EEE211

PSpice experiment – Part 1

Design of Basic Transistor Amplifiers

QUESTION FORM

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<table>
<tr><th>Question</th><th>Answer</th><th>For use by the marker</th></tr>
<tr><td>1) Enter the Early voltages you have obtained for the transistors:
a) Q2N2222
b) Q2N2907.</td><td>For finding the Early voltage for a transistor, we must first plot the output characteristics of the transistor and find the slope of one of the lines, which corresponds to a value of I_B, and then enter the find the voltage of the point for which the current is equal to zero.

a) For the Q2N2222 transistor, the following circuit was assembled using a software called PSpice (Figure 1). It should be noted that this transistor could be found in the eval library of the mentioned software.

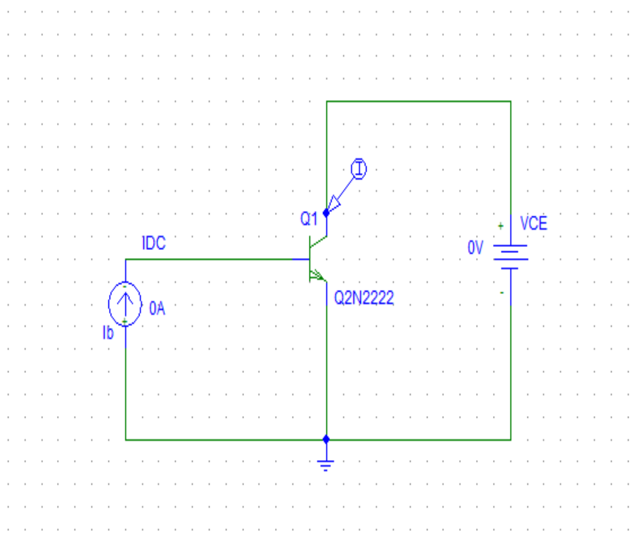


Figure 1: The Q2N2222 transistor's circuit diagram</td><td></td></tr>
</table>

Accordingly, we needed to perform a DC sweep on the assembled circuit to simulate the output characteristics. As instructed, the values of V_{CE} and I_B were set to be from 0-20V and 0-40µA with 0.5V and 4µA increments respectively. By running the simulation, the following graph was obtained (Figure 2). As it is also shown in the mentioned figure, two arbitrary points were used in order to find the slope for the line corresponding to I_C= 2mA.

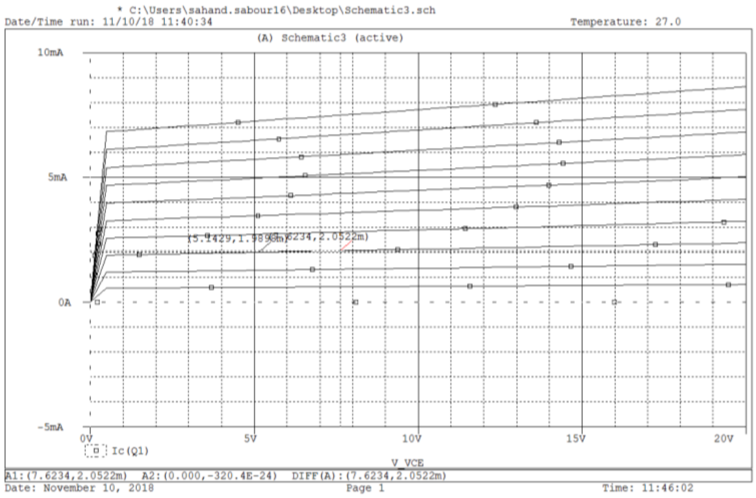


Figure 2: The Q2N2222 transistor's output characteristics

The chosen points' coordinates are as follows:

Point A: (7.6234, 2.0522m)

Point B: (5.1429, 1.9898m)

Moreover, the obtained slope was used to find the X value of a point for which Y=0 (where X is the V_{CE} and Y is I_C).

$$\frac{2.0522 - 1.9898}{7.6234 - 5.1429} = \frac{2.0522 - 0}{7.6234 - X}$$

Solving the above equation would give X=-73.9548388. Therefore, it can be claimed that the Early voltage V_A for part a was simulated to be approximately 74V.

$$\boldsymbol{a)\ V_A = 74V}$$

b) For the Q2N2907 transistor, the following circuit was assembled using PSpice (Figure 3). It should be noted that this transistor could also be found in the eval library.

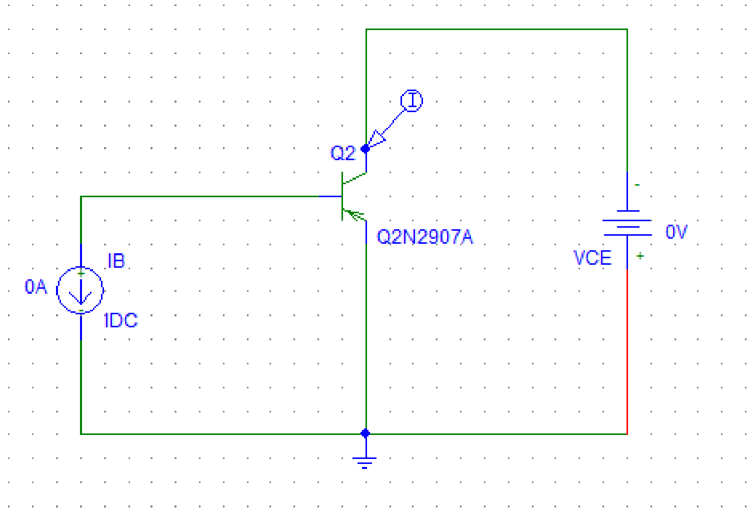


Figure 3: The Q2N2907 transistor's circuit diagram

Similar to part a, we needed to perform a DC sweep to simulate the output characteristics. As instructed, the same values of V_{CE} and I_B were used with respect to part a. By running the simulation, the following graph was obtained (Figure 4). As it is also shown in the mentioned figure, two arbitrary points were used in order to find the slope for the line corresponding to I_C= -2μA.

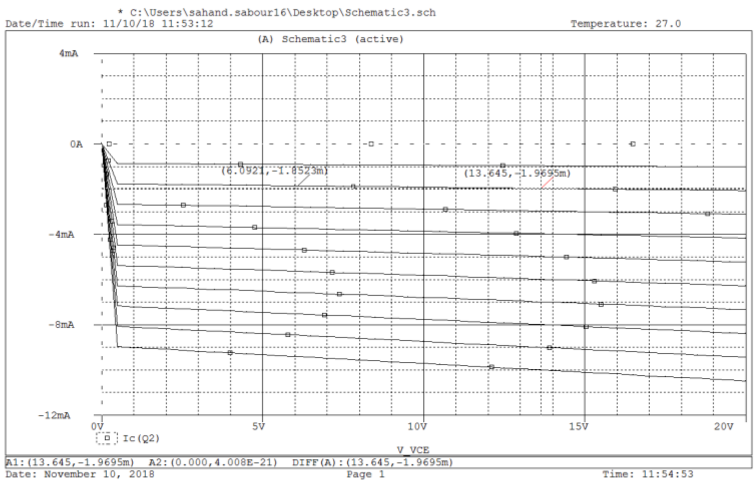
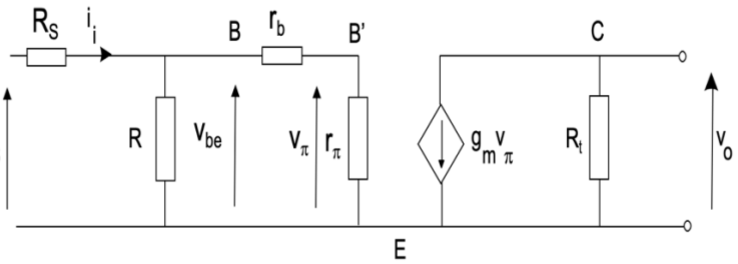


Figure 4: The Q2N2907 transistor's output characteristics

	The chosen points’ coordinates are as follows: Point A: (6.0921, -1.8523m) Point B: (13.645, -1.9695m) Moreover, the obtained slope was used to find the X value of a point for which Y=0 (where X is the V_{CE} and Y is I_C). $$\frac{-1.9695+1.8523}{13.645-6.0921}=\frac{-1.9695-0}{13.645-X}$$ Solving the above equation would give X=-113.27852. Therefore, it can be claimed that the Early voltage V_A for part b was simulated to be approximately 113V. $$\boldsymbol{b)\ V_A = 113\mathrm{V}}$$	
2) Derive Eqn. 1 and explain the validity of it.	The following figure (Figure 5) displays the small signal equivalent circuit for a common emitter configuration. As mentioned in the lecture notes, we must analyse this circuit in order to obtain the required equation.  Figure 5: Small signal equivalent circuit for CE configuration By applying the chain rule, we can obtain the following equation: $$A_V=\frac{V_O}{V_S}=\frac{V_O}{V_\pi}\times\frac{V_\pi}{V_{be}}\times\frac{V_{be}}{V_S}$$ Which gives $$A_V=-g_mR_t\times\frac{r_\pi}{r_\pi+r_b}\times\frac{R//(r_\pi+r_b)}{R_S+R//(r_\pi+r_b)}$$ Where R_T is obtained from the following equation: $$R_t=R_C//r_o$$	

	Note the absence of R_L as there is no resistor on the load. By assuming $r_b \ll r_\pi$ we get $$A_V = -g_m R_t \times \frac{R//r_\pi}{R_S + R//r_\pi}$$ If we assume that $r_\pi \ll R$, $r_\pi \ll R_S$ and $R_C << r_o$, we get $$A_V = -g_m R_t \approx -g_m R_C = -40 I_C R_C \ (1)$$ Now, by applying KVL on the collector emitter (CE) loop of the DC equivalent circuit (Fig 1 in the provided lab manual), the following equation would be acquired: $$V_{CC} = I_C R_C + V_{CEQ} - V_{CC}$$ Where $V_{CEQ}=V_{CC}$, due to the output voltage being biased at 0V. Which gives $V_{CC} = I_C R_C$ (2) By placing equation (2) in (1), we would obtain the following: $$\boldsymbol{|A_V| = 40V_{CC}}$$ As assumed in the circuit design, V_{CC} is set to 9V. Therefore, voltage gain of 360 units would be obtained (A_V=360). However, this measurement was made based upon many assumptions that are not true in a real-world environment. It should be noted that this value can be regarded as the maximum value of voltage gain for this circuit and is not a good presentation for the real voltage gain of the circuit.	
3) Give the three values of R_C that you used and the corresponding *measured* and *theoretical* values for the	In this section, there are a number of steps to take in order to obtain both the measured and theoretical values of the voltage gain A_V. Firstly, we need to a DC sweep of the circuit with current source IBQ set to 0 to find the point for which the Vout is 0. Next, we would set the value of IBQ current source to the obtained value, set the value of voltage source V_S to 0.1V and do an AC sweep of the circuit.	

<table>
<tr>
<td>circuit voltage gains.</td>
<td>After simulating the circuit, we can add a trace using the features of PSpice. In the trace options, we would enter Vout/Vin as that is the formula for voltage gain.
Accordingly, a graph would be displayed that shows the voltage gain of the circuit. The measured value will further be shown as $A_{Vmeasured}$.
$A_{Vtheoretical}$ would be calculated in each section respectively. For this measurement we need to find r_o, which depends on I_{CQ}, V_{CC} and V_A (since $r_o = \frac{V_A+V_{CE}}{I_{CQ}}$).
As we know V_{CC}=9V and have already found the value of V_A in the first section of this experiment, we would only need to find the value of I_{CQ} in each case. After obtaining the value of r_o, we can find the theoretical value of the voltage gain, as we already know $A_{Vtheoretical} = g_m(R_C//r_o)$.

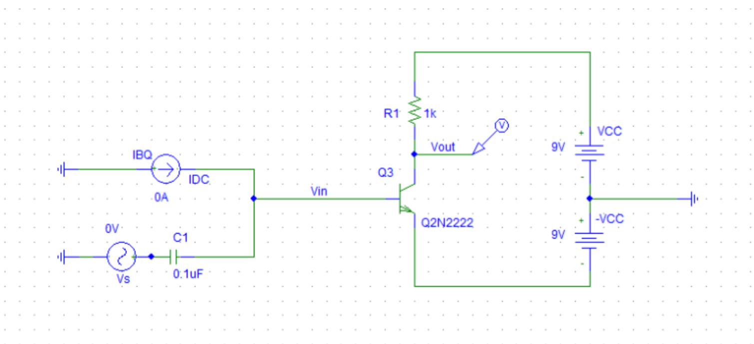
a) R_C = 1kΩ
The following figure shows the circuit used for the DC sweep of this section (Figure 6):


Figure 6: circuit for DC sweep with R_C = 1kΩ
According to the graph in Figure 7, the following point was obtained: Point A: (46.883µ, 627.372µ)</td>
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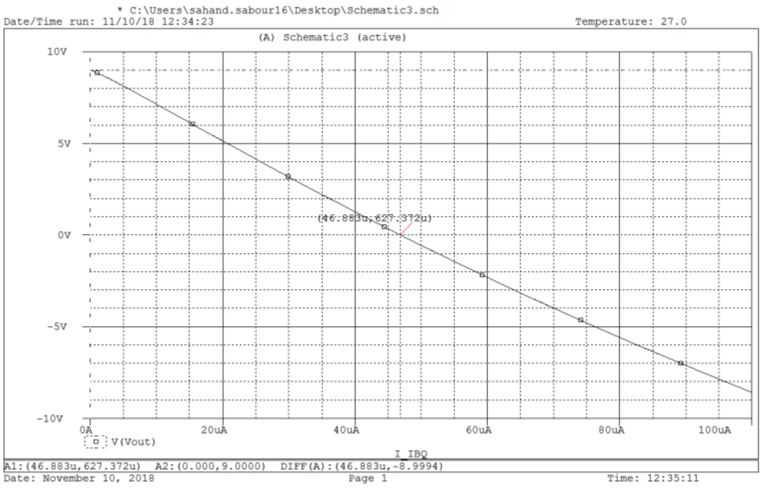

Figure 7: IBQ vs Vout graph

Moreover, the following circuit (Figure 8) was used to simulate the AC sweep of the circuit:

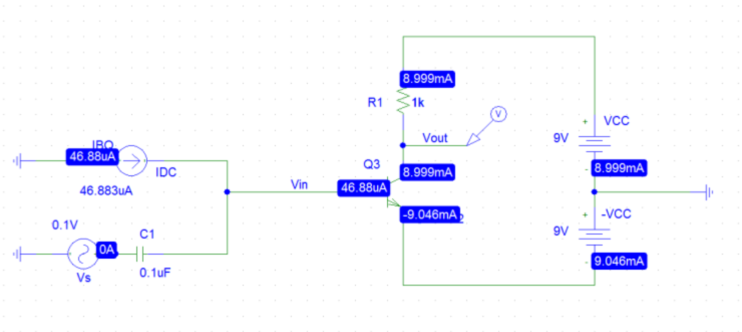

Figure 8: circuit for AC sweep with R_C = 1kΩ

By simulating the AC sweep, a graph of the characteristics would be displayed. By adding the mentioned trace, the following figure (Figure 9) and the measured value of voltage gain would also be obtained.

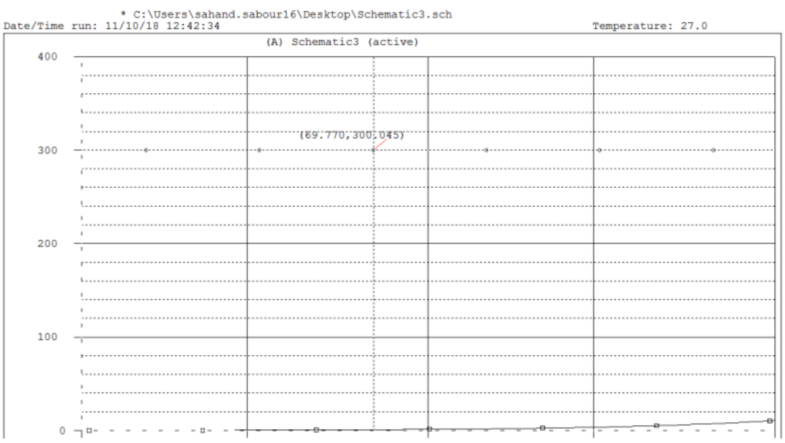

Figure 9: result of the added trace with R_C = 1kΩ

$A_{V measured}$ = 300.045

For the theoretical voltage gain, the following equations were calculated:

$$r_o = \frac{V_A + V_{CE}}{I_{CQ}} = \frac{74 + 9}{8.999} = 9.23k\Omega$$

$$A_{\text{Vtheoretical}} = g_m(R_C//r_o) = -40I_{CQ}(R_C//r_o)$$

$$A_{\text{Vtheoretical}} = -40 \times 8.999 \times \frac{1 \times 9.23}{1 + 9.23}$$

$A_{\text{Vtheoretical}}$ = 324.773294

b) R_C = 2kΩ

The following figure shows the circuit used for the DC sweep of this section (Figure 10):

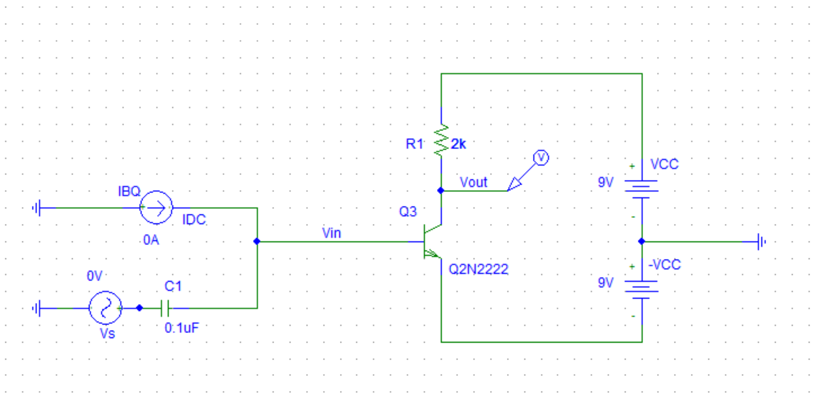

Figure 10: circuit for DC sweep with R_C = 2kΩ

According to the graph in Figure 11, the following point was obtained: Point B: (24.286μ, 37.987m)

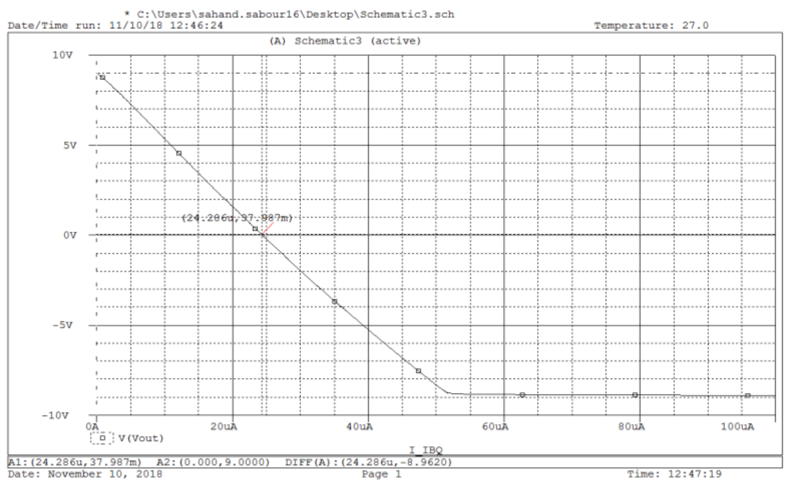

Figure 11: IBQ vs Vout graph

Moreover, the following circuit (Figure 12) was used to simulate the AC sweep of the circuit:

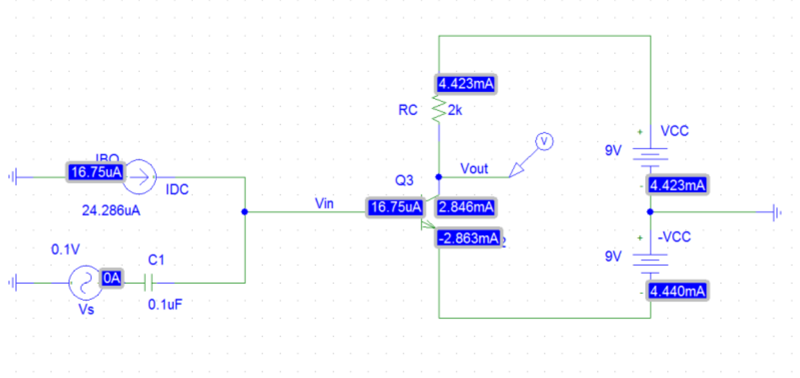

Figure 12: circuit for AC sweep with R_C = 2kΩ

By simulating the AC sweep, a graph of the characteristics would be displayed. By adding the mentioned trace, the following figure (Figure 13) and the measured value of voltage gain would also be obtained.

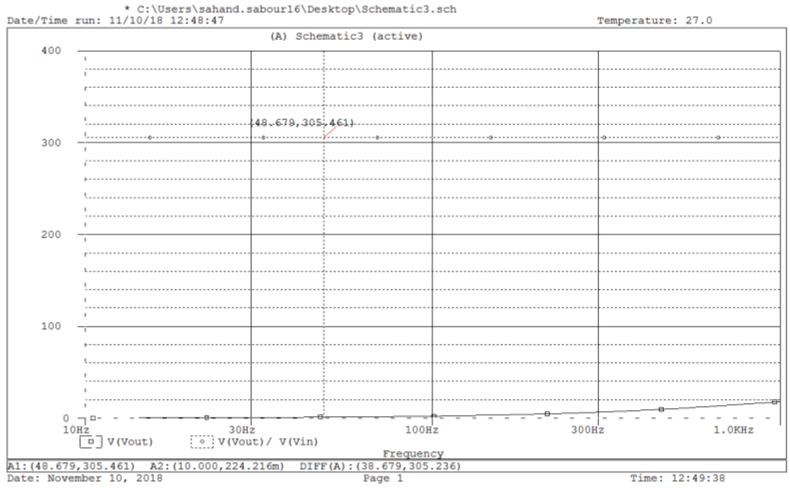

Figure 13: result of the added trace with R_C = 2kΩ

$A_{V\text{measured}}$ = 305.461

For the theoretical voltage gain, the following equations were calculated:

$$r_o = \frac{V_A + V_{CE}}{I_{CQ}} = \frac{74+9}{4.423} = 18.77k\Omega$$

$$A_{V\text{theoretical}} = g_m(R_C//r_o) = -40I_{CQ}(R_C//r_o)$$

$$A_{V\text{theoretical}} = -40 \times 4.423 \times \frac{2 \times 18.77}{2+18.77}$$

$A_{V\text{theoretical}}$ = 319.76778

c) $R_C = 3k\Omega$

The following figure shows the circuit used for the DC sweep of this section (Figure 14):

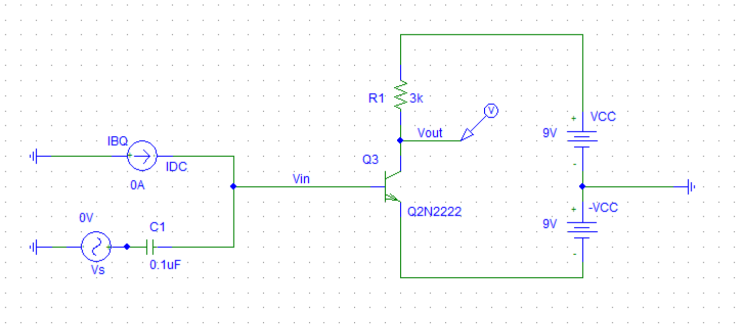

Figure 14: circuit for DC sweep with $R_C = 3k\Omega$

According to the graph in Figure 15, the following point was obtained: Point C: (16.753µ, -4.7895m)

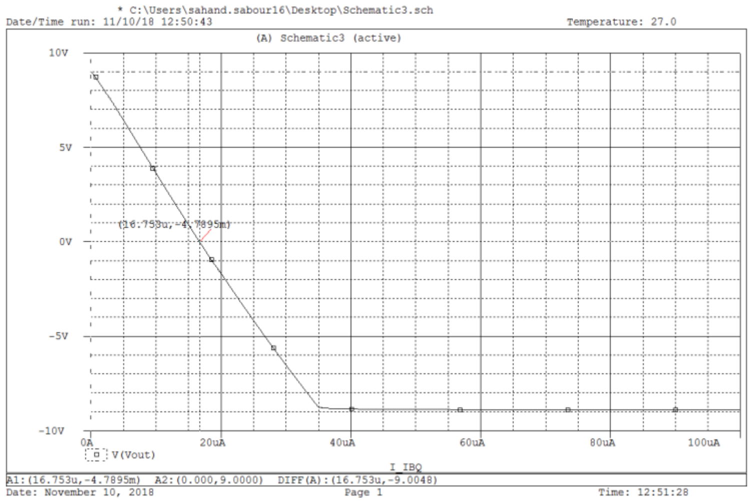

Figure 15: I_{BQ} vs Vout graph

Moreover, the following circuit (Figure 16) was used to simulate the AC sweep of the circuit:

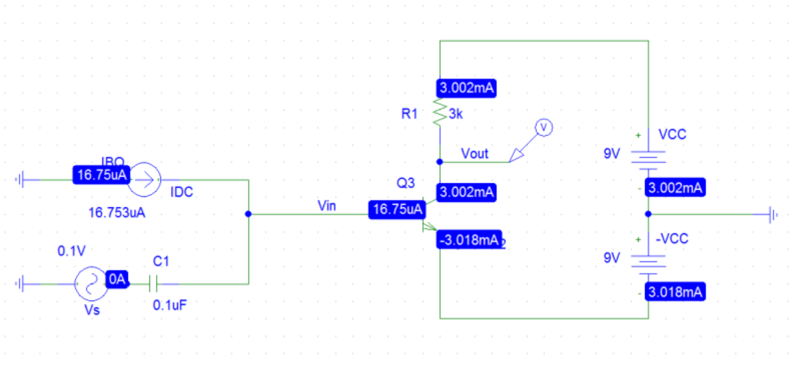

Figure 16: circuit for AC sweep with $R_C = 3k\Omega$

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By simulating the AC sweep, a graph of the characteristics would be displayed. By adding the mentioned trace, the following figure (Figure 17) and the measured value of voltage gain would also be obtained.

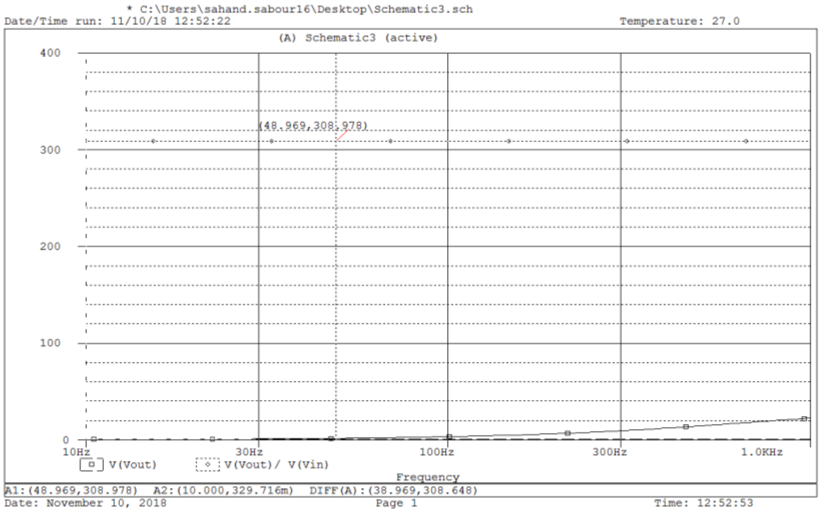

Figure 17: result of the added trace with $R_C = 3k\Omega$

$A_{V\text{measured}}$ = 308.978

For the theoretical voltage gain, the following equations were calculated:

$$r_o = \frac{V_A + V_{CE}}{I_{CQ}} = \frac{74+9}{3.002} = 27.65k\Omega$$

$$A_{\text{Vtheoretical}} = g_m(R_C//r_o) = -40I_{CQ}(R_C//r_o)$$

$$A_{\text{Vtheoretical}} = -40 \times 3.002 \times \frac{3 \times 27.65}{3 + 27.65}$$

$A_{V\text{theoretical}}$ = 324.979967

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<tr>
<td>4) Consider R_L to –Vcc same of R_C. Repeat for A_I.</td>
<td>In this section, the same circuits for the previous section were reassembled. However, an extra resistor RL, which had equal values to the values of RC used in the previous section, was added on the output. Accordingly, an AC sweep of the new circuit would be by adding a trace for I_{out}/I_{in} we would get the graph representing the current gain of the circuit. The value of β would be assumed to be approximately 167, as it was obtained from the values in the first question.</td>
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d) $R_C = R_L = 1k\Omega$

The following figure shows the circuit used for the AC sweep of this section (Figure 18):

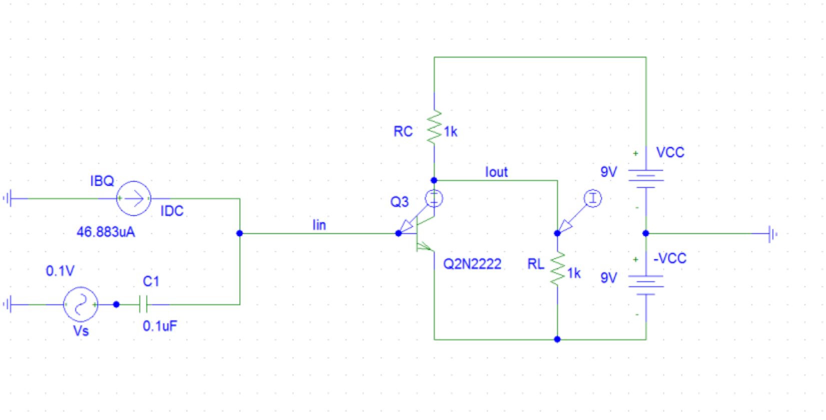


Figure 18: circuit for AC sweep with $R_C = R_L = 1k\Omega$

By simulating the AC sweep, a graph of the characteristics would be displayed. By adding the mentioned trace, the following figure (Figure 19) and the measured value of current gain would also be obtained accordingly.

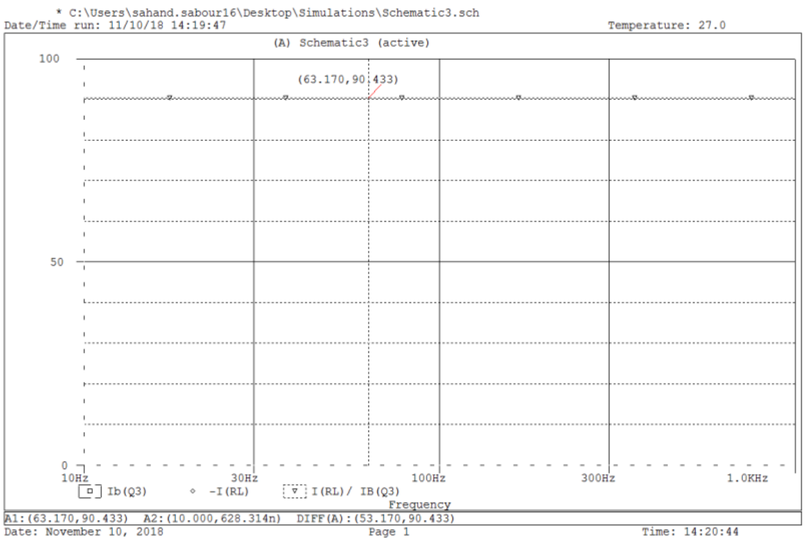


Figure 19: graph of current gain for $R_C = R_L = 1k\Omega$

$$A_{I measured} = 90.443$$

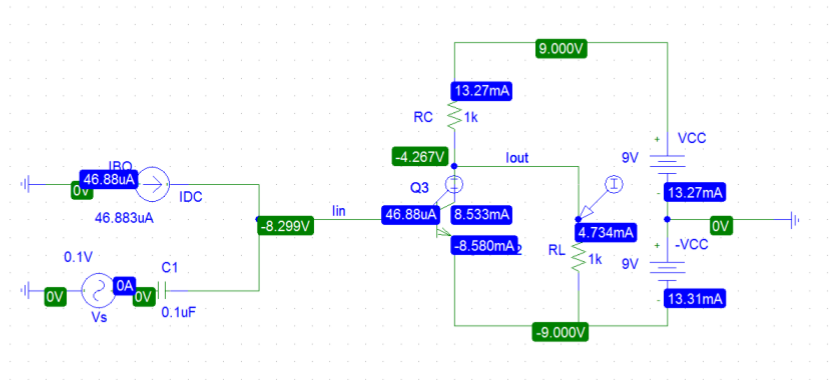


Figure 20: AC sweep circuit with details

$$A_{\text{Itheoretical}} = \beta \times \frac{r_0//R_C}{r_0//R_C + R_L}$$

Where

$$r_o = \frac{V_A + V_{CE}}{I_{CQ}} = 9.23\text{k}\Omega$$

Giving

$$A_{\text{Itheoretical}} = 167 \times \frac{\frac{9.23 \times 1}{9.23 + 1}}{\frac{9.23 \times 1}{9.23 + 1} + 1}$$

Therefore

$$\mathbf{A_{Itheoretical} = 79.106}$$

e) $R_C = R_L = 2k\Omega$

The following circuit (Figure 21) was assembled for use in AC sweep stimulation of this section.

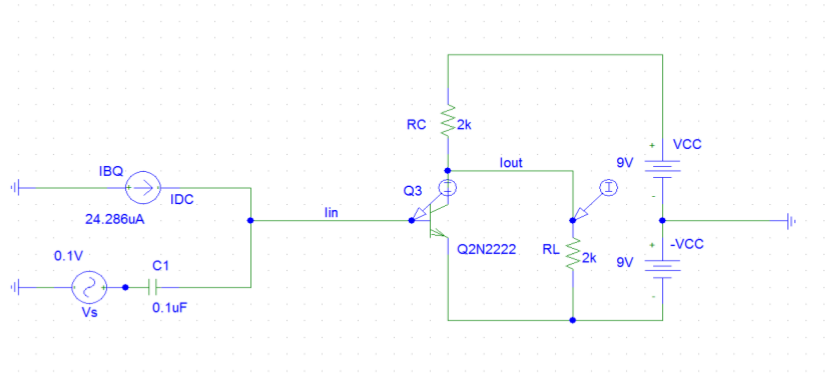


Figure 21: circuit for AC sweep with $R_C = R_L = 2k\Omega$

After conducting the AC sweep analysis of the mentioned circuit and adding the required trace, the following graph, which shows the graph for the current gain, would be obtained as a result (Figure 22).

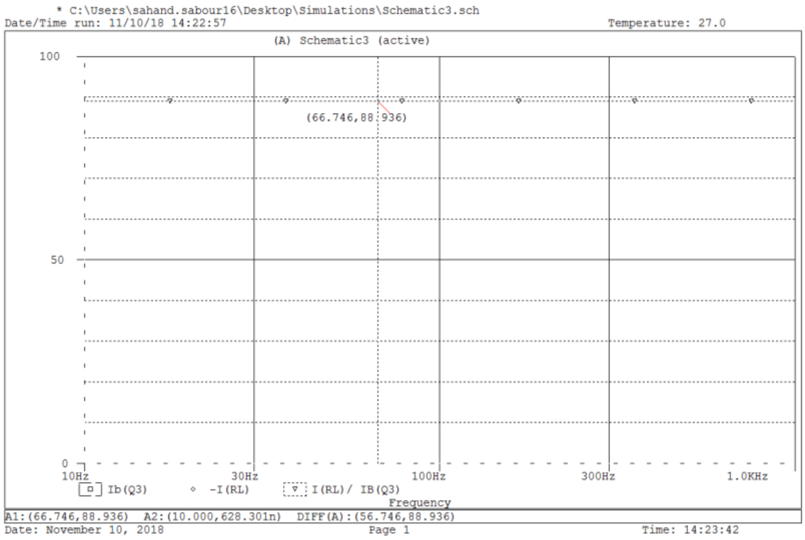


Figure 22: graph of current gain for $R_C = R_L = 2k\Omega$

$\mathbf{A_{Imeasured} = 88.936}$

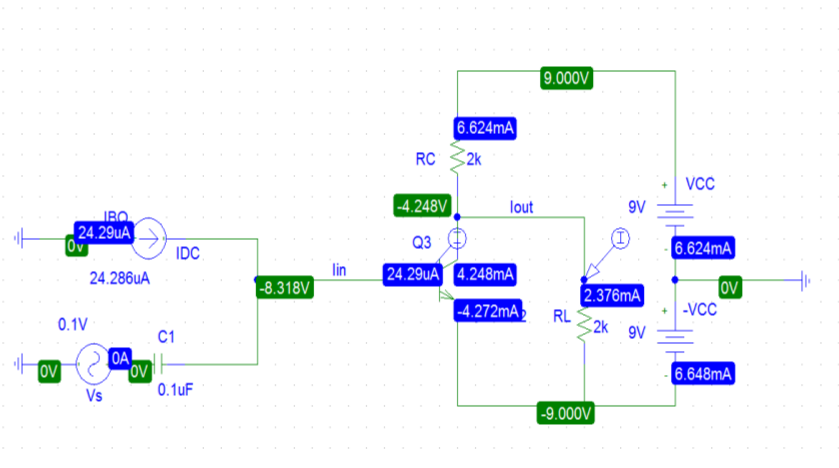


Figure 23: AC sweep circuit with details

$$A_{\text{Itheoretical}} = \beta \times \frac{r_0//R_C}{r_0//R_C + R_L}$$

Where

$$r_o = \frac{V_A + V_{CE}}{I_{CQ}} = 18.77\text{k}\Omega$$

Giving

$$A_{\text{Itheoretical}} = 167 \times \frac{\frac{18.77 \times 2}{18.77 + 2}}{\frac{18.77 \times 2}{18.77 + 2} + 2}$$

Therefore

$\mathbf{A_{Itheoretical} = 79.106}$

f) $R_C = R_L = 3k\Omega$

Similar to previous sections, we assembled a circuit with the exception of values of RC and RL set to 3kΩ. Figure 24 presents the mentioned circuit.

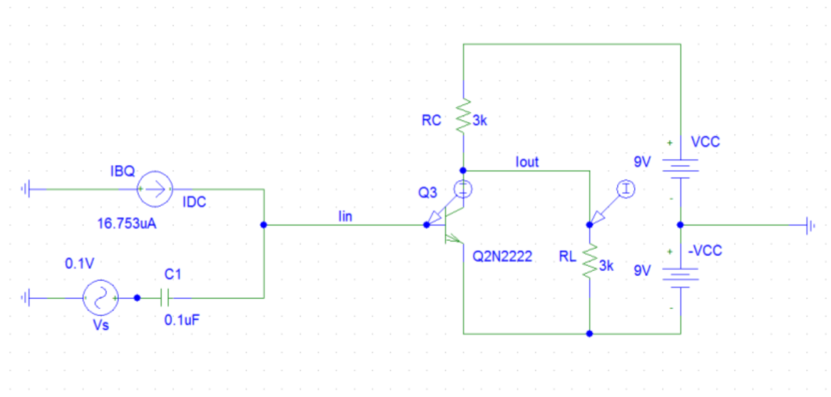


Figure 24: circuit for AC sweep with $R_C = R_L = 3k\Omega$

Furthermore, by adding the current gain trace to the obtained AC sweep graph, the following graph (Figure 25) would be displayed as the result.

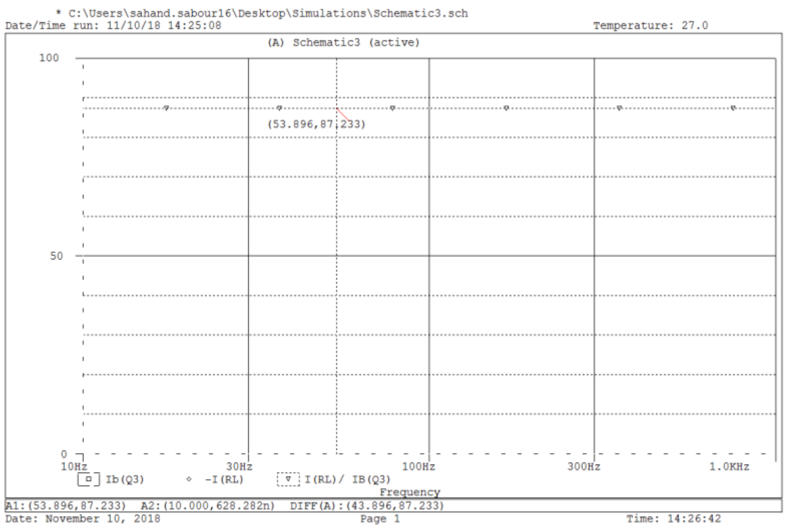


Figure 25: graph of current gain for $R_C = R_L = 3k\Omega$

$A_{I\,measured}$ =87.223

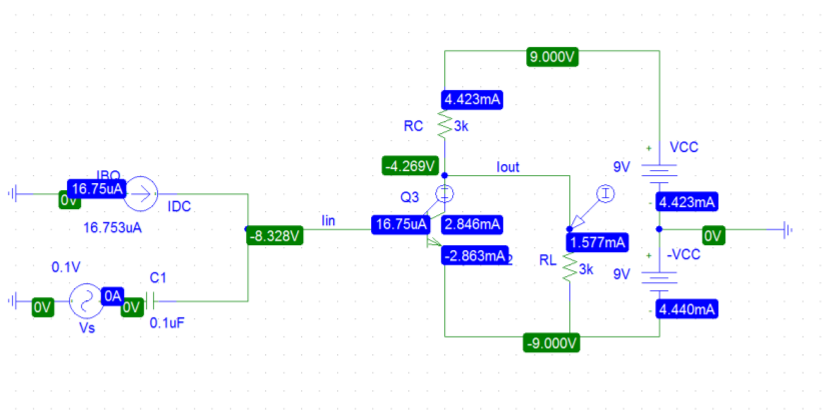


Figure 26: AC sweep circuit with details

$$A_{\text{Itheoretical}} = \beta \times \frac{r_0//R_C}{r_0//R_C + R_L}$$

Where

$$r_o = \frac{V_A + V_{CE}}{I_{CQ}} = 27.65\text{k}\Omega$$

Giving

$$A_{\text{Itheoretical}} = 167 \times \frac{\frac{27.65 \times 3}{27.65 + 3}}{\frac{27.65 \times 3}{27.65 + 3} + 3}$$

Therefore

$$\mathbf{A_{Itheoretical} = 79.106}$$

5) Give the measured output resistance and voltage limits of the circuit.

How are these values related to the transistor characteristics?

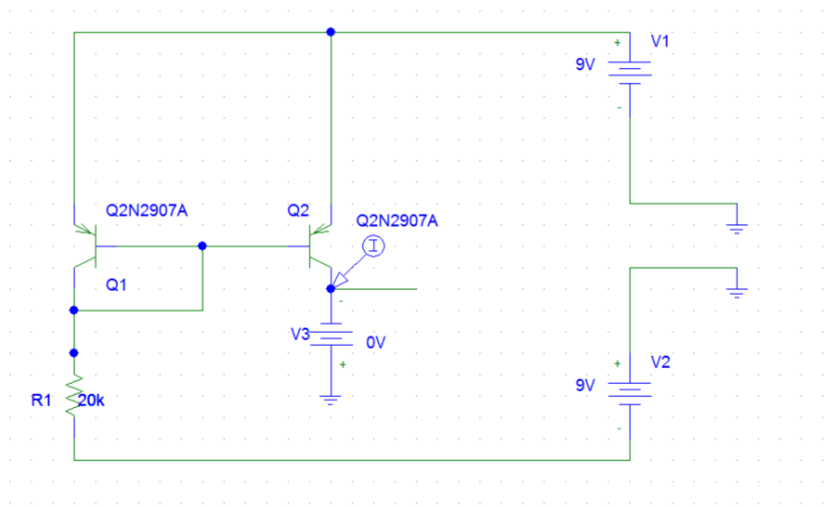


Figure 27: the preliminary current mirror circuit

As the first step of this section of the experiment, the required circuit was assembled (Figure 27). However, there is a requirement that mentions that the current drawn from the power supply must not exceed 5mA.

Therefore, in order to meet this requirement, we need to increase the value of R_1 until the value of current on the power supply is decreased to lower than 5mA. For this section of the experiment, R1 was assumed to be 20kΩ (Figure 28).

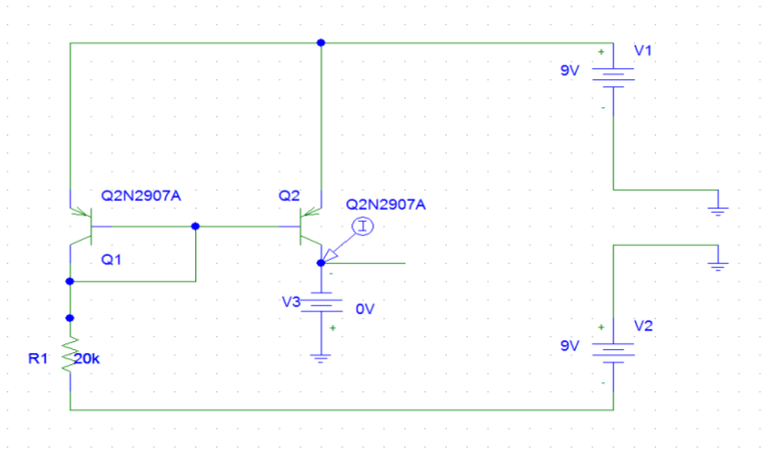


Figure 28: current mirror after modification

Moreover, a DC sweep of the circuit was simulated, where the value of V_{CC} was changed from -9V to 9V in 0.2V increments. The following figure (Figure 29) was obtained as the result:

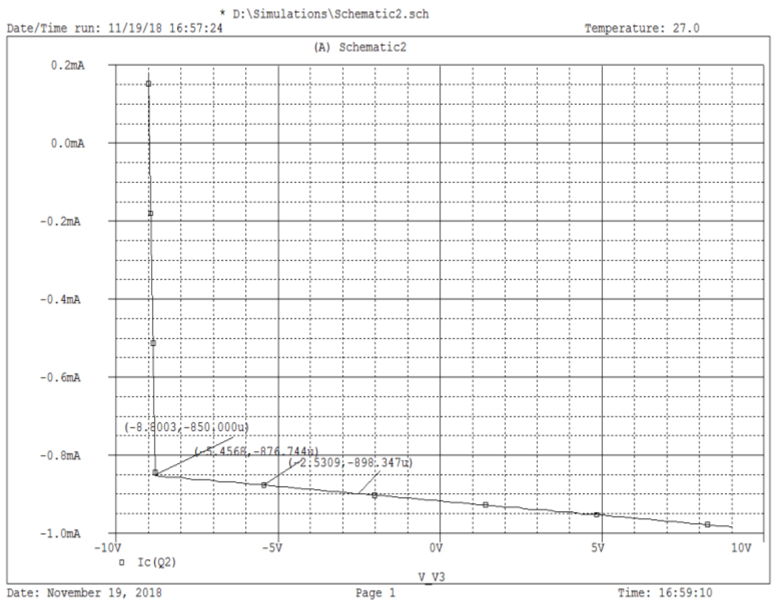
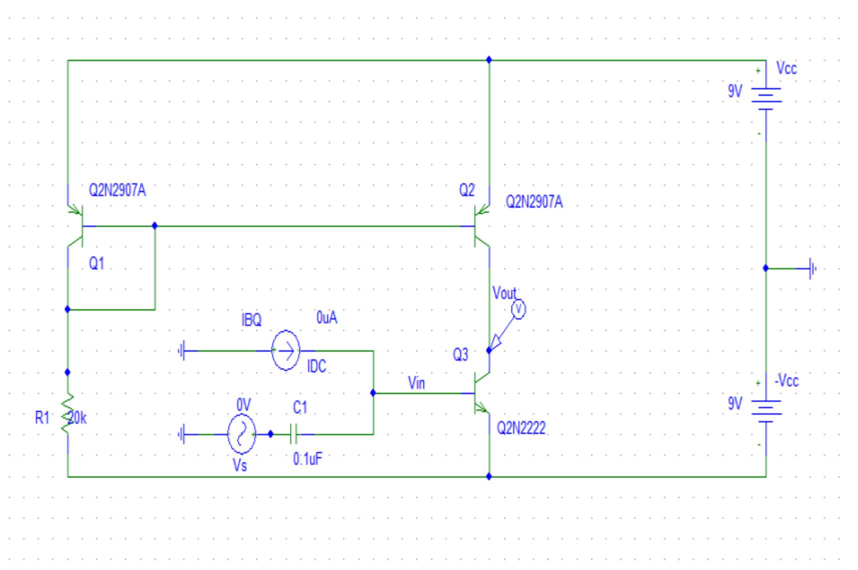
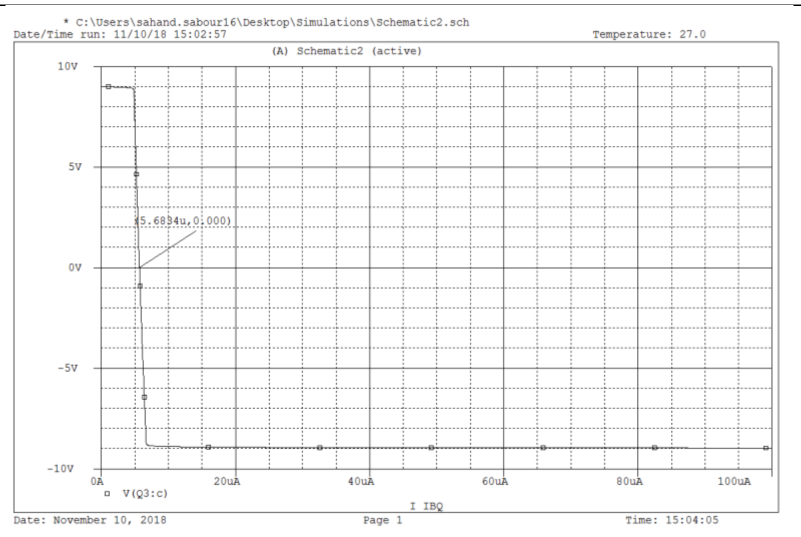


Figure 29: DC sweep simulation result

As inverse of the output resistance is equal to the slope of the curve, two arbitrary points were chosen on the curve and the slope of the line was calculated.

	Chosen point A: (-5.4568, -876.744µ) Chosen point B: (-2.5309, -898.347µ) $\frac{1}{R_{out}} = \frac{-898.347 + 876.744}{-2.5309 + 5.4568}$ Which gives **R_{out} = 135.44Ω** Furthermore, since the slope of the curve changes drastically at the point (-8.8003, -850.000µ), this x-value of this point can be regarded the lower limit voltage. **$V_{lower\ limit}$ = - 8.8V**	
6) Copy your circuit in which current mirror acting as the collector load of the common emitter stage.		
7) Enter the values you have obtained for the voltage gain, A_V and the current drawn from the voltage supply, I_{CC}.	 Figure 30: DC sweep result After replacing RC with a constant current source, a DC sweep was simulated in order to find the value of I_{BQ} for which V_{CE} is 0. The following figure (Figure 30) was obtained as the result.	

Furthermore, the value of the current source IBQ was set to the obtained value (I_{BQ}=5.6834 μA). Accordingly, an AC sweep of the circuit was simulated and after adding the required trace for showing the voltage gain graph, Figure 31 was displayed as the result.

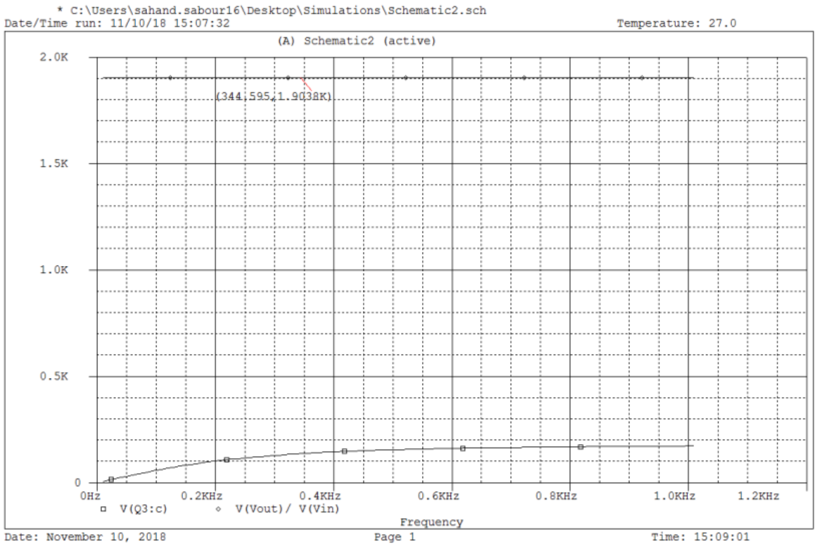


Figure 31: AC sweep result with A_V trace

Therefore, by choosing an arbitrary point on the curve, it can be concluded that

A_V = 1903

As for finding the value of ICC, the circuit assembled for the AC sweep was revisited (Figure 32).

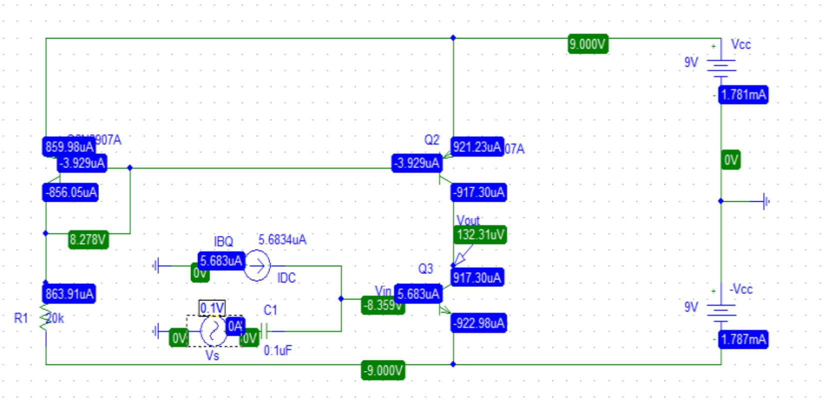


Figure 32: AC sweep circuit with details

By summing up the current values going that relate to the collector, the following can be obtained:

$$I_{CC} = 859.98\mu A + 921.23\mu A = 1.78121mA$$

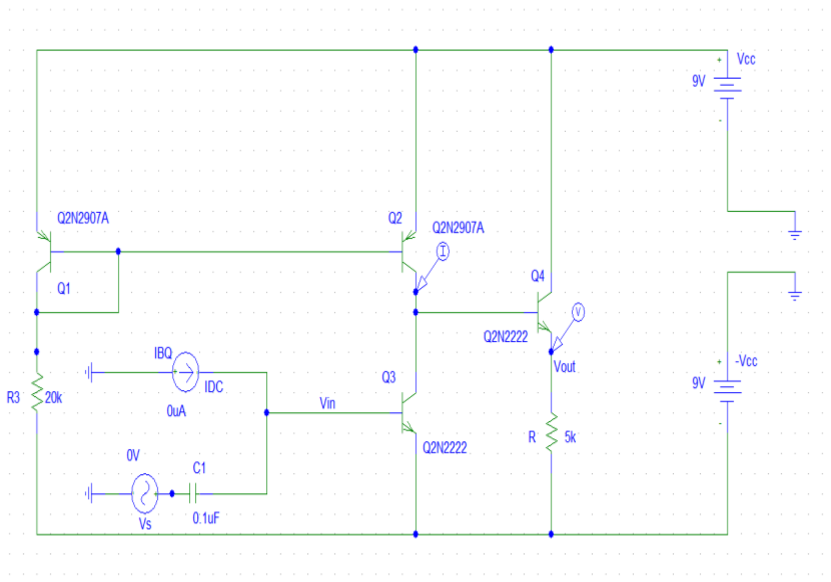
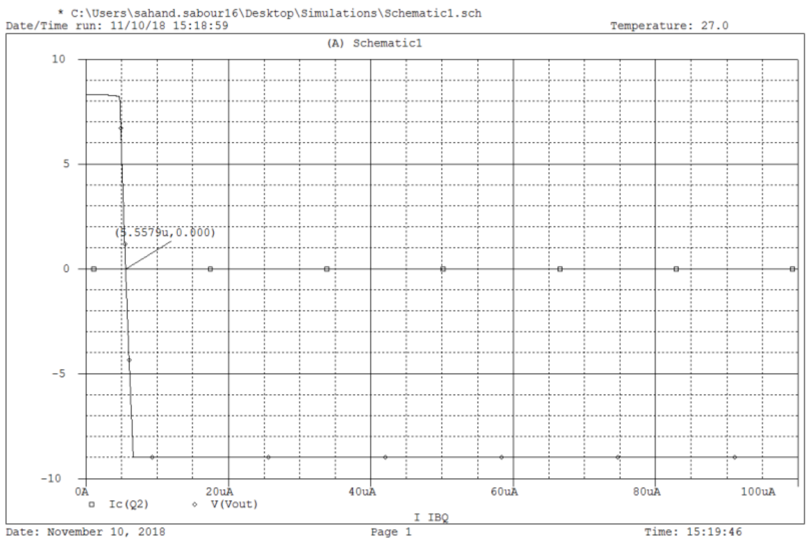
<table>
<tr><td></td><td>I_{CC} = 1.78121mA</td><td></td></tr>
<tr><td>8) Copy your circuit here.</td><td>
</td><td></td></tr>
<tr><td>9) Enter the values for the voltage gain A_V, I_{CC} and the output resistance R_O</td><td>As done in the previous sections of this experiment, a DC sweep was simulated as the first step of this section's procedure. This is to find the value of the current for which voltage is zero (I_{BQ} value). The resulting point is shown in figure below (Figure 33).


Figure 33: DC sweep result showing required I_{BQ} value
Then we set the value of the current source IBQ to the obtained value. Similar to previous sections, an AC sweep was simulated and the figure below was obtained (Figure 34) after adding the corresponding trace of A_V.</td><td></td></tr>
</table>

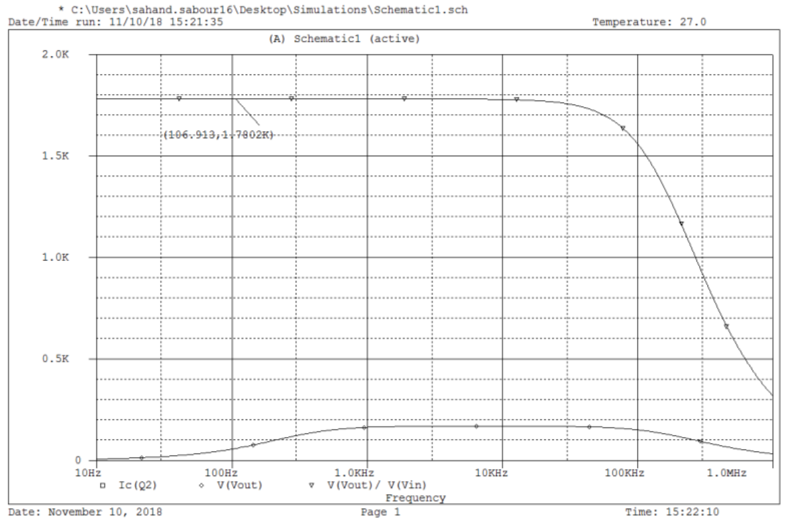


Figure 34: AC sweep result with A_V trace

Therefore, by choosing an arbitrary point on the curve, it can be seen that

A_V = 1,7802K

Furthermore, to acquire the value of ICC, we were required to sum up all the currents leading to the collectors. The full circuit with current and voltage details is displayed in Figure 35.

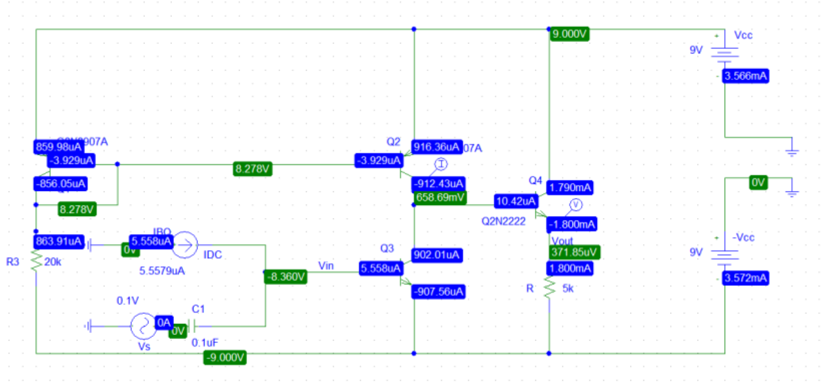


Figure 35: AC sweep circuit with details

By summing up these current values, the following can be achieved:

$$I_{CC} = 859.98\mu A + 916.36\mu A + 1.790mA$$

I_{CC} = 3.56634mA

As for the value of Ro, an AC voltage source was added to the coupling capacitor while the ac current source was set to 0. Then, the AC sweep of the circuit was simulated and by adding a trace that graphs the voltage/current graph of the ac source, the following figure (Figure 36) was displayed.

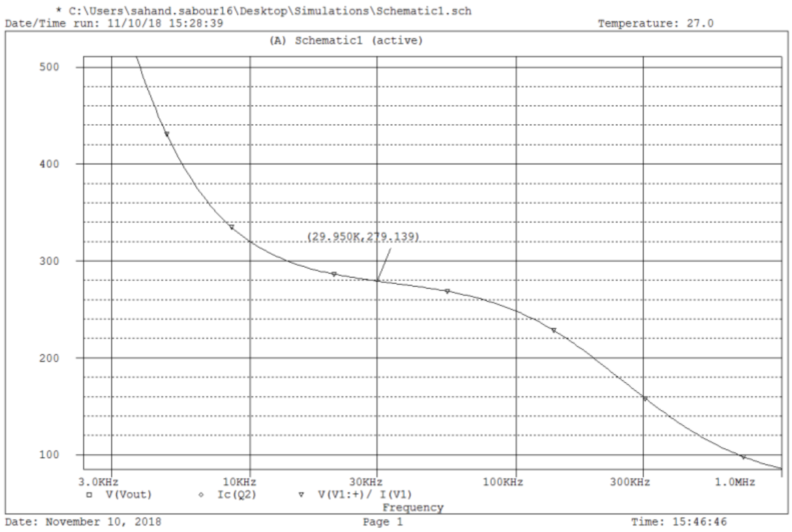


Figure 36: AC sweep with V/I trace

The point at which the curve changes its slope marks the effective output resistance of the circuit. Therefore, it was concluded that

R_O = 279.139Ω