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Lab 3: Transistor amplifiers
Group L16

Monday 11:35-2:25

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Objective:

The objective of this lab was to achieve a better understanding of the different types of transistor amplifiers and most importantly how to design a cascade amplifier that would fulfil the requirements. This Laboratory was divided into three different parts. First part was analyzing common base, common emitter and common collector BJT amplifiers. That would be necessary to determine the small signal parameters of the BJT both by calculation and by measuring data from the designed circuit to compare both of them later on. Second part was to design the cascade amplifier with all its requirements. Such Calculations will include both DC biasing along with small signal analysis which would be used in lab. The third part will cover how to implement and measure the required circuit. This part will require comparisons with the requirements along with power consumption and frequency to gain observation.

Theory:

The Main point behind using a transistor as an amplifier is to try to control the current through collector and emitter from the voltage consumed across the emitter and base. The output voltage can be controlled based on the chosen gain. The difference between the three BJT amplifiers (CC, CE and CB) is simply determined based on if resistor is parallel to capacitor which causes resistor to be shorted and ignored in small signal analysis. To choose cascade amplifiers in part two and part three can be done by observing the differences in part one and based on that cascade amplifiers can be chosen.

Characteristics of Transistor Amplifier:

This part of lab will cover the three transistor amplifier shown below in Figure 1. Several Calculations will be made later on using the small signal model to find all parameters and that will follow all measurements that will be compared to all values calculated.

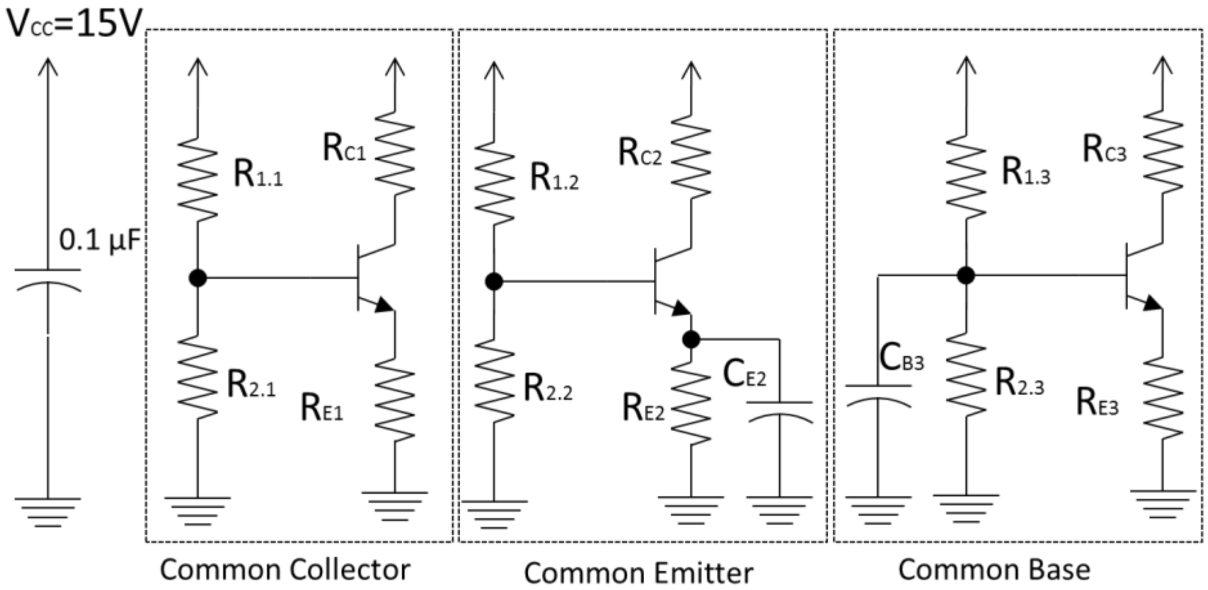

Figure 1: The 3 Transistor BJT Amplifier

Calculations for small signal parameters

The gain Av, input resistance R_{in}, output resistance R_{out} along with high frequency f_h and low frequency cut-off f_L are all the small signal parameters that will be calculated. The β will be assumed to have a 200 value as that was very close to what was calculated in Lab 1 for all three transistors. The values for all resistors and capacitors that were used are in Table 1. The high frequency values came from lab 1, r_μ was assumed to be infinite which makes it an open circuit, r_o 79.3,Cµ 4pF,Cπ 42.6pF.,Cin 10µF and C_{out} 1µF.

R1.1	*R2.1*	*R3.1*	***100kΩ***
R1.2	**R2.2**	**R3.2**	39KΩ
R_{C1}	**R_{C2}**	**R_{C3}**	5.6KΩ
R_{E1}	**R_{E2}**	**R_{E3}**	3.3KΩ
-	**C_{E2}**	**-**	100µF
-	**-**	**C_{B3}**	1 µF

Table 1: All Values for BJT amplifiers

CC Amplifier:

The circuit on left side of figure 1 is the common collector which is shown in DC biasing. Figure 2 was used to show small signal analysis.

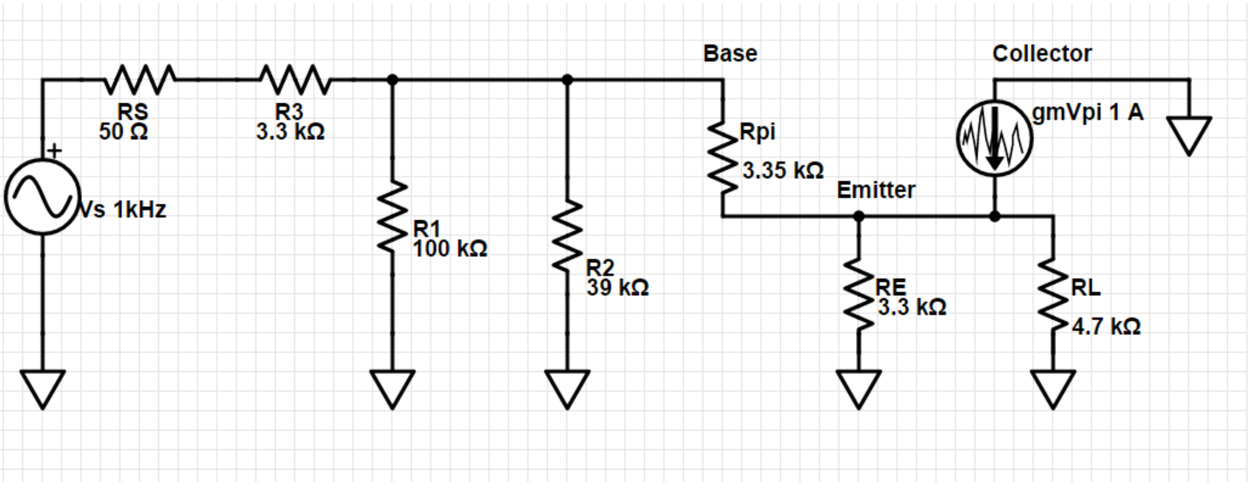

Figure 2: Small signal analysis of common collector equivalent circuit

It can be noted in figure 2 that R_c has been shorted to ground because of the property of common collector that was intended to include a capacitor that is shorting the resistor. As noted in instructions of lab to include resistor in DC biasing and removing it after. With that being noted to determine the gain:

$$V_{out} = \frac{(R_E||R_L)(\beta+1)}{(R_E||R_L)(\beta+1)+r\pi} * V_{Base} = 0.99\, V_{Base}$$

$$V_{Base} = \frac{(R1||R2||[R_E||R_L + r_\pi)(\beta+1)}{(R1||R2||[R_{E|}|R_L + r_\pi)(\beta+1)+(R_S+R3)}$$

Using that, it can be determined that gain is:

$$Av = \frac{V_{out}}{V_{in}} = 0.87\ v/v$$

The input resistance can be determined to be:

$$R_{in} = R2\big|\big|R1\big|\big|[r\pi +)(R_E\big|\big|R_L)(\beta+1)\big] = 25.5K\Omega$$

The output resistance can be determined to be:

$$R_{out} = ro\big|\big|R_E\big|\big|\frac{\big(R1\big|\big|R2\big|\big|(Rs+R3)+r_\pi\big)}{\beta+1} = 30.6\Omega$$

The low frequency pole is the sum of all impedances of each capacitor can be determined to be:

$$f_L = \frac{1}{2\pi\big(R3+Rs+R1\big|\big|R2\big|\big|r_\pi\big)C_{in}} + \frac{1}{2\pi(R_L + ro||RL||RE||\frac{\big(R1\big|\big|R2\big|\big|(Rs+R3)+r\pi\big)}{\beta+1})C_{out}}$$

$$f_L = 7.66\ Hz$$

The high frequency pole is determined by calculating summation of inverses for patristic capacitors:

$$\frac{1}{2\pi((Rs+R3)\big|\big|R1\big|\big|R2||(r\pi+\beta(RL||RE))(C\mu+\frac{C\pi}{1+gm(RL||RE)})}$$

$$f_H = 11.7\ MHz$$

CE Amplifier:

The Common emitter is shown in Figure 1 and the small signal analysis of the circuit in Figure 3:

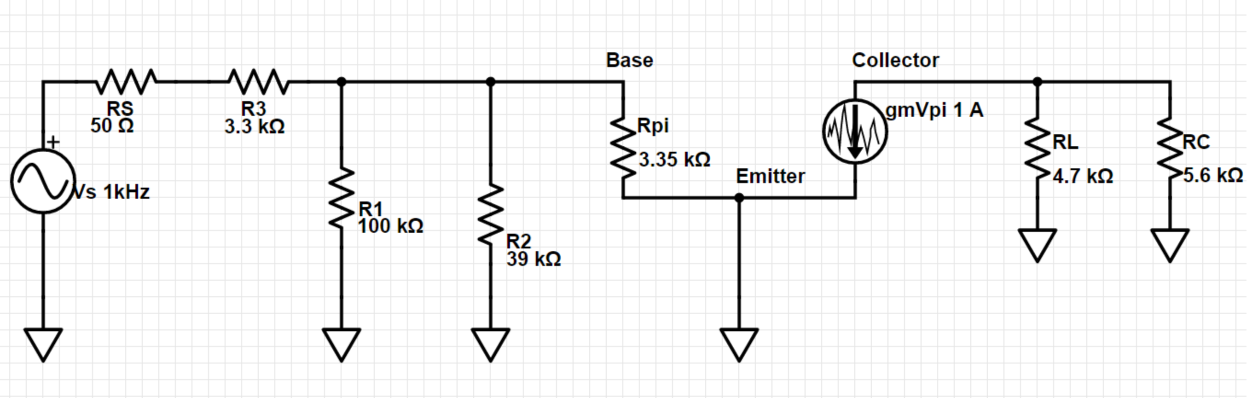

Figure 3: Small Signal analysis model for Common emitter

It can be noticed The capacitor C_{E2} in figure 1 is shorted to ground and not ignored like in Common Collector reason for that is because it would effect the DC biasing because R2 is shorted out. This would cause VBE to equal 0 and would cause current to not pass through the collector. The gain for small signal parameters for the amplifier is:

$$Vout = -gm\ v\pi(Rc||RL) = -102.2\ v\pi$$

$$\frac{r\pi||R1||R2}{r\pi||R1||R2 + Rs + R3} * Vin = 0.466Vin$$

Where gm can be determined to be close to 0.04 siemens, therefore gain is:

$$\text{Av}=\frac{Vout}{Vin} = -47\ v/v$$

The input resistance can be determined to be:

$$R_{in} = R3+R1||R2||r\pi = 5.22\ \text{K}\Omega$$

The output resistance can be determined to be:

$$Rout - Rc||ro = 5.1\ K\Omega$$

The low frequency pole can be determined to be:

$$f_L = \frac{1}{2\pi\left(R3 + Rs + R1||R2||r\pi\right)Cin} + \frac{1}{2\pi(RL + RC)_{Cout}} + \frac{1}{2\pi(\frac{r\pi + R1||R2(R3 + Rs)}{\beta + 1}||RE)CE}$$

$$f_L = 68.7\ Hz$$

The high frequency pole can be determined to be:

$$f_H = \frac{1}{2\pi}[(C\pi + C\mu(1 + gm(RL||Rc)))(R1||R2||R3||r\pi) + (Rc||RL)C\mu]^{-1}$$

$$f_H = 217\ kHz$$

CB Amplifier:

The common Base can be seen on figure 1. It can be noticed that capacitor which is connected at base is shorting out R1 and R2 in small signal analysis. The input voltage is connected at the collector and output is in emitter. The small signal analysis can be seen in figure 4 in which T model was used:

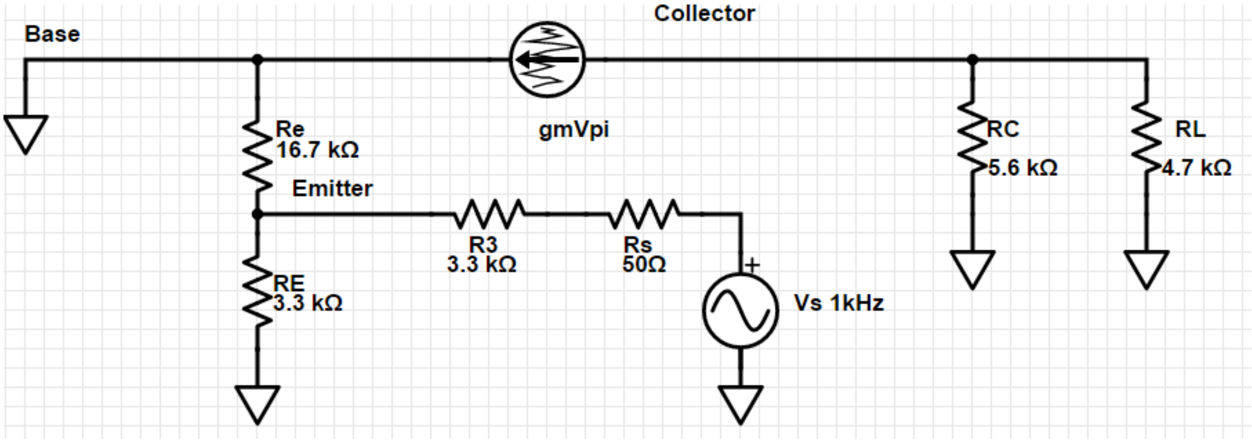

Figure 4: Small Signal analysis for common base circuit

As T model was used re can be determined to be:

$$r_e = \frac{r\pi}{\beta+1}$$

The gain can be determined to be:

$$Vout = gmv\pi(Rc||RL) = 102.12\ v\pi$$

$$v\pi = \frac{re||Re}{re||RE + Rs + R3} * Vin = 0.0072\ Vin$$

$$Av = \frac{Vout}{Vin} = 0.756\ v/v$$

The input resistance can be determined to be:

$$Rin = R3 + RE||re = 3.3\ K\Omega$$

The output resistance can be determined to be:

$$Rout = Rc = 5.6\ K\Omega$$

The low frequency pole can be determined to be:

$$fL = \frac{1}{2\pi(R3 + Rs + RE||re)Cin} + \frac{1}{2\pi(RL + RC)Cout} + \frac{1}{2\pi((R3||RE + re)(\beta + 1) + R1||R2)CB}$$

$$fL = 20.8\ Hz$$

The high frequency can be determined to be:

$$\frac{1}{2\pi}[(Rc||RL)C\mu + RE||re||(R3 + Rs)C\pi]^{-1}$$
$$f_H = 14.56\ MHz$$

Explanations:

The calculations that were done above are methods that would approximate the small signal frequencies of the amplifiers with expectations on the transistor. It can be noted that in some cases different types of amplifier have similar values and in other case they differ by big margin. The CC amplifier has a gain of approximately 1 , low output resistance and a large cut-off frequency. The CE amplifier has a large gain but have a high frequency cut-off that occurs at a much lower frequency than the other two amplifiers. The CB has values that were close to the other two amplifiers with again of 0.756 which is close to 1, input and output of few KΩ resistances that were also close to other amplifiers and high frequency cut-off over 10 MHz. All these differences will result in amplifier to have different positions and rules in circuit. Such roles can differ from a voltage buffers, voltage amplifiers and currents buffers.

Amplifier's Measurements:

All the measurements of the small signal analysis were based on small branches that were used for input and output signals of the amplifiers. Figure 5 shows the branch for the input signal and figure 6 shows the output branch. With these nodes available the gain , input and output can be all calculated as shown below :

$$R_{in} = \frac{Vin}{i_{in}} = = \frac{v_U}{v_U - v_T}R3$$
$$Rout = \frac{v'o - vo}{i_{RL}}$$
$$Av = \frac{vo}{v_U}$$

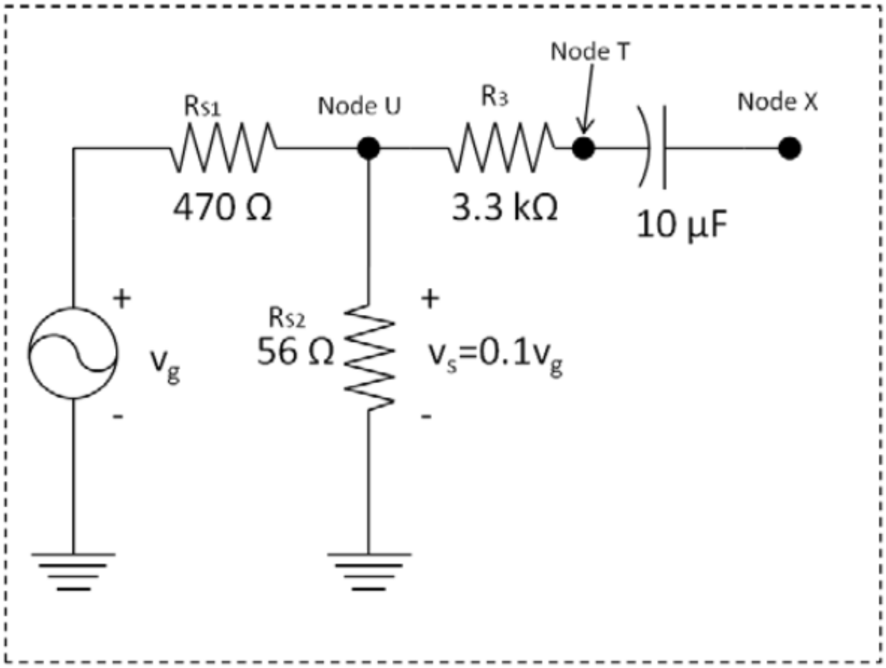

Figure 5: input Signal Branch

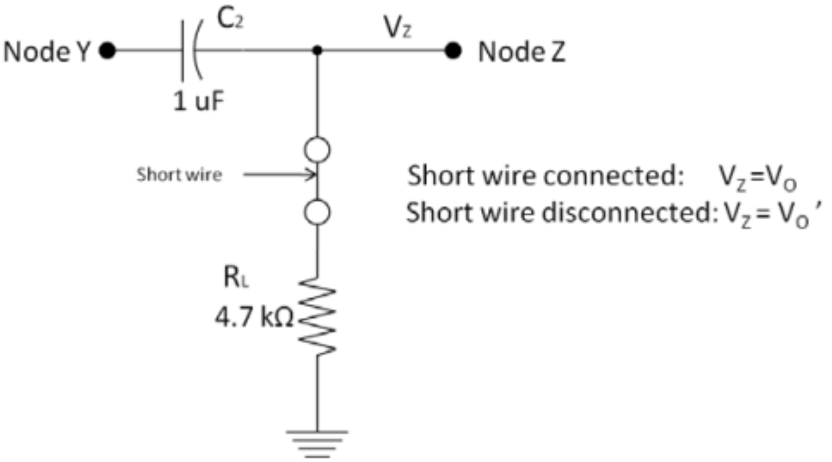

Figure 6: output signal Branch

The high and low frequency cutoffs can be determined when changing the frequency up until the magnitude of output drops by 30%. The output is 2V peak to peak at frequency of 1kHz and the point where output drops to 1.4 is the cut-off frequency points.
The measured values can be shown below in table 2:

Resistor (Ω)	*CC*	*CE*	*CB*
RE	3.25K	3.24 k	3.25 k
R1	100 k	100 k	100 k
R2	39 k	39 k	39 k
R3	5.56 K	5.62 k	5.53 k
Voltages (V)	-	-	-
VB	4.06	4.05	4.05
VC	9.27	9.30	9.31
VE	3.41	3.40	3.41
VCC	15	15	15
Currents (A)	-	-	-
IB	4.2µ	4.9 µ	4.9 µ
IC	1.03 m	1.02 m	1.03 m
IE	1.05 m	1.03 m	1.05 m
Calculated β	-	-	-
B	245	208	210

Table 2: Measurements of all values during DC bias

Table 2 includes all information needed to complete all the calculations below for small signal parameters. The β was calculated from collector and base currents.

CC Amplifier:

While measuring at 1KHz the common collector had the following values:
Vo=1.96V
Vo'=1.96V
V_U=2.39V
V_T=1.98V

Using these values, the parameters were determined to be:
Av=0.878 V/V
R_{in}=29.4 kΩ
R_{out}=Negligible
It should be noted that in lab there were minor variations between Vo and Vo' nevertheless they were extremely small to extract because of resistance which is smaller than 50Ω.

The low and high frequencies were determined to be:
f_H=>4 MHz f_L=11Hz
it should also be noted that high cut-off frequency was extremely big to be measured in device with that in mind its greater than 4MHz.

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CE Amplifier:

While measuring at 1KHz the common emitter had the following values:
Vo=1.97V
Vo’=4.22V
V_U=40mV
V_T=24mV

Using these values, the parameters were determined to be:
A_v=49.28 V/V
R_{in}=8.25kΩ
R_{out}=5.33kΩ

The low and high frequencies were determined to be :
f_H= 280kHz f_L=33Hz

CB Amplifier:

While measuring at 1KHz the common emitter had the following values:
Vo=2.02 V
Vo’=4.29 V
VU=2.66 V
VT=160mV

Using these values, the parameters were determined to be:
Av =0.79 V/V
R_{in}=3.53 KΩ
R_{out}=5.42 KΩ

The low and high frequencies were determined to be:
f_H=3.42 MHz f_L=10Hz

Calculation and measurement Comparison:

The comparison between the Calculated and measured values for small signal parameters are included in Table 3 below:

AMPLIFER	PARAMETER	CALCULATED	MEASURED	UNITS
COMMON COLLECTOR	|Av|	0.87	0.878	v/v
	R_{in}	25.5	29.4	kΩ
	R_{out}	30.6	Negligible	Ω
	f_L	7.66	11	Hz
	f_H	11.7	>4	MHz
COMMON EMITTER	|Av|	47	49.28	v/v
	R_{in}	5.22	8.25	kΩ
	R_{out}	5.1	5.33	Ω
	f_L	68.7	33	Hz
	f_H	217	280	MHz
COMMON BASE	|Av|	0.756	0.79	v/v
	R_{in}	3.3	3.53	kΩ
	R_{out}	5.6	5.42	Ω
	f_L	20.8	10	Hz
	f_H	14.56	3.42	MHz

The results that were calculated for CC can be noticed to have extremely similar to measured values. The input and output resistances had a difference of a few kΩ and in low frequency cut-off there was a few hertz difference. The CE had a very similar values for the gain and the output resistance. Other values such had major difference reasons are down some assumptions that were made inside BJT which effected parameters such as input and cut-off frequencies. For example, the input resistance has an assumed $r\pi$ which contributed to the difference. If it was slightly larger a closer value to the value measured would have occurred. The cut-off frequency value could be down the lack of supplies in lab as some capacitors have different values that what it is supposed to equal too. The difference if f_L would be explained by the doubled value for the capacitor since its inversely proportional with the frequency. Most of values for the high frequency cut-off came from assumptions e.g. internal parasitic capacitances ($C\pi$ and $C\mu$) which were assumed to be the same in BJTs. This educated assumption will lead to slightly large differences like in f_H. In CB the only noticeable differences in values were in frequency cut-off which can due again to using different capacitors with parasitic resistances that were assumed. The amplifiers usually have common purposes depending on their properties. The common collector can be used as a voltage buffer as the gain is close to 1. It is also useful as it has a high impedance while its output impedance is close to 0. This makes the receiving circuit avoid being unable to affect the reference circuit. The common emitter amplifier is often linked with being a voltage amplifier. The Common base amplifier can be used as a current buffer due its current, which is caused by the reference current to control the receiving circuit. In it also common to have a low output impendence and have a high input, which is not noticeable in this lab.

Two transistor Amplifiers

This section of the lab will deal with two transistor amplifiers CE-B, CC-CB and CC-CE. In this section several calculations will be made to find small signal parameters and will also be compared to measurements that were taken in day 1.

CE-CB

The diagram for CE-CB can be seen in Figure 7.

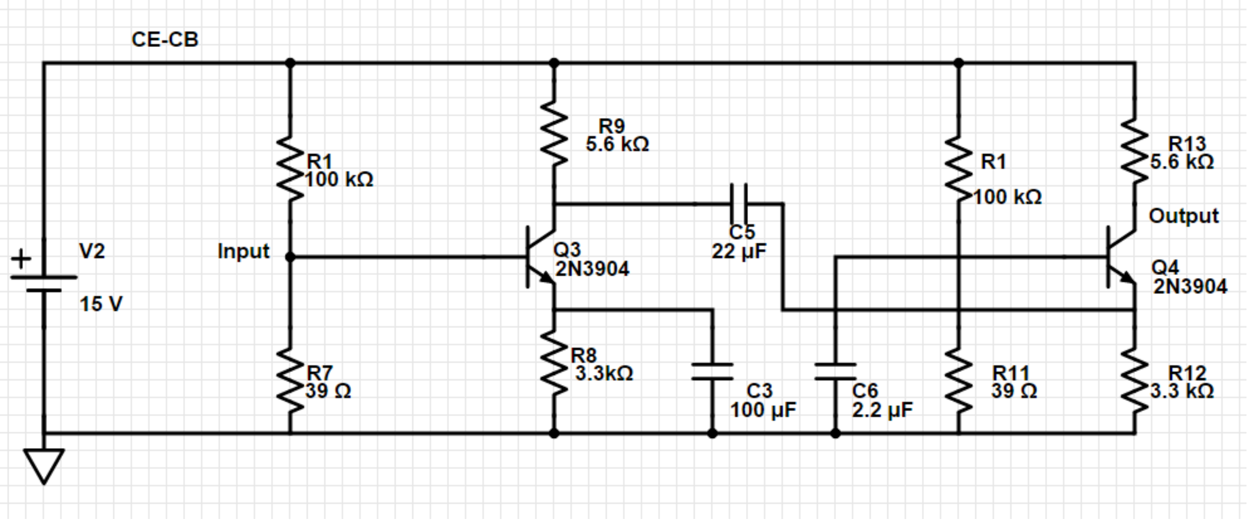

Figure7: CE-CB amplifier

The small signal analysis for CE-CB can be seen in figure 8.

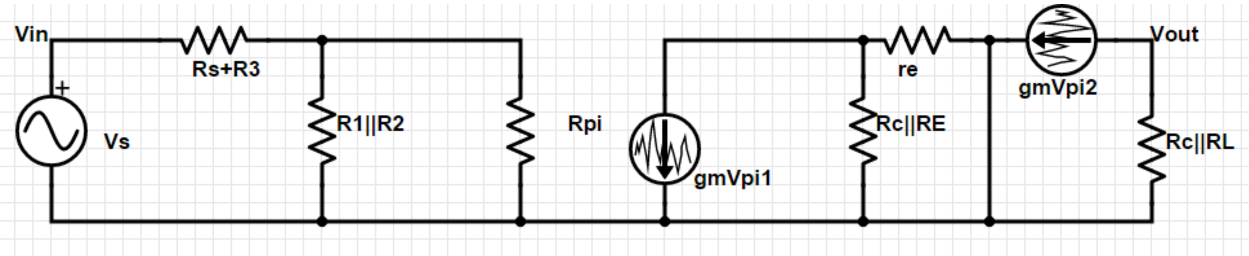

Figure8: Small signal analysis for CE-CB

Using Figure 8 the expressions gain can be determined to be:

$$V_{out} = -gmV\pi 2(Rc||RL)$$

$$V_{\pi 2} = gmV\pi 1(re||RE||RC) \approx V_{\pi 1}$$

$$V_{\pi 1} = \frac{r\pi||R1||R2}{r\pi||R1||R2 + Rs + R3} * V_{in}$$

The gain Av can be determined to be:

$$Av = \frac{Vout}{Vin} = -gm(RC||RL)\frac{r\pi||R1||R2}{r\pi||R1||R2 + RS + R3} = -39.1\frac{v}{v}$$

The input and output resistances can be determined to be:

$$R_{in} = R3 + R1||R2||r\pi = 6.3k\Omega$$

$$R_{out} = R_C||\left(ro + re + R_C||R_E||re\right) = 5.2k\Omega$$

The Low Frequency cut-off can be determined to be:

$$\omega 1 = \frac{1}{Cin(Rs + Rin)}$$

$$\omega 2 = \frac{1}{Cout(RL + Rout)}$$

$$\omega 3 = \frac{1}{Ccoupling(RE||re + RC)}$$

$$\omega 4 = \frac{1}{CE(RE||\dfrac{r\pi + R1||R2||(Rs + R3)}{\beta + 1}}$$

$$\omega 5 = \frac{1}{CB(R1||R2||[re + Rc||RE)(\beta + 1)]}$$

$$f_L = \frac{1}{2\pi}(\omega 1 + \omega 2 + \omega 3 + \omega 4 + \omega 5) = 76.1\ Hz$$

The High Frequency cut-off can be determined to be:
Using Miller's theorem to separate some capacitors as seen in Figure 9, for the values they can be determined below:

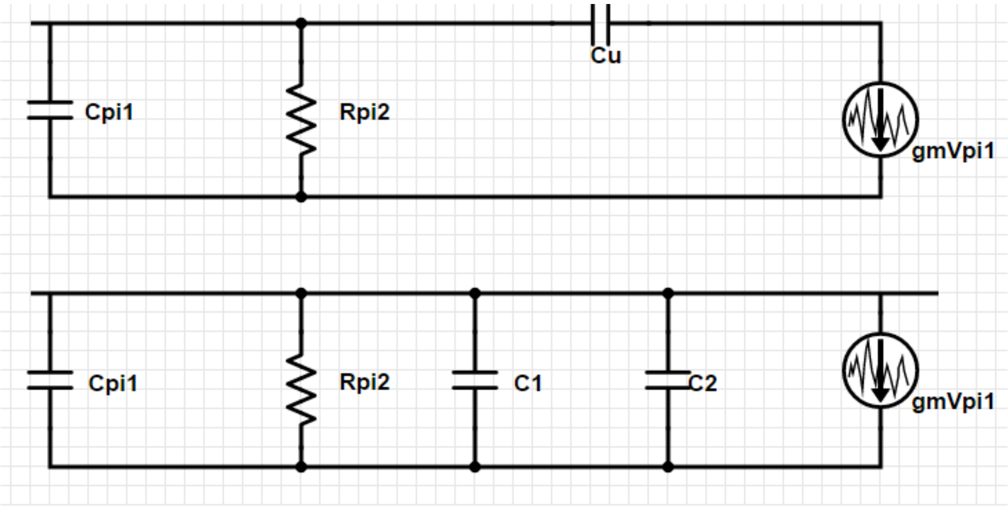

Figure 9: Small signal analysis, separating the Capacitors using miller's Theorem

$$C1 = C\mu(1 - \frac{vc}{vb})$$

$$C2 = C\mu 1(1 - \frac{vb}{vc})$$

$$\frac{vc}{vb} = \frac{-gmv\pi(Rc||RE||re)}{v\pi} \approx -1$$

$$C1 = 2C\mu 1$$

Using these the high frequency pole is:

$$\omega 1 = \frac{1}{(r\pi||R1||R2||(R3 + Rs)(C\pi 1 + C1)}$$

$$\omega 2 = \frac{1}{(RC||RE||re)(C\pi 2 + C2)}$$

$$\omega 3 = \frac{1}{(RC||RL)C\mu 2}$$

$$fH = \frac{1}{2\pi}\left(\frac{1}{\omega 1} + \frac{1}{\omega 2} + \frac{1}{\omega 3}\right)^{-1} = 1.66MHz$$

CC-CB

The CC-CB transistor can be seen in figure 10 which is planned to be done in lab:

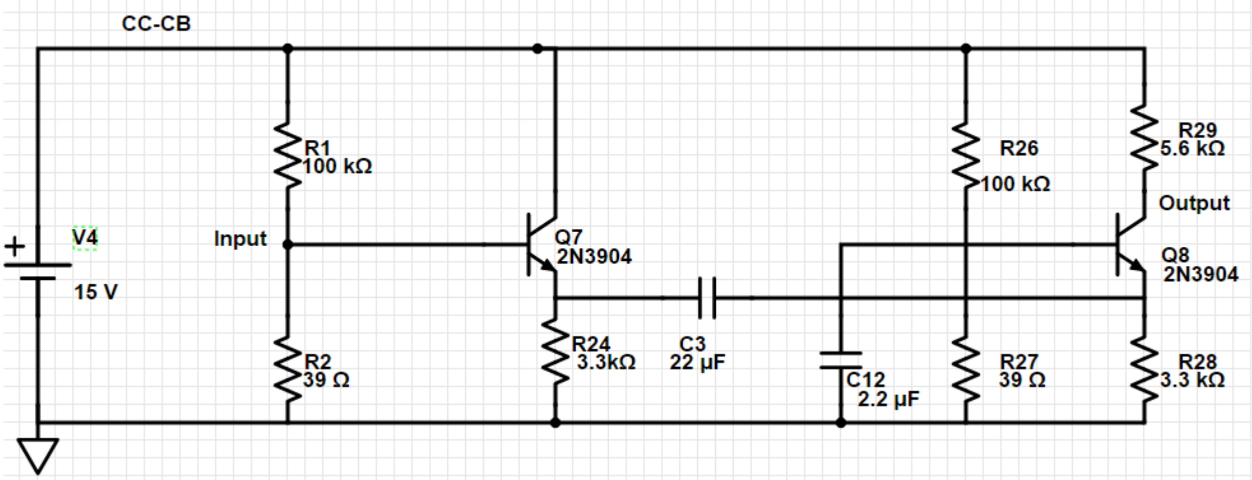

Figure 10: CC-CB amplifier

The small Signal analysis of diagram above can be shown in Figure 11:

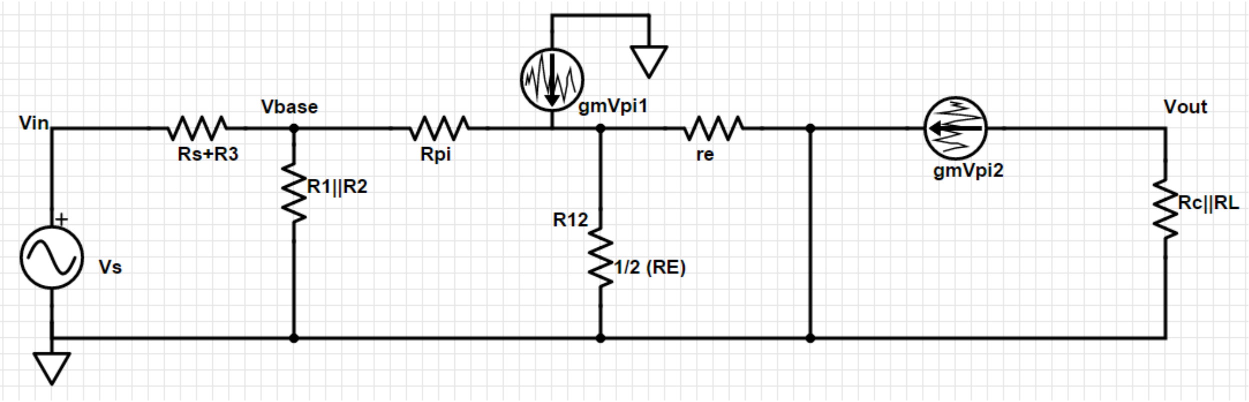

Figure 11: Small signal analysis of CC-CB

Using small signal analysis, the gain expressions can be determined:

$$Vout = gmv\pi 2(Rc||RL) = 102.1$$

$$V_{\pi 2} = -Vbase1\frac{(0.5RE)||re}{(0.5RE)||re + \frac{r\pi}{\beta + 1}} = -0.5Vbase1$$

$$V_{base1} = Vin\frac{R1\left|\right|R2\left|\right|[r\pi + ((0.5RE||re)(\beta + 1)}{R1\left|\right|R2\left|\right|[r\pi + \left((0.5RE)\right||re)(\beta + 1)\big] + Rs + R3} = 0.6\,Vin$$

$$Av = \frac{V_{out}}{V_{in}} = -31\ \frac{v}{v}$$

Input and output resistances can be determined to be:

$$R_{in} = R3 + R1||R2(r\pi + 0.5RE)||re)(\beta + 1) = 8.71\ K\Omega$$

$$Rout \approx RC||ro = 5.22k\Omega$$

The low frequency cut-off can be determined to be:

$$\omega 1 = \frac{1}{Cin(R_{in} + Rs)}$$

$$\omega 2 = \frac{1}{Cout(RL + Rout)}$$

$$\omega 3 = \frac{1}{CB(R1||R2||(re + RE\left|\right|RE\left|\right|\frac{r\pi + R1\left|\right|R2\left|\right|R3}{\beta + 1})(\beta + 1))}$$

$$\omega 4 = \frac{1}{Ccoupling(RE||re + RE||\frac{r\pi + R1\left|\right|R2\left|\right|R3}{\beta + 1})}$$

$$fL = \frac{1}{2\pi}(\omega 1 + \omega 2 + \omega 3 + \omega 4) = 183Hz$$

The High frequency cut-off can be determined by:

$$\omega 1 = \frac{1}{(R3\left|\right|R2\left|\right|R1||\left(r\pi + \beta\left(re\right|\left|re\right|\left|RE\right)\right))(C\mu + \frac{C\pi}{1 + gm\left(RE\right|\left|RE\right|\left|re\right)})}$$

$$\omega 2 = \frac{1}{(re||RE||RE|\left|\frac{r\pi + R1\left|\right|R2\left|\right|R3}{\beta + 1}\right)C\pi 2}$$

$$\omega 3 = \frac{1}{C\mu 2(RC||RL)}$$

$$fH = \frac{1}{2\pi}(\frac{1}{\omega 1} + \frac{1}{\omega 2} + \frac{1}{\omega 3})^{-1} = 2.4\ MHz$$

CC-CE:

The full circuit of CC-CE can be seen below in Figure 12:

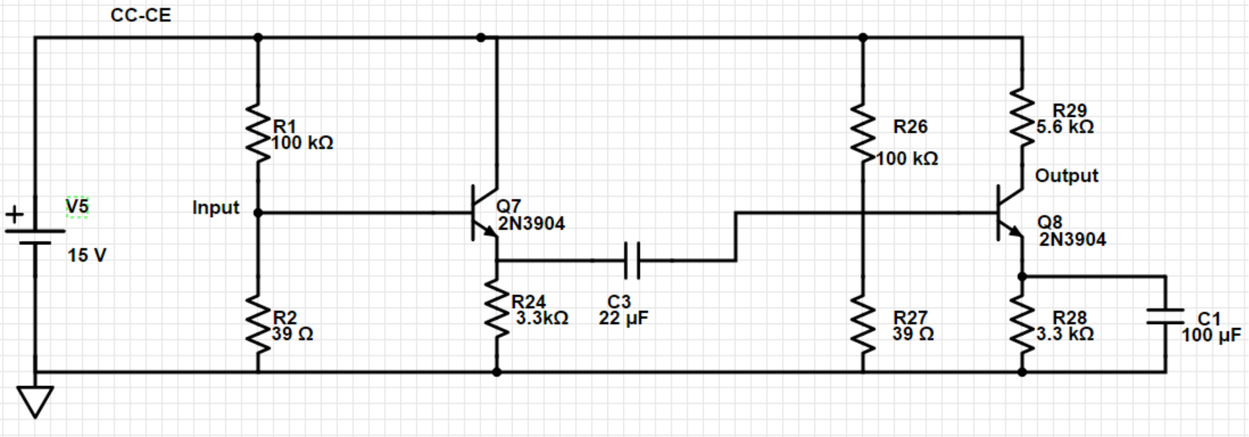

Figure 12: CC-CE amplifier

The small signal analysis of Figure 12 can be seen in Figure 13:

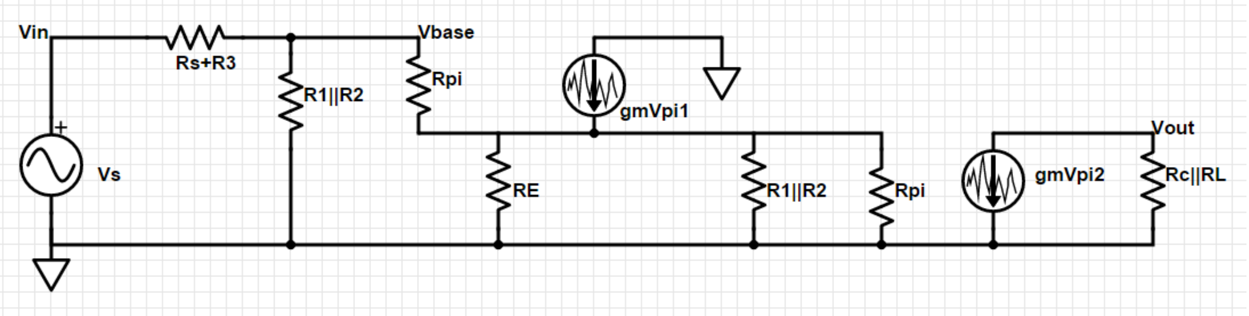

Figure 13: Small signal analysis of CC-CE

Using small signal analysis, the gain expressions can be determined:

$$Vout = -gmv\pi 2(RC||RL) = -102.2$$

$$v\pi 2 = Vbase\frac{r\pi||R1||R2||RE}{r\pi||R1||R2||RE + \frac{r\pi}{\beta + 1}} = 0.99Vbase1$$

$$Vbase1 = Vin\frac{R1||R2||(r\pi + (RE||R1||R2||r\pi)(\beta + 1)}{R1||R2||(r\pi + (RE||R1||R2||r\pi)(\beta + 1) + R3 + Rs} = 0.88Vin$$

$$Av = \frac{V_{out}}{V_{in}} = -89.5$$

The input and output resistances can be determined:

$$R_{in} = R3 + R1||R2||(r\pi + (RE||R1||R2||r\pi)(\beta + 1) = 25.7\ k\Omega$$

$$Rout = Rc||ro = 5.23\ \Omega$$

The low frequency cut-off can be determined to be:

$$\omega 1 = \frac{1}{Cin(Rin + Rs)}$$

$$\omega 2 = \frac{1}{Cout(RL + Rout)}$$

$$\omega 3 = \frac{1}{CE(RE|| \dfrac{r\pi + RE||R1||R2||(\dfrac{r\pi + R1||R2||R3}{\beta + 1})}{\beta + 1}}$$

$$\omega 4 = \frac{1}{Ccoupling(R1||R2||r\pi + RE|| \dfrac{r\pi + R1||R2||R3}{\beta + 1})}$$

$$fL = \frac{1}{2\pi}(\omega 1 + \omega 2 + \omega 3 + \omega 4) = 98Hz$$

The High frequency cut-off can be determined by:

As seen on Figure 9 in CE-CB amplifier using miller's theorem to divide Cμ parasitic capacitance:

$$C1 = C\mu 2(1 - \frac{vc}{vb})$$

$$C2 = C\mu 2(1 - \frac{vb}{vc})$$

$$\frac{vc}{vb} = \frac{-gmv\pi 2(RL)}{v\pi 2} \approx -102.2$$

$$C1 = 103.2C\mu 2, C2 = C\mu 2$$

$$\omega 1 = \frac{1}{(R3||R2||R1|| \left(r\pi + (\beta + 1)(RE||R1||R2||r\pi)\right))(C\mu + \dfrac{C\pi}{1 + gm(RE||R1||R2||r\pi)})}$$

$$\omega 2 = \frac{1}{(r\pi||RE||R1||R2| \left| \dfrac{r\pi + R1||R2||R3}{\beta + 1} \right) (C1 + C\pi)}$$

$$\omega 3 = \frac{1}{C2(RC||RL)}$$

$$fH = \frac{1}{2\pi}(\frac{1}{\omega 1} + \frac{1}{\omega 2} + \frac{1}{\omega 3})^{-1} = 3.66\ MHz$$

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Measurements for parameters:

CE-CB Amplifier:

While measuring at 1KHz the CE-CB had the following values:
Vo=2.00V
Vo'=4.11V
V_U=50.1V
V_T=26.3mV

Using these values, the parameters were determined to be:
A_V=40.1 V/V
R_{in}=6.99 kΩ
R_{out}=5.0 kΩ

The low and high frequencies were determined to be :
f_H=1.55 MHz f_L=35Hz

CC-CB Amplifier :

While measuring at 1KHz the CC-CB had the following values:
Vo=2.00V
Vo'=4.27V
V_U=66mV
V_T=40.7mV

Using these values, the parameters were determined to be:
A_V=29.78 V/V
R_{in}=8.35kΩ
R_{out}=5.46kΩ

The low and high frequencies were determined to be:
f_H= 1.85kHz f_L=131Hz

CC-CE Amplifier :

While measuring at 1KHz the common emitter had the following values:
Vo'=4.30 V
V_U=22.6 V
V_T=20.02 mV

Using these values, the parameters were determined to be:
A_V =87.1 V/V
R_{in}=28.6 KΩ
R_{out}=5.51 KΩ

The low and high frequencies were determined to be:
f_H=1.77 MHz f_L=65.1Hz

Calculation and measurement Comparison:

The comparison between the Calculated and measured values for small signal parameters are included in Table 4 below:

CE-CB	**|AV|**	**39.1**	**40.1**	**V/V**
	Rin	6.3	6.99	kΩ
	Rout	5.2	5.0	kΩ
	f_L	76.1	35	Hz
	f_H	1.66	1.55	MHz
CC-CB	|Av|	31	29.378	v/v
	R_{in}	8.71	8.35	kΩ
	R_{out}	5.22	5.46	kΩ
	f_L	183	131	Hz
	f_H	2.4	1.85	MHz
CC-CE	|Av|	89.5	87.1	v/v
	R_{in}	25.7	28.6	kΩ
	R_{out}	5.23	5.51	kΩ
	f_L	98	65.1	Hz
	f_H	3.66	1.77	MHz

The CE-CB amplifier can be noticed to have both the measured results and calculated results to be quiet close. However, that is not the case in f_L which has a significant difference, that can be explained by the limited supplies in capacitors which are key to low frequency cut-off. The CC-CB amplifier's measured parameters were very close to calculated values, while f_H was significantly different. That could be very easily due to the assumption of its internal parasitic capacitance. Like mentioned before since BJTs have a wide range of Cπ, assuming the value for all of them can cause significant difference if its tied to the dominant pole. The CC-CE had also the same issue as the CC-CB as it caused high frequency cut-off to also be quiet different. Although they have related characteristics, all three cascade amplifiers have characteristics which makes it have more shared purposes. As an example the CE-CB had the lowest cut-off frequencies which resulted in possible larger bandwidth while still being simple but effective voltage amplifiers. As with CC-CB has both voltage and a current buffer, it also has a lower gain than the other two amplifiers. The CE-CE has the highest gain due to voltage buffer being paired with a voltage amplifier what make it easier for the voltage to be more extracted.
The biggest advantage of the CE-CB cascade is the fact that input and output are totally split as the common emitter is splitting them apart as it can be seen in Figure 8. This permits the input and output circuits to not be influenced by miller's theorem. That is the idea that joined branches can be integrated and influence the main circuit. The CC-CE has a common emitter which allows split the input and output while still have a larger gain. The CB acts as a current buffer which helps to avoid feedback from output and input. The result is quiet a high gain and a high steadiness amplifier.

There is a connection between part one and part two, in part one using CE, CB, or CC independently resulted in different characteristics. CB has low input impedance, so the source delivers current to the input instead of voltage. CB works as voltage amplifier rarely. As for CE, the bandwidth tends to be low witch results in miller's effect. This makes CE circuit used as a junction. CE amplifier has higher input impedance and lower output impedance comparing to CB. Lastly, CC amplifier has much higher input resistance than output Load Resistance R_L for a large current gain. CC amplifier also have small output impedance.

Using multiple transistors, the impedance of the input and the output can be decreased, this allows high input resistance, low output resistance with a high gain, without having the mishaps of using Each amplifier transistor independently.

Part 3: Cascade specification / Design

3.1 Circuit requirement:

A PNP cascade circuit was constructed and designed to the specified values of the 3509 lab 2 manual. **Table 5** shows all the required values.

The first required calculation was the Gain, in which it was acquired using the magnitude of gain function:

$$A_V = (\frac{Z^3}{40} - 1.03Z^2 + 11Z + 12) \pm 5\% \qquad (1)$$

The variable Z was the addition of the last three digit of student number (of Al Omari). The value of Z was 348, using the previous equation the gain was found to be 29.625±5% was obtained

To find the Load resistance R_L, Z=348 was used in them equation below:

$$R_L = 5(Z + 51)^2 \qquad (2)$$

Table 5 below discuss the circuit requirements. Those requirements were met and discussed further into this report

Table 5: Circuit Requirement List

VARIABLE	REQUIREMENT
TYPE OF CIRCUIT	PNP
GAIN OF THE CIRCUIT (Z=348)	29.625±5%
LOAD RESISTANCE (R_L)	21.78
HIGH FREQUENCY CUT-OFF(F_H)	f_H>600kHz
TOTAL POWER OF THE CIRCUIT	P< 50mW
DC CURRENT	R_L and the generator do not have DC current through then
LOW FREQUENCY CUT-OFF (F_L)	60 Hz< f_L<200Hz
COLLECTOR CURRENT (I_C)	I_C= 1mA±10%
POWER SUPPLY	15V and Ground
DC CURRENT	R_L and the generator do not have DC current through them

3.2 DC bias Network Design

Design selections were made to estimate all the parameters of the DC design chosen. The estimations, calculations, and procedure are found below:

The circuit used calculate the DC parameters is in **Figure 14,** which its shows the final DC circuit design

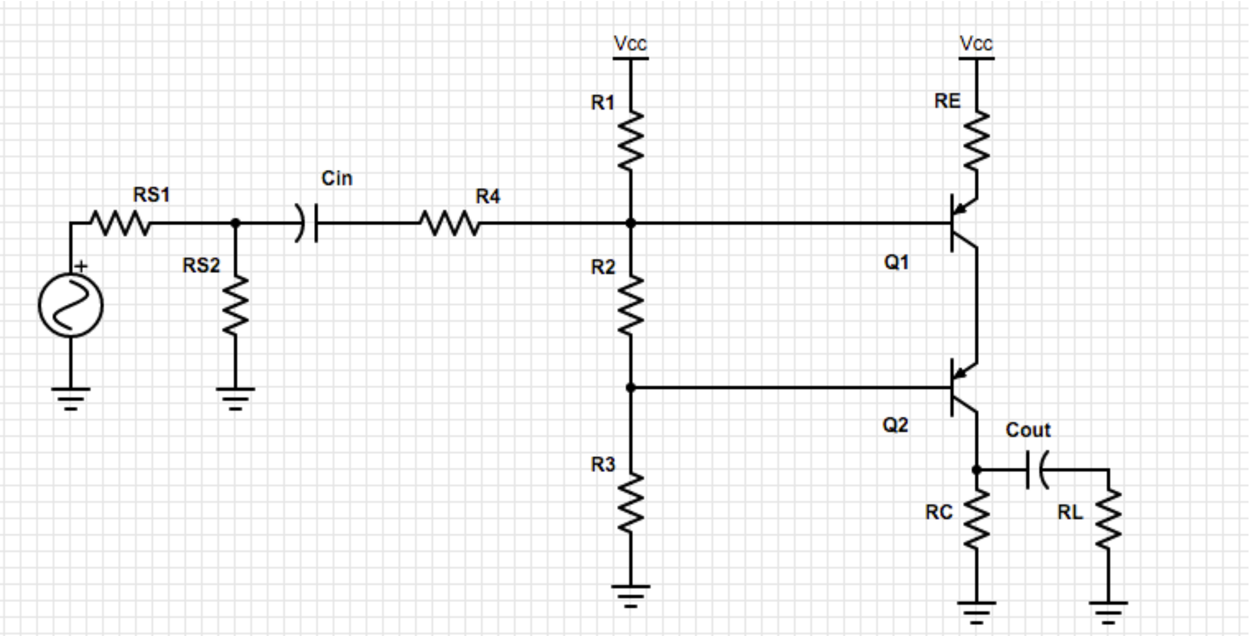

Figure 14: DC circuit design of a PNP circuit

Method:

On the first hand, it was important to maximize the voltage swing. So, it was essential to assign the right branch a voltage drop across. The voltage swing of $0.2V_{CC}$ was apportioned to R_E, this makes the voltage drop across load resistor equal to 8V.

The voltage drop across the two transistors were assumed to be 2V for each Q1 and Q2. This assumption was made to ensure that the lower transistor is in active mode, this helps preserve an output voltage drop that is reasonable.

So using the previous assumptions it leaves R_C with a voltage drop of 3V.

The collector current was given to be I_C=1mA, so the second step was to find all other currents. To find the base current, the collector current was used in the formula below:

$$I_B = \frac{I_C}{\beta} = \frac{1}{152} = 6.57\mu A \tag{3}$$

Using he β to be equal to 100, the base current was found to be 10µA =I_B

Later, the current through the left branch (I_{REF}) was found, as a rule of thumb the left branch current is $2(10I_B)$, so the I_{REF}=0.2mA

$$I_{Degeneaion} = I_{C1} + I_{B1} = 1mA + 6.578\mu A = 1mA$$

$$R_{Degeneaion} = \frac{3V}{1mA} = R_{E1} + R_{E2} = 3.00k\Omega$$

$$I_{R3} = 10 * (I_{B1} + I_{B2}) = 10 * (6.578\mu A + 6.578\mu A) = 131.56\mu A$$

$$I_{R2} = I_{R3} + I_B = 10 * (131.56\mu A + 6.578\mu A) = 138.138\mu A$$

$$I_{R1} = I_{R2} + I_B = 138.138\mu A + 6.578\mu A = 144.716\mu A$$

Finally, finding the remaining values of R1, R2, R3.RC, and RE. Resistors values were found using the equations below

$$R_3 = \frac{V_{CC}-V_{B1}}{I_{R3}} = \frac{15-(15-0.7-3)V}{131.56\mu A} = 28.12K\Omega \qquad (4)$$

$$R_2 = \frac{V_{B1}-V_{B2}}{I_{R2}} = \frac{11-(11.3-2)V}{138.138\mu A} = 14.47K\Omega \qquad (5)$$

$$R_1 = \frac{V_{B2}}{I_{R2}-2I_B} = \frac{9.3V}{138.138\mu A-2(6.578\mu A)} = 78.54K\Omega \qquad (6)$$

$$R_C = \frac{V_{C2}}{I_C} = \frac{5V}{1\mu A} = 5K\Omega \qquad (7)$$

$$R_E = 3K\Omega = R_{E1} + R_{E2} \qquad (8)$$

-R_4 was assigned a value of 500Ω

3.3 Designs for Gain Specification

AC design obtaining the small signal parameters (more importantly total output gain) of the circuit after successfully completing the DC design was necessity. All the important calculations need to find the parameters including the output gain are found below:
The small signal model below (in figure 15) is for the circuit in figure 14.
Figure 15 uses a merge between Hybrid-π and a T model drawn in the Hybrid-π type. All capacitor C_1, C_2, and C_3 are all shorted which makes R_{E2} shorted too.

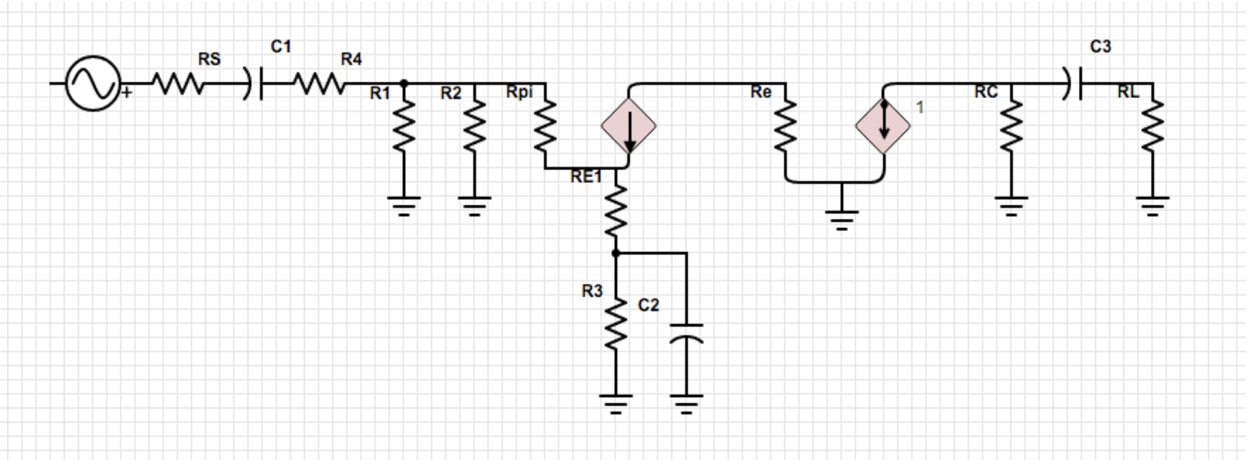

Figure 15: AC analysis for the small signal model

Small signal parameters in AC analysis:

$$r_\pi = \frac{V_T}{I_B} = 2.5K\Omega$$

$$g_m = \frac{I_C}{V_T} = 40\frac{mA}{V}$$

$$r_e = \frac{V_T}{I_E} = 25\Omega$$

Equation 8 is used to find the total gain, taking the difference between voltage points and then the equation is than derived:

$$A_v = \frac{V_o}{V_{\pi 2}} * \frac{V_{\pi 2}}{V_{\pi 1}} * \frac{V_{\pi 1}}{V_s} \qquad (9)$$

$$R_{in} = (R_1 || R_2) || (R_E + R_E(1+\beta))$$

$$R_{OUT} = R_C$$

$$R'_L = R_L || R_C$$

Equivalent resistance equations set: 1

$$V_o = -gm V_{\pi 2}(R_L')$$

$$V_{\pi 2} = -r_e \, gm(V_{\pi 1})$$

$$V_{\pi 1} = V_1 \left(\frac{r_\pi}{(r_\pi + R_{E1}(1+\beta))}\right)$$

$$V_1 = V_S \left(\frac{R_{in}}{R_{in} + R_S}\right)$$

Equivalent voltage equations set: 2

$$A_V = \frac{R_{in}}{R_{in}+R_S} * \frac{r_\pi}{(r_\pi + R_{E1}(1+\beta))} * r_e \, gm_1 * gm_2 \, (R_L')$$

$$A_V = gm^2 (R_L || R_C)(r_e) \frac{R_2 || R_3 || (r_e + R_E(1+\beta))}{((R_{470} || R_{56}) + R_4) + (R_2 || R_3 || (r_\pi + R_E(1+\beta)))} \frac{r_\pi}{(r_\pi + R_E(1+\beta))}$$

$$\approx 28.2$$

(10) Total Output Gain

Using equation 10, R_{E1} was found and R_{E2} was found using equation 8

Table 6 shows the calculated values from the equations derived above

VARIABLE	VALUE
R_1	$65.12 K\Omega$
R_2	$14.63 K\Omega$
R_3	$28.5 K\Omega$
R_C	5 KΩ
R_4	10 KΩ
R_E	3KΩ
R_{IN}	5.217 KΩ
R_{OUT}	8 KΩ
R_L	21.78KΩ
GAIN	29.625

3.4 Frequency specification Design

Next step after finding the AC and the DC designs is to find the associated high and low frequency cut-offs, those design aspects are explained in depth below:

Low frequency Cut-off

Low frequency cut-off (f_L) can be found using the equivalent resistance around each capacitor, this equation can found below:

$$2\pi f_L = \frac{1}{R_{Cin}C_{in}} + \frac{1}{R_{Cout}C_{out}} + \frac{1}{R_{CE}C_E} + \frac{1}{R_{CB}C_B} \qquad (11)$$

Finding C_{in}:

To find the equivalent resistance that is passed by C_{in}, **figure 16** circuit was used:

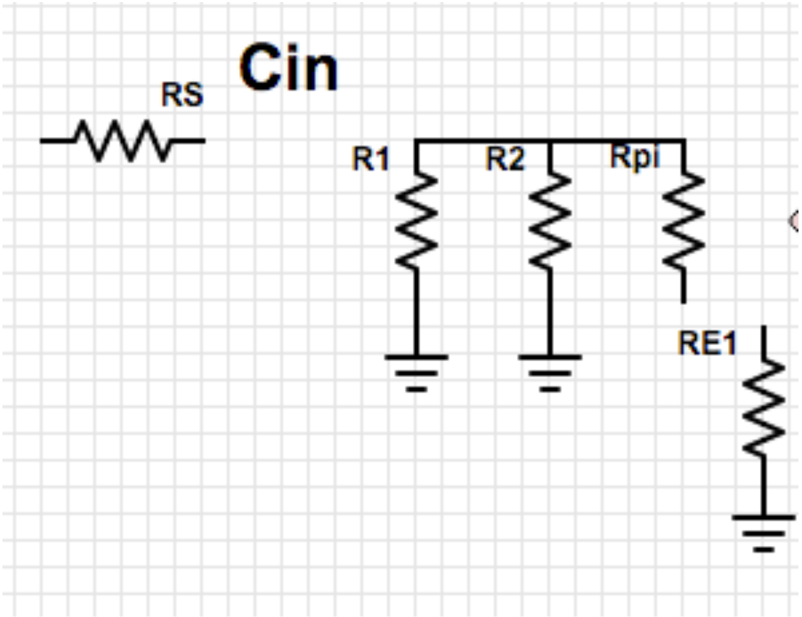

figure 16: The circuit passed by C_{in}

By analysing **figure 16** the equivalent resistance of R_{Cin} can achieve this equation:

$$R_{C_{in}} = [\{r_\pi + R_{E1}(\beta + 1)\}||(R_1 + R_2)] + R_s$$

Finding C_{out}:

To find the equivalent resistance that is passed by C_{out}, **figure 17** circuit was used:

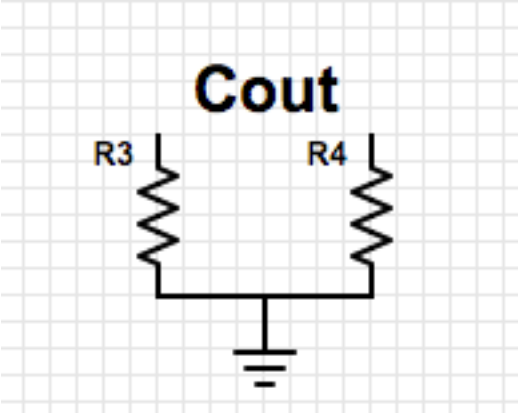

figure 17: The circuit passed by C_{out}

By analysing **figure 17** the equivalent resistance of R_{Cin} can achieve this equation:

$$R_{C_{out}} = R_C + R_L$$

Finding C_E:

To find the equivalent resistance that is passed by C_E, **figure 18** circuit was used:

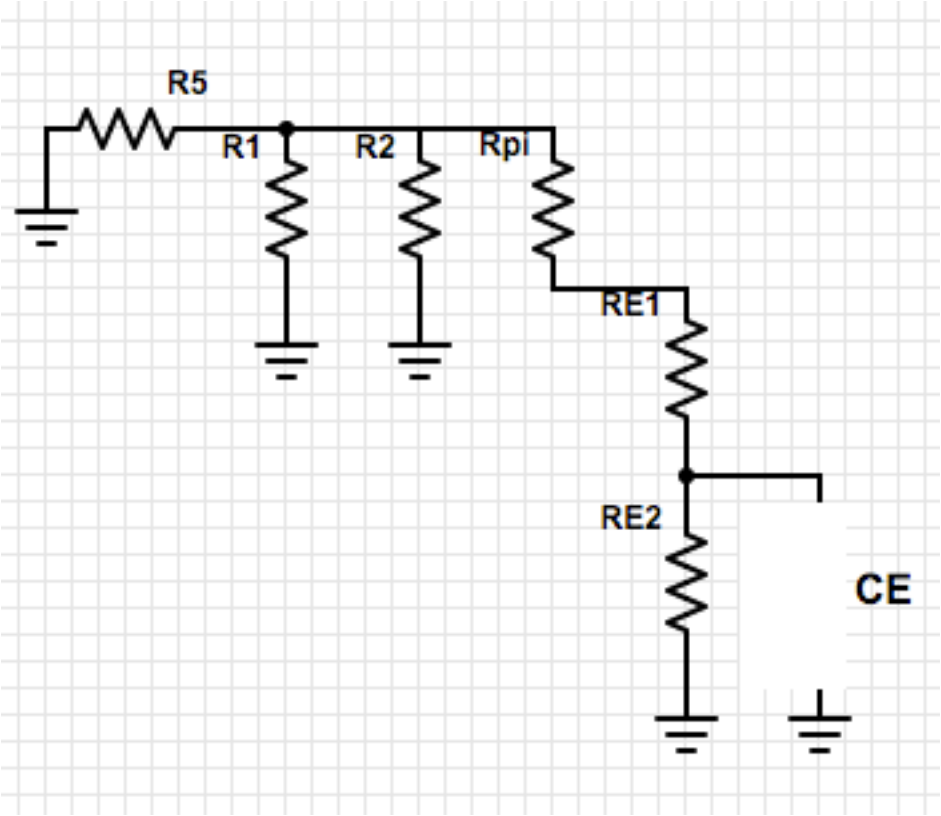

Figure 18: The circuit passed by C_E

By analysing **figure 18** the equivalent resistance of R_{CE} can achieve this equation:

$$R_{C_E} = \frac{R_S||R_1||R_2 + r_{\pi 1}}{\beta + 1} + R_{E1}||R_{E2}$$

Finding C_B:

To find the equivalent resistance that is passed by C_B, **figure 19** circuit was used:

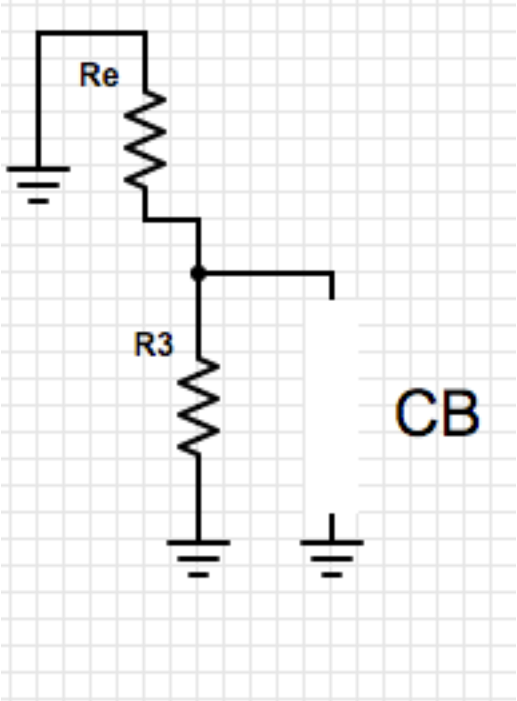

Figure 19: The circuit passed by C_B

By analysing **figure 19** the equivalent resistance of R_{CB} can achieve this equation:

$$R_{C_B} = r_e(\beta + 1)||R_3$$

To calculate the values of the capacitors from the equivalent resistance, an assumption of low cut-off frequency was made:

$$f_L = 180 \text{ Hz}$$

The magnitudes of the capacitors were split to aid in the design, the magnitudes were divided as follows (using equation 11):

$$70\% \ (2\pi f_L) = \frac{1}{R_{CE}C_E}$$

$$30\%(2\pi f_L) = \frac{1}{R_{Cin}C_{in}} + \frac{1}{R_{Cout}C_{out}} + \frac{1}{R_{CB}C_B}$$

Magnitude of Low cut- off frequency **Equations set: 1**

Found equivalent resistance values are found in **table 7** below:

R_{Cin}	$R_{C_{out}}$	R_{CE}	R_{CB}
5.78 KΩ	30 KΩ	244.6 Ω	2.39 KΩ

Table 7: Equivalent Resistance (Calculated)

By using F_L=180 Hz and the Equivalent Resistance into equation set 1 above, each capacitor was calculated and the values can be found in table 8:

C_{IN}	C_{out}	C_E	C_B
1.6 µF	0.294 µF	5.16 µF	3.7 µF

Table 8: capacitor values (Calculated)

The values of C_E and C_{out} were not available in the lab, so the values that were used in the lab were unlike the values of **table 8**. C_{in} and C_B values were altered to balance the differences between C_E and C_{out}. The values used in the lab are in **table 9** below:

C_{IN}	C_{out}	C_E	C_B
10 µF	2.2 µF	3.3 µF	2.2 µF

Table 9: capacitor values (Used)

High frequency cut-off

High frequency cut-off (f_H) can be found by modifying **figure 15,** and adding few capacitors $C_{\pi 1}$, $C_{\pi 2}$, $C_{\mu 1}$, and $C_{\mu 2}$. This lead to the modified circuit **figure 20:**

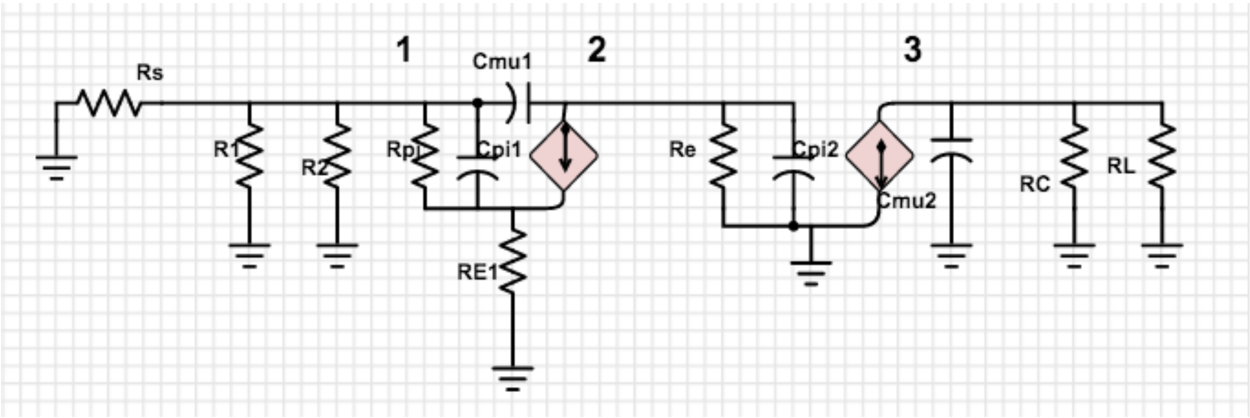

Figure 20: the modified circuit

R_{E1} is insignificant value and may cause obstacle in calculating the cut-off, so if was overlooked. C_π and C_μ used in this lab were the values used in the previous lab (lab1):

C_Π	C_μ
42.6PF	4pF

In figure 20, there are few nodes. At node 1, miller's theorem is applied to find $C_{\mu 1}$ to create capacitor C1 and C2. The procedure for obtaining them can be found below:

$$C_1 = C_{\pi 1}(1 - \frac{V_C}{V_B})$$

$$C_2 = C_{\pi 2}(1 - \frac{V_B}{V_C})$$

$$V_B = V_{\pi 1}$$

$$V_C = (g_m)(V_{\pi 1})(r_e)$$

By computing the result and the formulas mentioned above:

$$C_1 = C_2 = 8pF$$

Poles high frequency can be obtained using the data above to be expressed as:

$$W_{H1}=\frac{1}{(R_S||R_1||R_2||r_{\pi 1})(C_{\pi 1}+C_1)} = 46\ MHz$$

$$W_{H2}=\frac{1}{(C_{\pi 2}+C_2)} = 100\ MHz$$

$$W_{H3}=\frac{1}{(R_C||R_L)(C_{\mu 2})} = 3.37\ MHz$$

The dominant pole is the smallest pole value, which in this case is W_{H3}. This means that the calculated high frequency cut-off is:

$$f_H = W_{H3} = 3.37MHz$$

The following section will discuss the measured results using this section values of the design. These measured results will include parameters and plot frequencies. Also comparison between calculated and theoretical values will be covered.

3.5 Measured Values

Gain:

At the nodes, V_O and V_U were measured. Node U and node Z respectively. The points of U and Z are shown in the figure below.

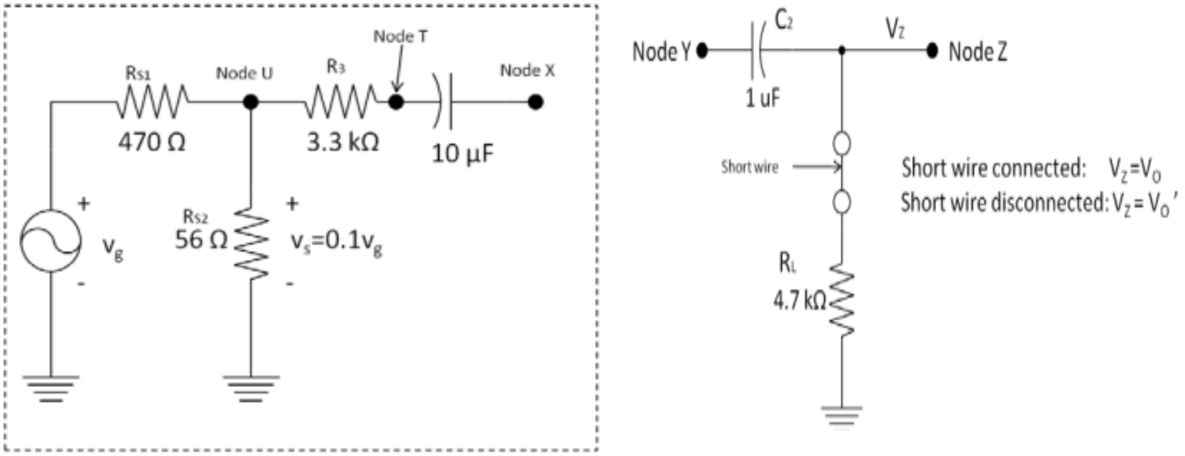

Figure 21: The position of Node U and Node Z

MEASURED V_O=500MV	**MEASURED V_U=31.3MV**

Equation 11 below measure the gain:

$$Av = \frac{V_O}{V_u} = 29.65\ V/V \qquad (11)$$

R_{in}:

Equation 12 below measure R_{in}:

$$R_{in} = \frac{V_u}{V_u - V_T} * R_3 \qquad (12)$$

Input resistance is found to be R_{in}: 5.6KΩ

R_{out}:

Equation 13 below measure R_{out}:

$$R_{out} = \frac{V\prime_u - V_o}{i_{Rl}} * R_3 \qquad (13)$$

V'_o that is present in equation 13, is a reference to the voltage measured at node Z in figure 20A which the short wire removed. The voltage which slightly larger than V_o is the voltage with the short wire connected.

MEASURED V'_O=2.66 V **MEASURED V_O=1.96 V** **MEASURED I_{RL}=93 µA**

The output resistance is R_{out}= 7.5KΩ

Power:

$$P = \frac{V^2}{R} \qquad (14)$$

To calculate the total power consumed by the circuit, the voltage drop across each resistor was measured and then using equation (14) to find the power of each resistor consumes. Table 10 below shows resistor power value.

Variable	*Voltage(v)*	*Resistance(kOhms)*	*Power Consumed (mW)*	*Summation*
R1	2.77	67.8	0.113169617	0.113169617
R2	1.95	14.8	0.256925676	0.370095292
R3	10.52	25.5	4.340015686	4.710110978
RC	7.52	4.9	11.54089796	16.25100894
RE1	0.2	0.238	0.168067227	16.41907616
RE2	0.3	2.66	0.033834586	16.45291075

Table 10: measured power Consumed by each Resistor

$$\sum P = 16.45\text{mW},\ 16.45\text{mW} < 50\text{mW}$$

$$I_{branch} \approx 0.134mA$$
$$I_{Total} = I_{branch} + I_C = 0.98mA + 0.134mA = 1.114mA$$
$$Power_{DC} = V_{Total} + \ I_{Total} = 15V * 1.114mA = 16.71mW$$

The total power consumed is 8.40mW which is below the required power consumption of (50mW)

Collector Current is:

$$I_C = \frac{V_{R_C}}{R_C} = \frac{4.8V}{4.9K} = 098mA \approx 1mA$$

Cut off frequencies:

Using the 2V peak to peak signal, frequencies of high and low were found. Later, by adjusting the input frequencies while maintaining the currents level.
Frequencies were changed until an output of 1.4V was reached, this without should is done without having any distortion in the signal.
The cut-off frequencies were

LOW CUTOFF F_L	HIGH CUTOFF F_H
150 HZ	2.18 MHz

Data comparison:
The comparison between the values calculated and measured in the lab:

VARIABLE	MEASURED	CALCULATED
R1	67.85KOhms	65.1KOhms
R2	14.81KOhms	14.62KOhms
R3	26.82KOhms	28.5 Kohms
RC	4.91KOhms	5Kohms
RE1	238Ohms	238.6 Ohms
RE2	2.66Kohms	2.76 Kohms
RIN	5.6Kohms	5.217 Ohms
ROUT	7.5 Kohms	8Kohms
RL	21.78Khoms	22 Kohms
FL	150 Hz	180 Hz
FH	2.18 MHz	3.37MHz
GAIN	29.625V/v	30 +- 5%

Table 11: measured Vs. Calculated comparison

The measured and the calculated values are close to each other. This shows relation and the precision between the calculated and the equations derived in the prelab. Also this shows that the pre lab experimental values eliminate the assumptions and estimations for accurate results, which result in a more accurate gain
The visible variances are only present in the frequencies which is due to the components used in the lab.
Overall the results are fairly accurate and meet all requirement that were present in the lab manual.

Part 4 Cascade Implementation and verification

Theory:

The theoretical values as mentioned in the previous sections the low and high cut off frequencies are 180Hz and 3.37MHz respectively. In the table below shows the relationship between gain and frequency.

FREQUENCY (HZ)	20 LOG(AV)
18	3.9
180	23.9
1000	26.9
2000	26.9
40000	26.9
100000	26.9
200000	26.9
1000000	25
2000000	24
3370000	23.9
3370000	3.9

Table 12: Theatrical Gain vs. frequency

-The theoretical gain 29.625, this is converted to dB the gain becomes 29.32dB, this point is expected to be constant at many of points in the middle

-the gain is expected to drop by 3dB's at low and high cut off frequencies between 1000Hz and 180Hz (f_L).

- the gain is expected to drop 20dB/Decade, so at the low frequency 180Hz one decade would be 18Hz and the gain is expected to drop from 23.9 to 3.9 dB
- similarly, the high frequency 3.37MHz one decade would be 33.7Hz and the gain is expected to drop from 23.9 to 3.9 dB

Implementation:

20 measurements were put in which the frequency response of the circuit was measured. Table 13 shown below:

FREQUENCY (HZ)	V_{IN} (V)	V_{OUT} (V)	GAIN (V)	GAIN DB
10	50	190	3.800	11.596
25	68	550	8.088	18.157
50	68	890	13.088	22.338
100	70	1310	18.714	25.443
130	70	1490	21.286	26.562
160	68	1610	23.676	27.486
200	70	1710	24.429	27.758
300	70	1850	26.429	28.441
400	70	1950	27.857	28.899
500	70	2010	28.714	29.162
650	70	2070	29.571	29.417
1000	70	2080	29.714	29.459
2000	70	2080	29.714	29.459
4000	70	2070	29.571	29.417
15000	70	2050	29.286	29.333
40000	70	2030	29.000	29.248
100000	70	2020	28.857	29.205
300000	70	1910	27.286	28.719
550000	70	1710	24.429	27.758
700000	70	1530	21.857	26.792
840000	70	1410	20.143	26.082
1000000	70	1290	18.429	25.310
1500000	70	990	14.143	23.011
2000000	70	710	10.143	20.123
2500000	70	590	8.429	18.515
3000000	70	490	7.000	16.902

Table 13: measured Gain vs. frequency

-Low Cut-off Frequency: 150 Hz at V_{O}=1.4 V peak to peak
-High Cut-off Frequency: 2.18 MHz at V_{O}=1.4 V peak to peak
-Measured Gain: 28.92 at 1.96 V peak to peak

The plot of the gain measured and the frequency measured can be found below. The frequency is scaled to log scale. The maximum gain is highlighted using Gray line, and the minimum gain is marked in orange color lines. %5 deviation is allowed for the maximum and the minimum gains as per the required list. (Figure 21)

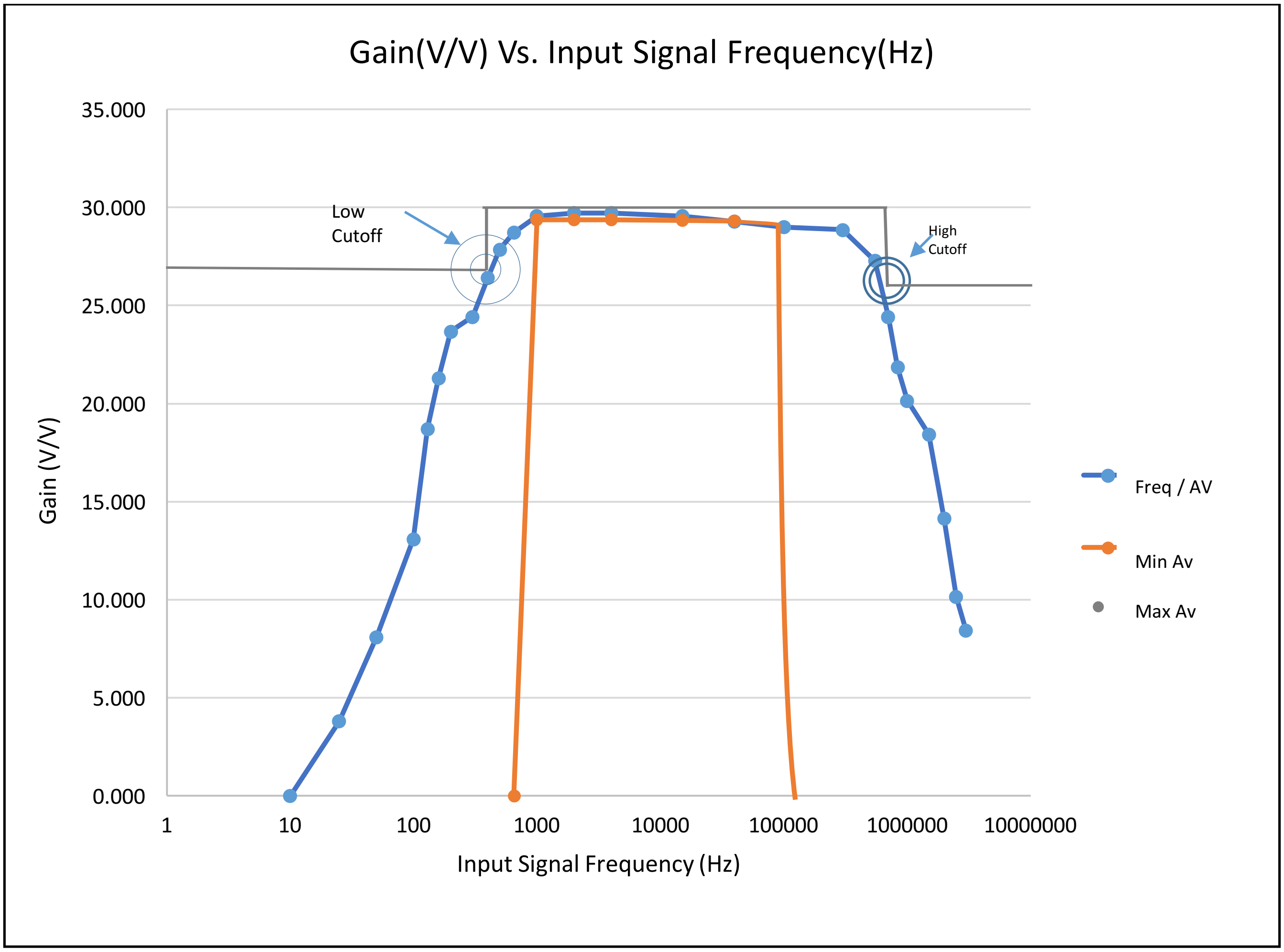

Figure 21: plot Gain(V/V) Vs. Input Signal Frequency(Hz)

-The gain is constant with little deviation as per the requirement.
-The high (f_H) and the low (f_L) frequencies are marked in blue circles

Verification:

Test 1: is the gain A_V constant?

To get this test done, the average of the gains might be calculated between the upper and the lower limits. The average gain is than compared to the ideal gain.
Average between those points is:

$$Average = \frac{28.714 + 29.429 + 29.714 + 29.714 + 29.571 + 29.286 + 29.0 + 28.857 + 27.286}{9} = 29.079$$

The average is found to be 29.079 which is close to the measured gain of 29.625. The test has be proven successful and the gain A_V is constant.

Test 2: Does the gain drop by 3dB at the low and high cut-off frequencies?

$$Gain\ in\ dB = 20\log(Gain)$$

At the cut-off gain is 21.286, so in dB is found to be 26.562 dB
Gain between the limits 29.571, converted to 29.417dB

$$Gain - Low\ Cuttoff = 29.417 - 26.562 = 2.85dB$$

The gain drops by approximately 3dB's

Comparison:

The theoretical values were close to the executed values in the experiment, all meet the criteria of requirement. Mentioned in the beginning of part 3. Those are proven in the previous section (verification). The biggest differences between the calculated and the theoretical are in the low and the high frequencies. For the low frequency cut-off (theoretical: 167Hz, measured: 150Hz), and the high frequency (theoretical: 2.18MHz, measured: 3.37MHz).
The reason beside the difference in frequencies is due to the theoretical calculation ignores the Rx, Ro, Ru. The wires create conductance within themselves and affect the values measured. However, with those differences the circuit still meets the requirements of the lab.

Conclusion:

Amplifiers can be found everywhere in electrical circuitry so handling them and knowing the proper way to use them is an important part of becoming an electrical circuit designer. Amplifiers are an effective method of sending and manipulating signal to the advantage of the designer, this could be by increasing or decreasing the strength of the signals.

In the beginning of the lab, three primary amplifiers were introduced common collector (CC), common base (CB), and common emitter (CE). Each had their own way of representing the value of the gain, Bandwidth (frequency cut-off), input and output resistances. Combining two transistors led to great advantages and fewer disadvantages than using a single transistor. Some of the advantages were noticed in stability of the gain, input and output resistances.
Common base (CB) and Common emitter (CE) where choosing to design a PNP amplifier, the PNP amplifier had requirements that was not supposed to follow to get the necessary results. The relation between the components contribute in the small signal parameters, those parameters demonstrate the importance of each component chosen.
In conclusion, the amplifier was functioning successfully with low power consumption and satisfies all the given requirements.