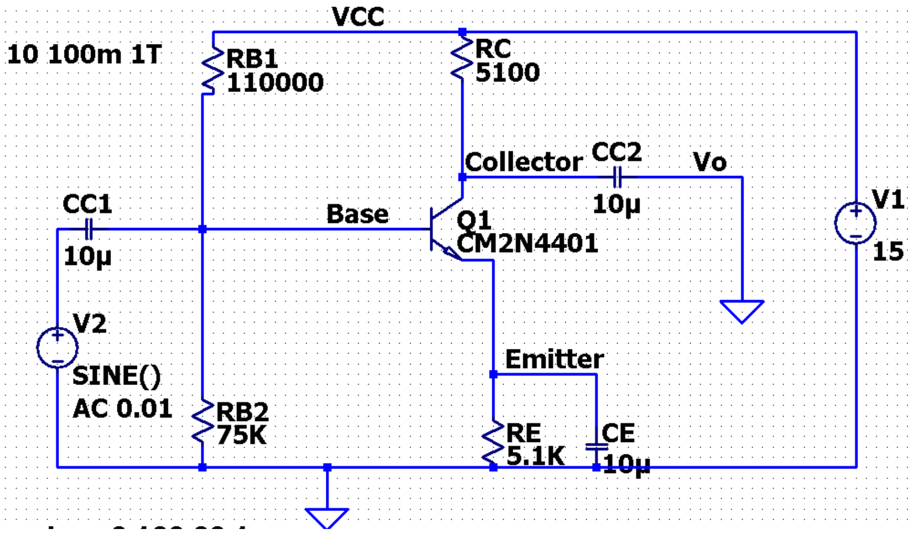

Figure 11: Circuit to determine input impedance of CE amplifier

VO/IO was plotted and measured at the midband frequency 100KHz to determine the impedance.

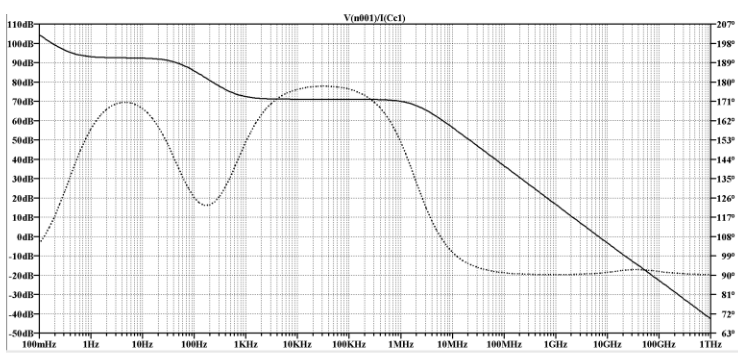

Figure 12: Input impedance (DB) vs. frequency of the 3904 CE amplifier

The impedance must be converted to Ω from DB so $|Z| = 10^{\frac{71.046324}{20}} = 3567.1\,\Omega$

The process was repeated for the 4401

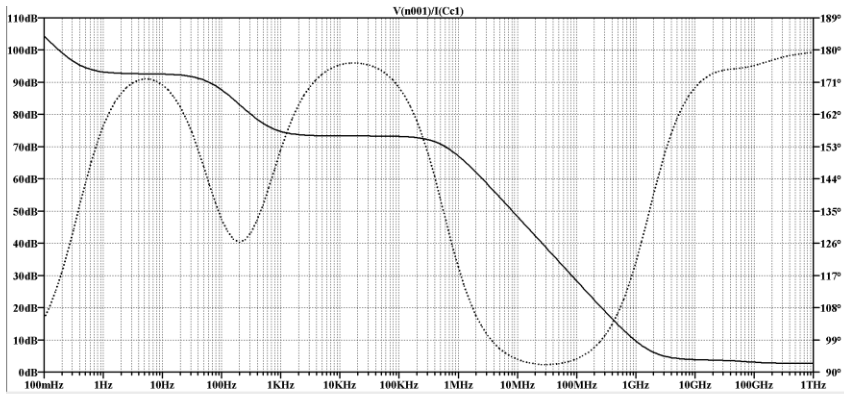

Figure 13: Input impedance (DB) vs. frequency of the 4401 CE amplifier

$$|Z| = 10^{\frac{73.195417}{20}} = 4568.5\,\Omega$$

Task 2 d)

To measure the output impedance at the midband of the 3904, the source was shorted and an AC sweep was performed at the output node.

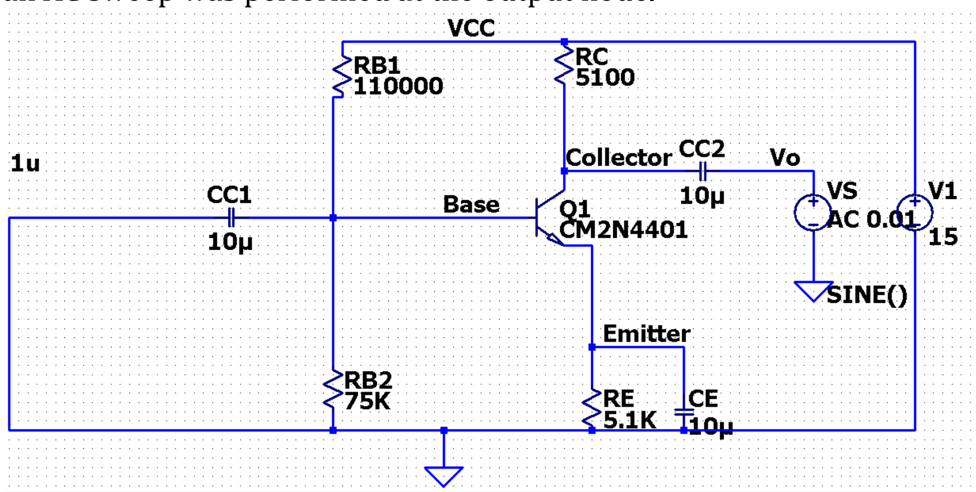

Figure 14: Circuit to determine output impedance of CE amplifier

VO/IO was plotted and measured at the midband frequency 100KHz to determine the impedance

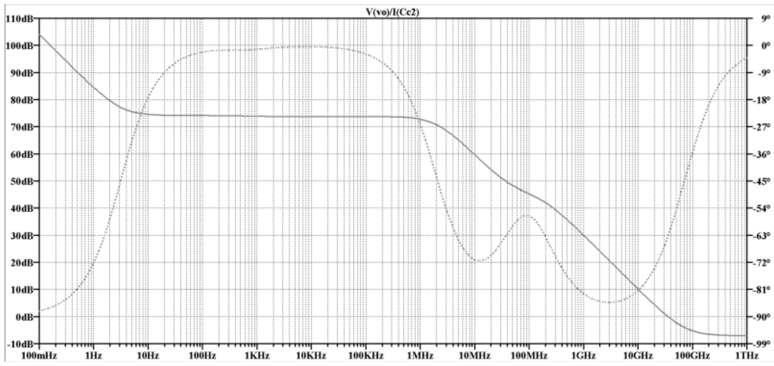

Figure 15: Output impedance (DB) vs. frequency of the 3904 CE amplifier

The impedance must be converted to Ω from DB so $|Z| = 10^{\frac{73.74203}{20}} = 4865.208\ \Omega$

The same process was repeated for the 4401

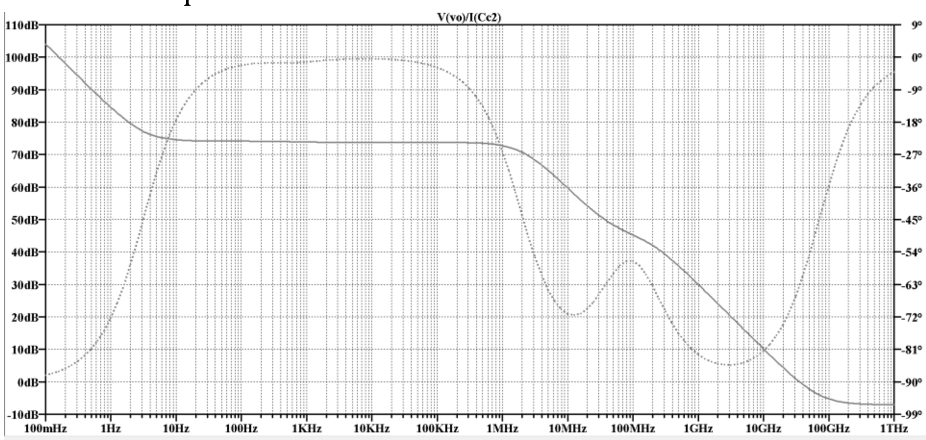

Figure 16: Output impedance (DB) vs. frequency of the 4401 CE amplifier

$|Z| = 10^{\frac{73.765747}{20}} = 4878.5117\Omega$

Task 2 e)

The main factor influencing my choice of transistor will be the bandwidth. The corner frequencies will be estimated by f_{Lp3} and f_{Hp1} on the bode plot. The 3904 has $f_{Lp3} =$ 804.308Hz and $f_{Hp1} = 10$MHz for a bandwidth of $\log\left(\frac{10^7}{804.308}\right) = 4.0946\ decades$

The 4401 has $f_{Lp3} = 687.76$Hz and $f_{Hp1} = 3.8566$MHz for a bandwidth of $\log\left(\frac{3.8566*10^6}{687.76}\right) =$ 3.7488$decades$. The 3904 has a larger bandwidth so I would choose it as giving superior performance.

Task 3a)

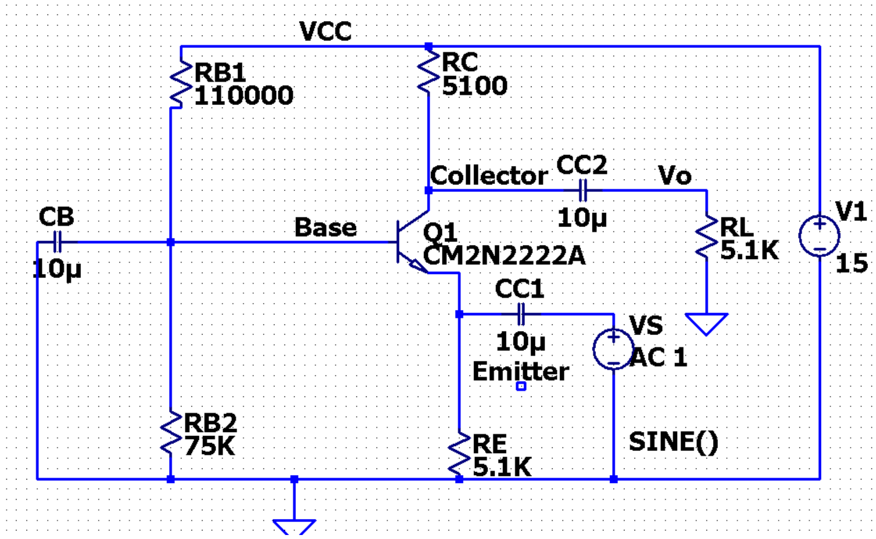

Figure 17: CB amplifier with the 2222A transistor

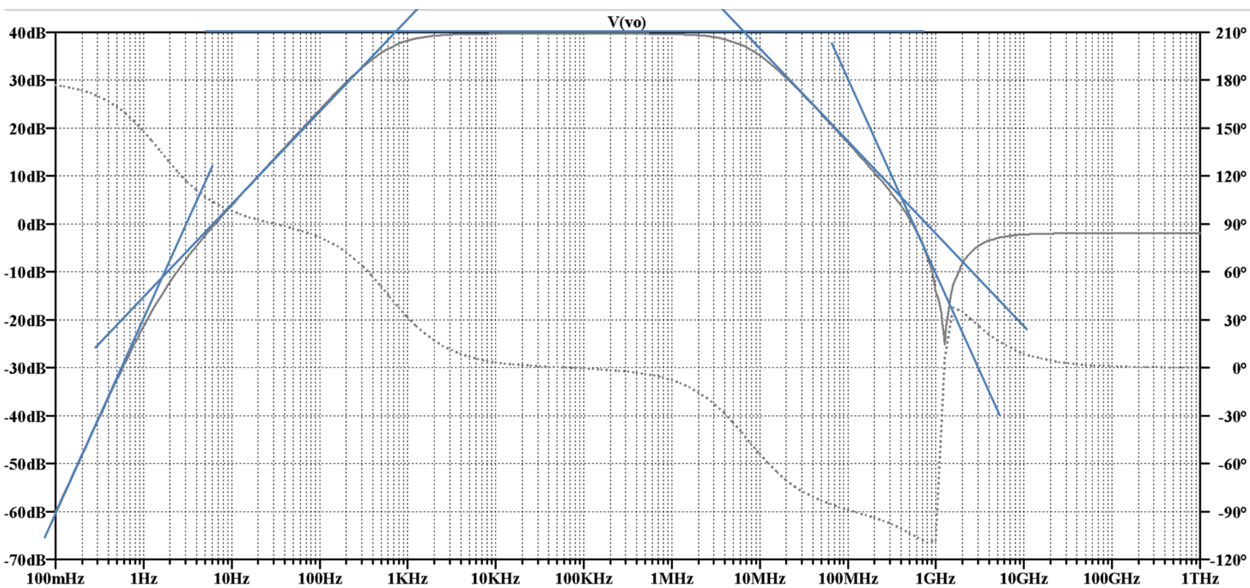

Figure 18: Bode plot of the 2222A CB amplifier

Due to the complex behvour at higher frequencies, it is highly impractical to estimate any poles or zeros at a higher frequency than f_{Hp2}.

f_{Lp1}	f_{Lp2}	f_{Hp1}	f_{Hp2}
1.7516Hz	694.672Hz	6.0423MHz	383.2096MHz

Task 3c)

A similar procedure to task 2C) was repeated to get the input impedance of the CB 2222A amplifier .

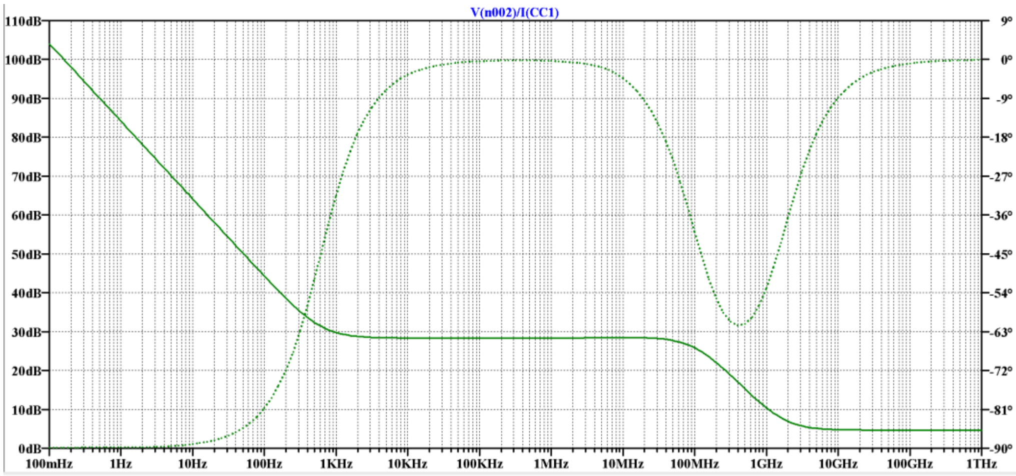

Figure 19: Input impedance (DB) vs. frequency of the 2222A CE amplifier

$$|Z| = 10^{\frac{28.353531}{20}} = 26.16234\Omega$$

Task 3d)

A similar procedure to task 2d) was repeated to get the output impedance of the CB 2222A amplifier.

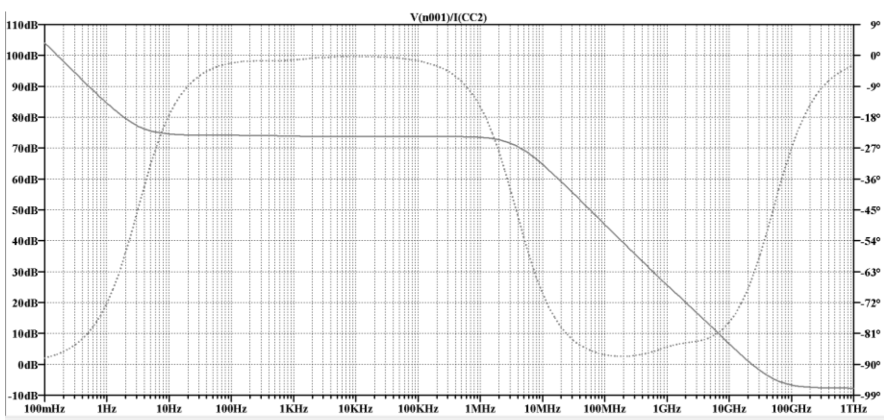

Figure 20: Output impedance (DB) vs. frequency of the 2222A CE amplifier

$$|Z| = 10^{\frac{73.765463}{20}} = 4878.35\Omega$$

Citations)

1) Elec 301 lecture slides
2) https://www.youtube.com/watch?v=S5ut1ef9c4s&t=18s&ab_channel=SalimKoteish
3) https://freebiesupply.com/logos/ubc-logo/