Department of Electrical, Computer, & Biomedical Engineering
Faculty of Engineering & Architectural Science

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Instructor	Fei Yuan
TA Name	Anahita Abbasnejad Seresti

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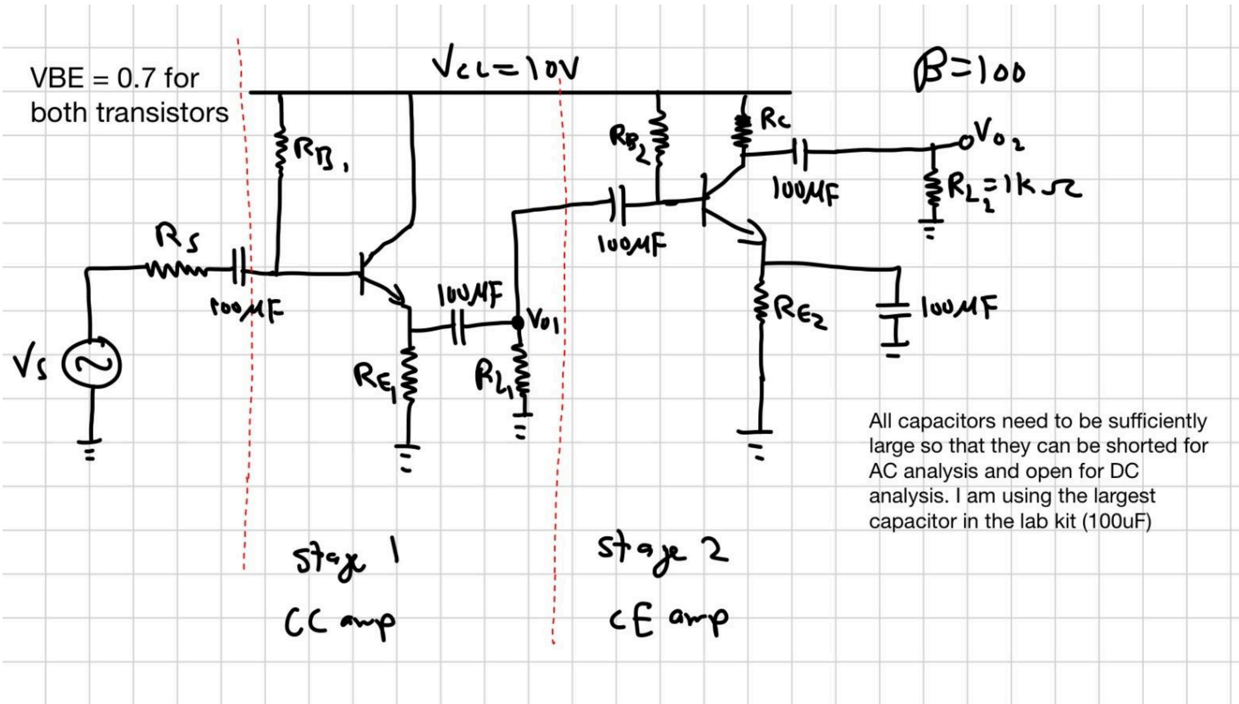
Student Name	Student ID	Signature
Harsh Solanki	XXXX67786	H Solanki

In this project I have designed a two stage BJT voltage amplifier. I used a Common-Collector amplifier and then a Common-Emitter amplifier. Below is the design of the multistage amplifier without any resistor values.

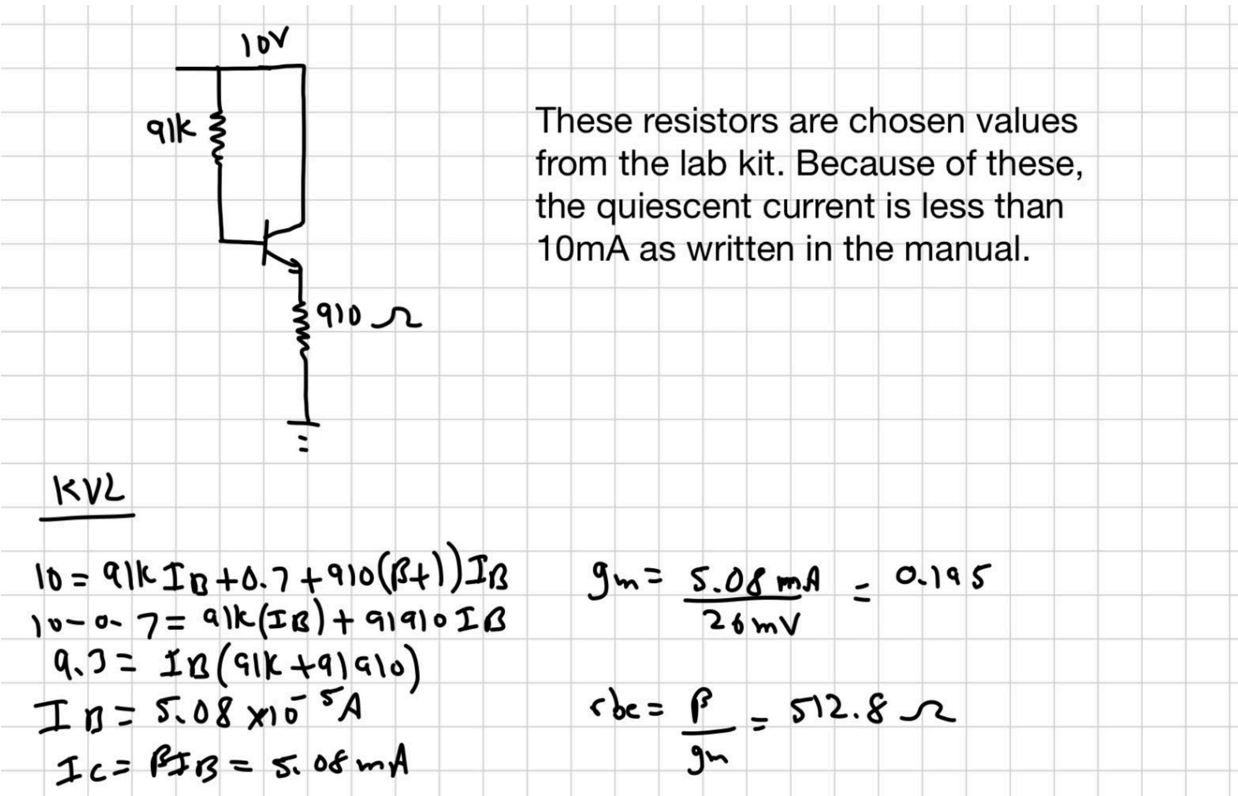
Figure1: Initial Design without resistors' values



I chose the β value to be 100, the voltage drop across the transistors to be 0.7V, and I chose all capacitors' values to be $100\mu F$ because it is the largest capacitor in the ELE404 lab kit. The CC amplifier was used to satisfy the high input resistance requirement in the manual. The voltage gain of the CC amplifier $\frac{v_{o1}}{v_{in}}$ is $1\frac{V}{V}$.

In the image below, I used a $91k\Omega$ resistor for R_{B1} and a 910Ω resistor for R_{E1}. Both of these resistors are in the ELE404 lab kit. Due to these values, I was able to make the V_{CC} supply generate a quiescent current less than 10mA, as instructed in the manual.

Figure 2: CC Stage Quiescent current analysis

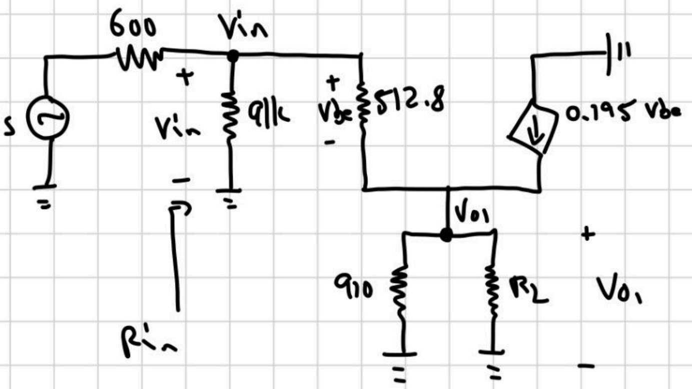


Since the R_{L1} resistor is connected after a capacitor, it is neglected in the DC analysis because capacitors are open-circuited. However, I had to calculate its appropriate value such that the voltage gain from the CC amplifier is 1.

Figure 3: AC small-signal analysis to calculate appropriate RL1 value

AC

$V_{bc} = V_{in} - V_{o1}$



What R_L value makes the gain ≤ 1?

KCL @ node V_{o1}

$$\frac{V_{o1}}{R_L} + \frac{V_{o1}}{910} + \frac{V_{o1} - V_{in}}{512.8} - 0.195(V_{in} - V_{o1}) = 0 \qquad \frac{V_{o1}}{V_{in}} = 1$$

$$\frac{V_{o1}}{R_L} + \frac{V_{o1}}{910} + \frac{V_{o1}}{512.8} + 0.195V_{o1} = 0.195V_{in} + \frac{V_{in}}{512.8} \qquad V_{o1} = V_{in}$$

$$V_{o1}\left(\frac{1}{R_L} + \frac{1}{910} + \frac{1}{512.8} + 0.195\right) = V_{in}\left(0.195 + \frac{1}{512.8}\right)$$

$$\frac{1}{R_L} + \frac{1}{910} + \frac{1}{512.8} + 0.195 = 0.195 + \frac{1}{512.8}$$

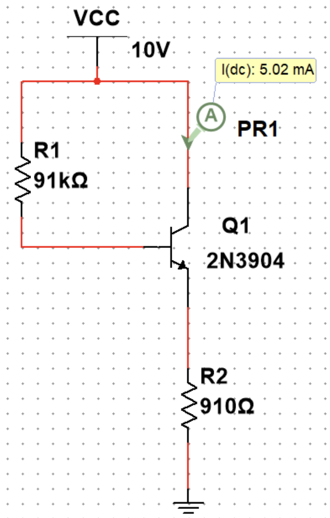
$$\frac{1}{R_L} + \frac{1}{910} = 0$$

$$R_L = 910$$

$$\frac{1}{R_L} = \frac{1}{910}$$

From this calculation we can see that the R_{L1} value must be 910Ω for the voltage gain to be 1.

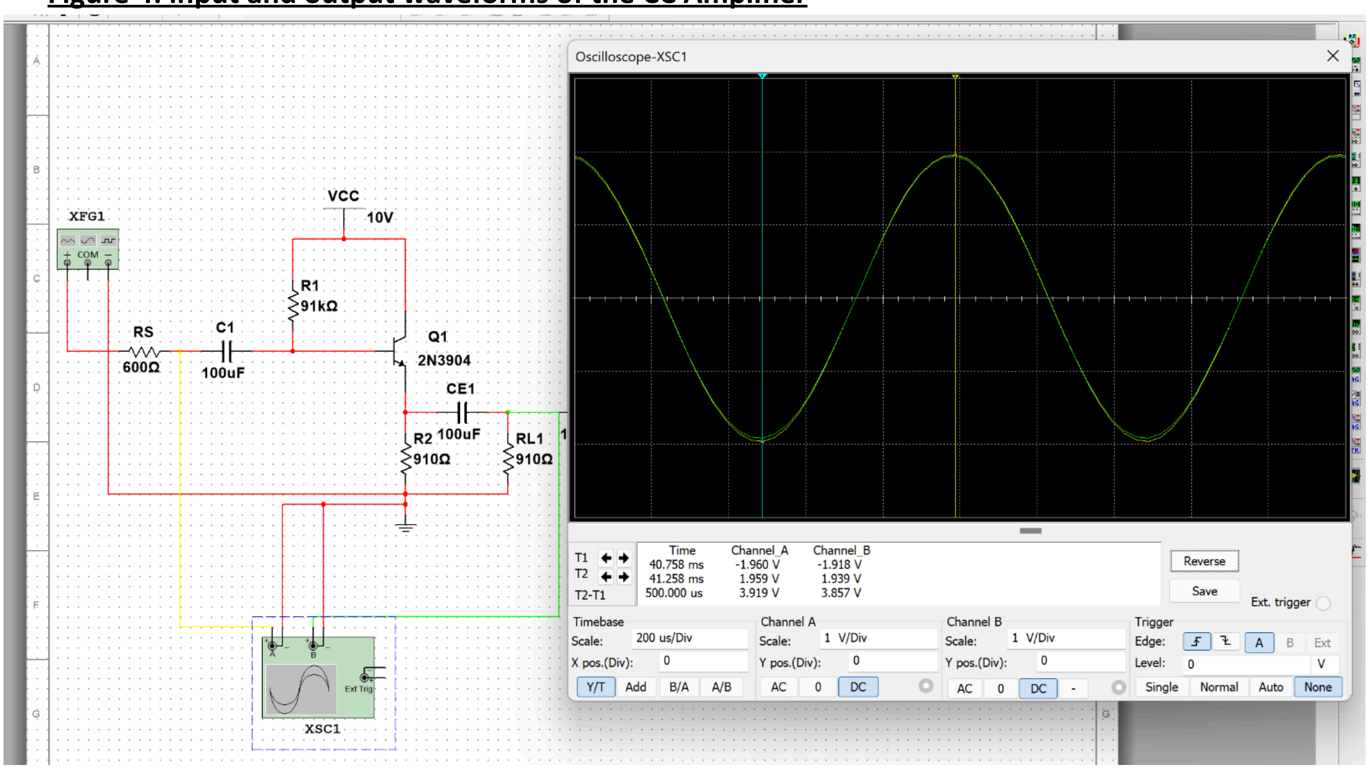
Below is a multisim screenshot of the collector current of the CC amplifier.



This current is approximately the theoretical calculated value from page R2. Possible discrepancies may be rounding values to certain decimal places.

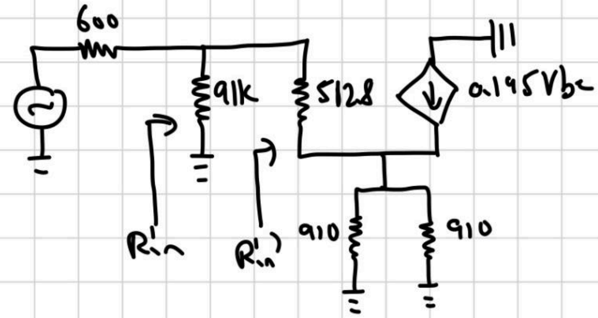
Below is a screenshot from multisim that shows the input and output waveforms of the CC amplifier.

<u>Figure 4: input and output waveforms of the CC Amplifier</u>



Channel A of the oscilloscope is connected to the v_{in} terminal and channel B is connected to R_{L1} which is the v_{01} terminal. Evidently, both waveforms overlap each other as they are identical, which implies that the voltage gain of the CC amplifier is 1.

Figure 5: calculation for input resistance of the multistage amplifier



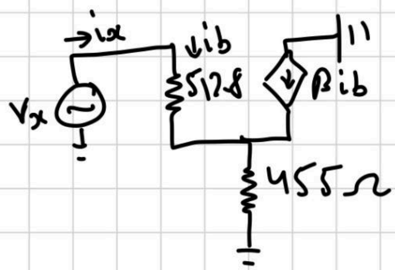
$R_{in} = 91K \parallel R_{in}'$

$R_{in}' = \frac{V_x}{i_x} = \frac{V_x}{i_b}$

$R_{in} = 91k \parallel 46.5K$

$R_{in} = 30760.44\ \Omega$

$\boxed{R_{in} \approx 31K\ \Omega > 20K\ \Omega \quad \therefore \text{requirement met}}$



$V_x = 512.8\, i_b + 455\, i_e$

$V_x = 512.8\, i_b + 455(\beta+1)\, i_b$

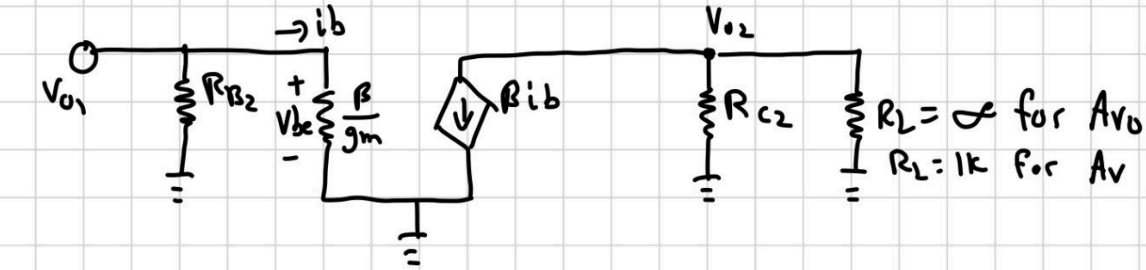
$V_x = i_b(512.8 + 455(101))$

$\frac{V_x}{i_b} = 46467.8 = R_{in}'$

The input resistance of the multistage amplifier is the input resistance of the first stage, which is the CC stage. The CC amplifier is known to have a high input resistance and a low output resistance. I calculated the input resistance above and it turned out to be $31k\Omega$ which satisfies the minimum input resistance of $20k\Omega$.

Next I analysed the small signal of the CE stage such that I can find a good R_{C2} value that can make the no-load voltage gain 50 and the loaded voltage gain 90% of 50. I created two equations because there are two type of voltage gains required. And I ended up using substitution to cancel out one of the unknowns and solved for R_{C2}.

Figure 6(a); small signal analysis to solve for R_{C2} considering $R_L = \infty$



no load gain AVo

$$\frac{V_{o2}}{R_{C2}} + \beta i_b = 0 \qquad V_{o1} = i_b \frac{\beta}{g_m}$$

$$\frac{V_{o2}}{R_{C2}} = -\beta i_b \qquad \frac{V_{o1}}{\beta} g_m = i_b \quad (2)$$

$$\frac{V_{o2}}{\beta R_{C2}} = i_b \quad (1)$$

$$(1) = (2)$$

$$\frac{V_{o2}}{\beta R_{C2}} = \frac{V_{o1}}{\beta} g_m$$

$$\frac{V_{o2}}{R_{C2}} = V_{o1} g_m$$

$$\frac{V_{o2}}{V_{o1}} = g_m R_{C2} = A_{Vo}$$

Figure 6(b): small signal analysis to solve for R_{C2} considering $R_L = 1k\Omega$

$$\frac{V_{o2}}{R_{C2}} + \frac{V_{o2}}{1k} + \beta i_b = 0$$

$$V_{o2}\left(\frac{1}{R_{C2}} + \frac{1}{1k}\right) = -\beta i_b$$

$$-\frac{V_{o2}}{\beta}\left(\frac{1}{R_{C2}} + \frac{1}{1k}\right) = i_b \quad (3)$$

$$(3) = (2)$$

$$-\frac{V_{o2}}{\beta}\left(\frac{1}{R_{C2}} + \frac{1}{1k}\right) = \frac{V_{o1}}{\beta} g_m$$

$$\frac{V_{o2}}{V_{o1}} = \frac{g_m}{\left(\frac{1}{R_{C2}} + \frac{1}{1k}\right)} = A_v$$

Figure 6(c): equating the two gains such that $A_{Vo} = 50$ **and** $A_V = 0.9A_{vo} = 45$

$$A_V = 0.9 A_{Vo}$$

$$\frac{g_m}{\frac{1}{R_{C2}} + \frac{1}{1K}} = 0.9 g_m R_{C2}$$

$$\frac{1}{\frac{1}{R_{C2}} + \frac{1}{1K}} = 0.9 R_{C2}$$

$$\frac{1}{R_{C2}} + \frac{1}{1K} = \frac{1}{0.9R_{C2}}$$

$$\frac{1}{R_{C2}} - \frac{1}{0.9R_{C2}} = -\frac{1}{1K}$$

$$\frac{1}{R_{C2}}\left(1 - \frac{1}{0.9}\right) = -\frac{1}{1K}$$

$$\frac{1}{R_{C2}}\left(-\frac{1}{9}\right) = -\frac{1}{1K}$$

$$\frac{1}{R_{C2}} = 9\times10^{-3}$$

$$\frac{1}{9\times10^{-3}} = R_{C2}$$

$$111.1 = R_{C2}$$

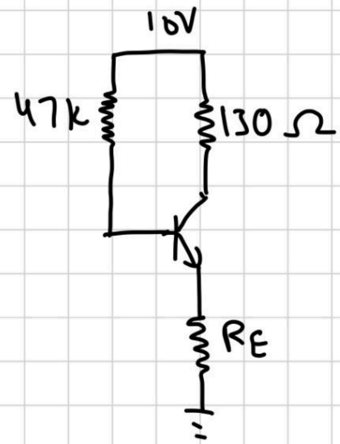
$\therefore$ R_{C2} value of 111.1 makes it so that $A_{Vo} = 50$ and $A_V = 45$

I solved for R_{C2} and ended up with 111.1Ω, which is not a resistor in the lab kit. When I solved for g_m, and then solved for the quiescent current from the power supply, I got a number higher than 10mA.

So in the image below, I modified the DC CE amplifier's resistance so that I can find a good value that makes the DC collector current less than 10mA.

Figure 7:DC analysis to calculate R_E, I_C, and r_{be} value.

CE stage quiescent current



KVL

$$10 = 47k\, I_B + 0.7 + R_E(\beta+1)\, I_B$$

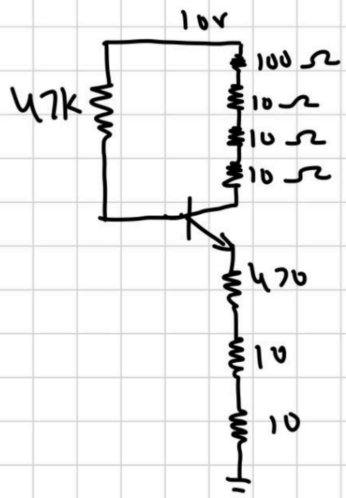
$$10 - 0.7 = I_B(47k + (101)R_E)$$

$$\frac{9.3}{10\times10^{-5}} = 47k + (101)R_E$$

$$\frac{93k - 47k}{101} = R_E$$

$R_E = 495 \approx 470\ \Omega + 10\Omega + 10\Omega$ in lab circuit

So with the resistor values from the lab kit, we get this circuit for the CE amplifier



KVL

$$10 = 47k\, I_B + 0.7 + (\beta+1)\, I_B(470+10+10)$$

$$10 - 0.7 = I_B(47k + (101)(490))$$

$$\frac{9.3}{96490} = I_B = 9.64\times10^{-5}\ A$$

$$I_C = \beta I_B = (100)(9.64\times10^{-5}\ A)$$

$$I_C = 9.6\ mA$$

$$g_m = \frac{9.6mA}{26mV} = 0.37\ \frac{A}{V}$$

$$r_{be} = \frac{100}{0.37} = 270\ \Omega$$

Finally, I used the lab kit values to rebuild the circuit and recalculated the voltage gain of the Ce amplifier. The images below show the no-load voltage gain of the CE amplifier and the loaded voltage gain.

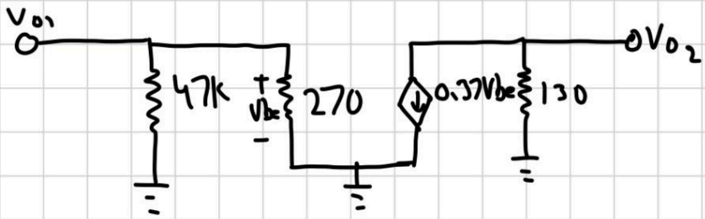
Figure 8(a): Using approximately similar values from lab kit to calculate no-load voltage gain:

AC analysis

no load voltage gain

$R_L = \infty$

$V_{be} = V_{o1}$



KCL @ V_{o2}

$$\frac{V_{o2}}{130} + 0.37\,V_{be} = 0$$

$$\frac{V_{o2}}{130} + 0.37\,V_{o1} = 0$$

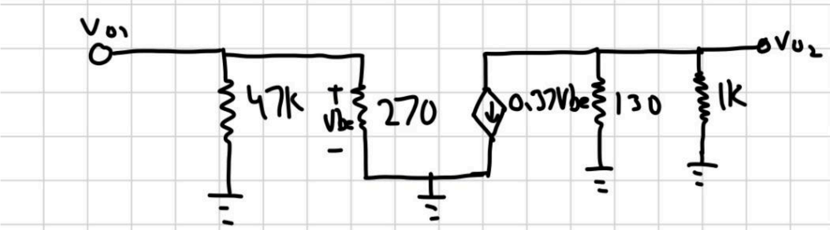
$$\frac{V_{o2}}{130} = -0.37\,V_{o1}$$

$$\frac{V_{o2}}{V_{o1}} = -(0.37)(130)$$

$$\frac{V_{o2}}{V_{o1}} = -48.1$$

$$\boxed{|A_{vo}| = 48.1\ \frac{V}{V}}$$

Figure 8(b): AC analysis of the loaded voltage gain:



KCL @ Vo2

$$\frac{V_{o2}}{130} + \frac{V_{o2}}{1K} + 0.37V_{be} = 0$$

$$V_{o2}\left(\frac{1}{130} + \frac{1}{1K}\right) = -0.37V_{o1}$$

$$V_{o2}\left(8.69 \times 10^{-3}\right) = -0.37V_{o1}$$

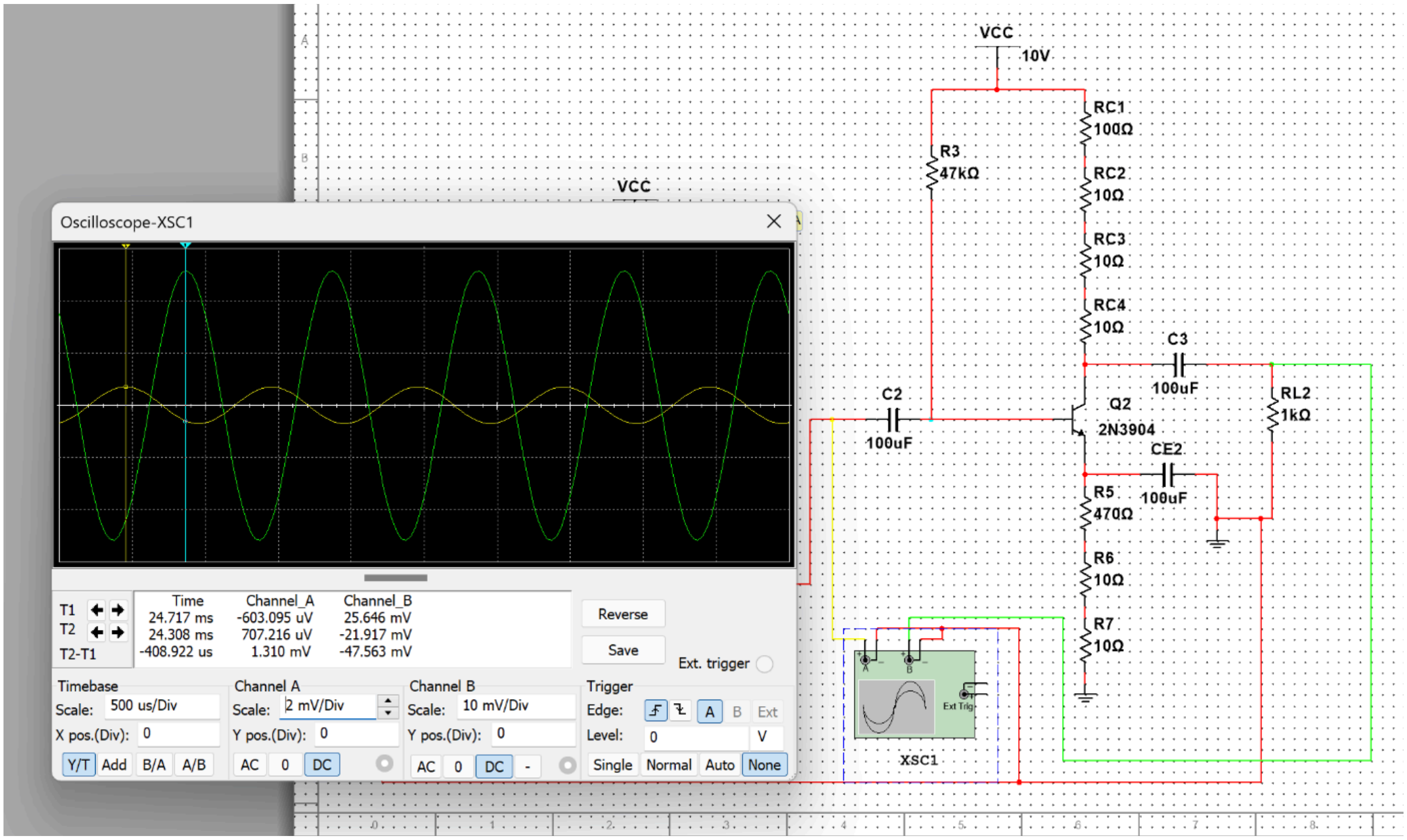
$$\frac{V_{o2}}{V_{o1}} = \frac{-0.37}{8.69 \times 10^{-3}}$$

$$\frac{V_{o2}}{V_{o1}} = -42.56$$

$$\boxed{|A_v| = 42.56\ \frac{V}{V}}$$

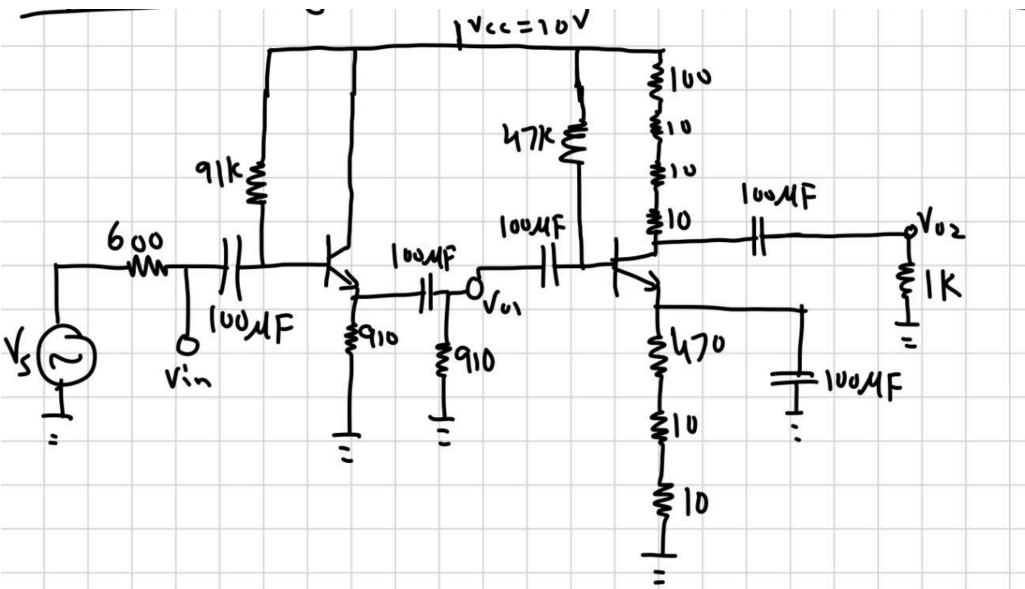
As you can see, the no-load voltage gain is 48.1 and the loaded voltage gain is 42.56 which is around 88% of the no-load gain. Although the manual says the loaded voltage gain can not be less than 90% of the no-load gain, the lab kit's resistor values were the reason the gain was off by only 2%.

Figure 9: Multisim screenshot of the CE amplifier.



Channel A of the oscilloscope is connected to the v_{O1} terminal, which is the output of the CC stage. And channel B is connected to the R_{L2} terminal which is also the v_{O2}terminal. As you can see. Channel A's peak is $707\mu V$ and channel B's peak is 25mV. This means that the signal has been amplified by a factor of 36.27. This might be one discrepancy where multisim's calculations are made differently and the loaded gain is off by 15%.

Figure 10: Final multi-stage amplifier design with all labels.



$$Av \text{ CC stage: } \frac{V_{o1}}{V_{in}} = 1$$

$$Av_o \text{ CE stage: } \frac{V_{o2}}{V_{o1}} = 48.1 \frac{V}{V} \qquad R_L = \infty$$

$$Av \text{ CE stage: } \frac{V_{o2}}{V_{o1}} = 42.56 \frac{V}{V} \qquad R_L = 1k$$

$$\text{total gain } R_L = \infty : \frac{V_{o2}}{V_{o1}} \times \frac{V_{o1}}{V_{in}} = \frac{V_{o2}}{V_{in}}$$
$$= 48.1 \times 1 = 48.1 \frac{V}{V}$$

$$\text{total gain } R_L = 1k = \frac{V_{o2}}{V_{o1}} \times \frac{V_{o1}}{V_{in}} = \frac{V_{o2}}{V_{in}}$$
$$= 44.56 \times 1 = 44.56 \frac{V}{V}$$