McMaster University

Electrical and Computer Engineering Department

EE3EJ4 Electronic Devices and Circuits II - Fall 2021

Lab. 2 Single-Stage Amplifiers

Lab Report Due on Oct. 10, 2021

Objective: To design and characterize the individual performance of a current sink, a common-emitter (CE) amplifier, and an emitter-coupled BJT pair (i.e., a differential amplifier) for their future combination to build an operational amplifier.

Attributes Evaluated: These are the attributes you need to demonstrate in your solutions.

- **Competence in specialized engineering knowledge to simulate circuit performance using SPICE-based circuit simulator and conduct analog circuit debugging;**
- **Ability to obtain substantiated conclusions as a result of a problem solution, including recognizing the limitations of the approaches and solutions; and**
- **Ability to assess the accuracy and precision of results.**

Test Equipment:

- Analog Discovery 2 (AD2)
- WaveForms from Digilent Link
- Analog Discovery 2 Quick Start Series Videos
- WaveForms Reference Manual

Components:

- Transistors: 4 × NPN-BJT 2N3904 1 × PNP-BJT 2N3906
- Resistors: 2 × 8.25 kΩ resistor 2 × 76.8 kΩ resistor 2 × 57.6 kΩ resistor
  2 × 8.06 kΩ resistor

Transistors in the circuit:

For a detailed description of these transistors, please check the following websites:

https://www.onsemi.com/products/discretes-drivers/general-purpose-and-low-vcesat-transistors/2n3904 or https://www.onsemi.com/pub/Collateral/2N3903-D.PDF

https://www.onsemi.com/products/discretes-drivers/general-purpose-and-low-vcesat-transistors/2n3906 or https://www.onsemi.com/pub/Collateral/2N3906-D.PDF

Reminder: Switch off the DC power suppliers first whenever you need to change the circuit configurations. Switch on the DC power suppliers only when you do not have to change the circuit connection anymore.

Part 1: Common-emitter (CE) Amplifier

Description of the CE Amplifier

This lab would like to design a CE amplifier using a PNP-BJT 2N3096 with a constant current sink connected between its collector and the lowest power supply V_{EE}. Due to the Early effect (as shown in Figure 6.18 of the textbook) of the transistor, the output current of the current sink changes with its collector voltage, which results in a finite output resistance R_o. Therefore, we usually model the current sink by an ideal current sink I_o in parallel with its output resistance R_o. This output resistance R_o also serves as the AC load resistance for the AC signal from the transistor. This lab starts with the characterization of the output resistance R_o of a current sink, followed by the design of a CE amplifier.

A. Pre-lab Simulation – Constant Current Sink

1.1 To characterize the output resistance of a current sink, construct the current sink in PartSim (or LTspice) with resistance values and supply voltages, as shown in Fig. 1.

1.2 **DC Characteristics:** Sweep V_{CC} from -3.9V to -0.6V with 0.3V step and measure the emitter voltage V_E and the collector I_C. Record the simulated I_C and V_E in the sheet "Step 1.2" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

1.3 **Output Resistance:** For V_{CC} higher than $V_{o,min}$, calculate the output resistance R_o of the current sink by $R_o = \dfrac{\partial V_{CC}}{\partial I_o}$, where I_o is the collector current I_C of Q1.

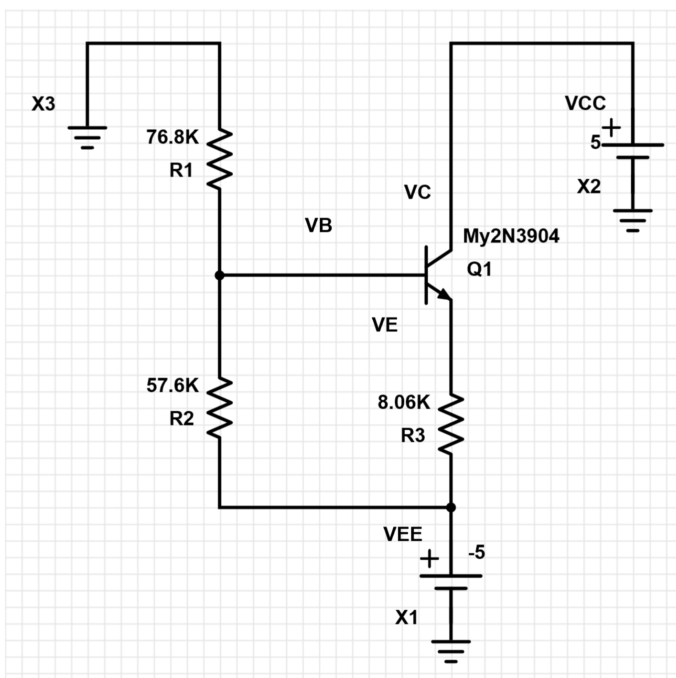

Fig. 1 The schematic diagram for the constant current sink

B. Pre-lab Simulation – CE Amplifier

1.4 Construct the CE amplifier, as shown in Fig. 2, using a PNP-BJT 2N3906 and the current sink that we characterized in Fig. 1. Here V_{sig} provides the required DC bias for Q_2 and the AC signal applied to the CE amplifier.

1.5 **Quiescent (Q-) Point:** Set the DC voltage of V_{sig} = 4.39V, measure the resulting DC voltage at V_o as V_{o1}. Set the DC voltage of V_{sig} = 4.41V, measure the resulting DC voltage at V_o as V_{o2}. Record the measured V_{o1} and V_{o2} in the sheet "Step 1.5" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

1.6 **DC Characteristics:** Sweep the DC voltage of V_{sig}, from 4.39 V to 4.41 V with 0.1 mV step. Measure the collector current I_{C2} and the voltage V_o at the collector of Q_2. Record the simulated I_{C2} and V_o in the sheet "Step 1.6" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx". Find the $V_{sig} = V_{BQ2}$ that results in $V_o \approx 0$V.

1.7 **Frequency Response:** Set the DC value of $V_{sig} = V_{BQ2}$ and the AC amplitude of V_{sig} = 1 mV, conduct AC analysis for V_o in DEC with Start Frequency = 100 Hz, Stop Frequency = 1 MHz, and Total Points Per Decade = 101. Choose REAL for magnitude unit and degree (DEG) for phase unit. Record the measured $|V_o|$ and $\angle V_o$ in the sheet "Step 1.7" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

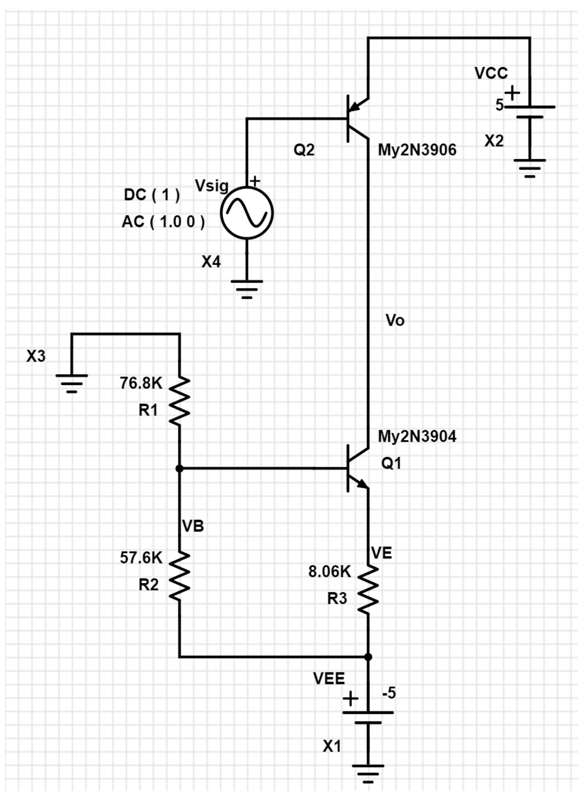

Fig. 2 Schematic diagram of the common emitter (CE) amplifier

C. In-lab Measurement – Constant Current Sink

1.8 Use the port definition diagram of AD2 shown in Fig. 3 when setting up your experiments.

1.9 Based on Fig. 1, construct the measurement setup for the constant current sink. Use Wavegen 1 (W1) for VCC and V- for VEE. Connect Scope Ch. 1 Positive (1+) to V_B (the base of Q_1) and Scope Ch. 2 Positive (2+) to V_E (the emitter of Q_1). Connect GNDV+, GNDV-, Scope Ch. 1 Negative (1-), and Scope Ch. 2 Negative (2-) to a common ground

1.10 **DC Characteristics:** Start WaveForms program, click Workspace, open the provided script function workspace file "Lab2_Step1.10.dwf3work", and press Run. This script sets V- = -5V, sweeps Wavegen 1 (W1) from -3.9V to -0.6V with 0.3V voltage step, and measures the base voltage V_B and the emitter voltage V_E of Q1. Click on the Script tag, select all data in the Output window, and right-click to save them into a text file "Lab2_Step1.10.txt".

1.11 Run Excel and open the text file "Lab2_Step1.10.txt". Choose Delimited as the file type, Comma in Delimiters, and General in Column data format to import the data. The first row is the VCC data, the second row is the VB data, and the third row is VE data, respectively.

1.12 Copy the whole data in a row, right-click the destination cell in the sheet "Step 1.10" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx", choose Paste Special from the context menu, and select Transpose to record the measured V_B and V_E. It calculates the output current I_o, which equals the collector current I_{C1} of Q1 as follows.

$$I_{R1} = \frac{0\text{ V} - V_B}{R_1} = -\frac{V_B}{R_1}, \tag{1}$$

$$I_{R2} = \frac{V_B - V_{EE}}{R_2} = \frac{V_B - (-5\text{ V})}{R_2} = \frac{V_B + 5\text{ V}}{R_2}, \tag{2}$$

$$I_{B1} = I_{R1} - I_{R2}, \tag{3}$$

$$I_{E1} = \frac{V_E - V_{EE}}{R_3} = \frac{V_E - (-5\text{ V})}{R_3} = \frac{V_E + 5\text{ V}}{R_3}, \tag{4}$$

and

$$I_o = I_{C1} = I_{E1} - I_{B1}. \tag{5}$$

1.13 Keep the constant current sink connected. We will use it again in Part D when designing a common-emitter (CE) amplifier.

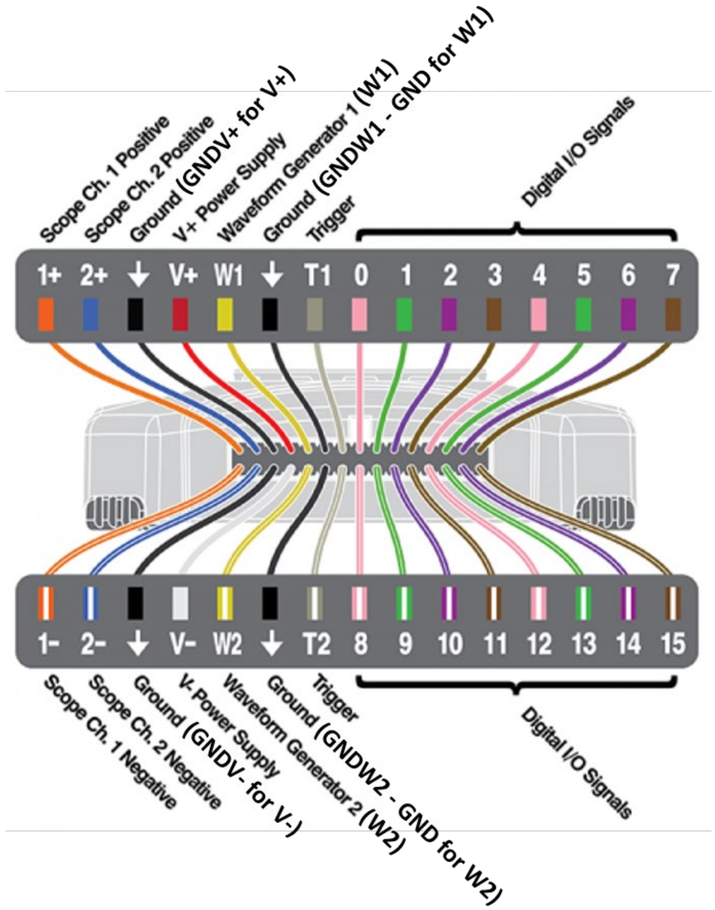

Fig. 3 Diagram for the port definition of an Analog Discovery 2 (AD2)

D. In-lab Measurement – CE Amplifier

1.14 Based on Fig. 2, construct the measurement setup for the common-emitter (CE) amplifier. Use V+ = 5V for V_{CC}, V- = -5V for V_{EE}, and Wavegen 1 (W1) for V_{sig}. Connect GNDV+, GNDV-, and GNDW1 to a common ground line.

1.15 Connect Scope Ch. 1 Positive (1+) to Wavegen 1 (W1), Scope Ch. 2 Positive (2+) to V_o (the collector of Q_2). Connect the Scope Ch. 1 Negative (1-) and Scope Ch. 2 Negative (2-) to the common ground.

1.16 **DC Characteristics:** In WaveForms, click Workspace, open the provided script function workspace file "Lab2_Step1.16.dwf3work", and press Run. This script sweeps the DC voltage of Wavegen 1 (W1) from 4.38 V to 4.40V with 1 mV step and uses Voltmeter in WaveForms to measure the output voltage from W1 and the corresponding voltage V_o at the collector of Q_2. Record the W1 setting, measured V_{sig}, and V_o values in the sheet "Step 1.16" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx". Find the DC voltage V_{BQ2} of Wavegen 1 (W1), which results in $V_o \approx 0$V.

1.17 **Quiescent (Q-) Point:** Connect Scope Ch. 1 Positive (1+) to V_B (the base of Q1) and Scope Ch. 2 Positive (2+) to V_E (the emitter of Q_1). Set W1 to the V_{BQ2} obtained in Step 1.16. Use Voltmeter in WaveForms to measure the base voltage V_B and the emitter voltage V_E of Q1. Record the measured V_B and V_E in the sheet "Step 1.17" of the Excel file "Lab 2 – Single-Stage

Amplifier.xlsx", which calculates the collector current $I_{C2} = I_{C1}$ using (1) to (5).

1.18 Connect Scope Ch. 1 Positive (1+) to Wavegen 1 (W1), Scope Ch. 2 Positive (2+) to V_o (the collector of Q_2). In WaveForms, Channel 1 (W1) window, set Type = Sine, Frequency = 100 Hz, Amplitude = 1 mV, Offset = V_{BQ2} from Step 1.16, Symmetry = 50% and Phase = 0°.

1.19 **Using Scopes:** Display the measurement results using the Scope function in WaveForms. In Scope 1, set Channel 1 with Offset = $-V_{BQ2}$ and Range = 1 mV/div to see the input waveform. For Channel 2, set Offset = 0 V and Range = 1 V/div. Use Y Cursors to set their upper and lower peak values and use the Ref function to calculate the difference. Record the measured amplitude of Scope Ch. 1 Positive (1+) and Scope Ch. 2 Positive (2+) in the sheet "Step 1.19" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx" to calculate the voltage gain in dB.

1.20 Disconnect the circuit from the power supply V_{CC} but keep the rest of the CE amplifier circuit connected. We will use it again in Lab 4 when we design a directly coupled operational amplifier.

E. Questions for Part 1:

For the common emitter amplifier designed, answer the following questions with simulated and measured data, and discuss any discrepancy between the simulation and measurement results.

Q1. (10 Points) (1) Based on the simulation data obtained in Step 1.2, what are the $V_{o,min}$, and I_o of the current sink? Use the measurement data obtained in Step 1.10 to verify the $V_{o,min}$ and I_o. (2) Based on the simulation data obtained in Step 1.2 and the measurement data obtained in Step 1.10, what are the ranges of the simulated and measured output resistance R_o of the current sink for VCC larger than $V_{o,min}$?

Q2. (10 Points) What are the values of V_{o1} and V_{o2} obtained in Step 1.5? Check the Q-points of Q2 under these two conditions and explain/justify the results obtained.

Q3. (15 Points) Based on the simulation data obtained in Step 1.6, (1) plot the simulated DC V_o vs. V_{sig} characteristics. Discuss/justify the simulated characteristics. (2) For the circuit to work as an amplifier, find the DC input range for V_{sig} and the output voltage range for V_o. (3) Find the V_{sig} value and its corresponding collector current I_{C2} that results in $V_o \approx 0$ V. (4) Based on the measurement data obtained in Step 1.16, plot the measured DC V_o vs. V_{sig} characteristics.

Q4. (10 Points) (1) Based on the simulation data obtained in Step 1.7, what are the magnitude (in dB) and phase of intrinsic voltage gain A_{vo} at low frequency (i.e., 100 Hz) and the upper 3-dB frequency f_{3dB} (i.e., the frequency at which the amplitude become $1/\sqrt{2} = 0.707$ of its low-frequency value, or the phase changes 45°) of this CE amplifier? (2) Verify the voltage gain A_{vo} using the measurement data obtained in Steps 1.18 and 1.19. (3) Increase the frequency of W1 to the upper 3-dB frequency f_{3dB} obtained from the simulation, check the value of A_{vo}, and see if it is about 0.707 of its low-frequency value obtained at 100 Hz. Provide WaveForms screenshots of your measurement results.

<u>Part 2</u>: Differential Amplifier - Common-mode (CM) Signal

A. Pre-lab Simulation for CM Signal

2.1 Construct the differential amplifier, as shown in Fig. 4, using two NPN-BJT 2N3904, two 8.25 kΩ resistors, and the current sink characterized in Fig. 1. We first analyze its characteristics for DC common-mode signal V_{CM}, followed by the AC common-mode signal v_{cm}. Here the source V_{cm} in Fig. 4 provides both V_{CM} and v_{cm} to the differential amplifier.

2.2 **DC Characteristics:** Sweep the DC voltage V_{CM} of V_{cm}, from -5 V to 5V with 0.1V step. Measure the voltages V_o and V_E at the collector and the emitter of Q_2, respectively. Besides, measure the collector current I_{C2} of Q_2. Record the simulated values of V_o, V_E, and I_{C2} in the sheet "Step 2.2" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

2.3 **Frequency Response:** Set the DC value V_{CM} of V_{cm} = 0 V and its AC amplitude v_{cm} = 1 mV, conduct AC analysis for V_o in DEC with Start Frequency = 0.1 Hz, Stop Frequency = 1 MHz, and Total Points Per Decade = 101. Choose REAL for magnitude unit and degree (DEG) for phase unit. Record the simulated magnitude and phase of V_o in the sheet "Step 2.3 of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

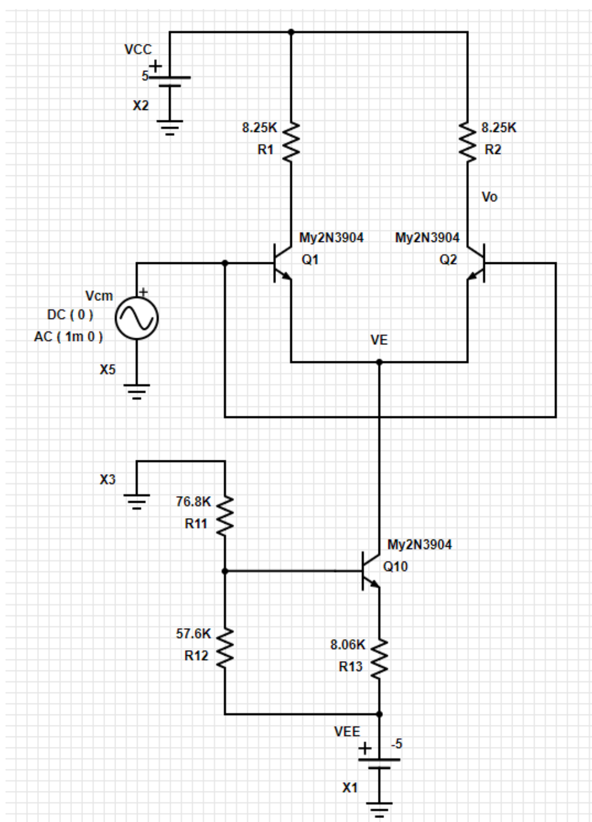

Fig. 4 Schematic diagram of the differential amplifier for common-mode analysis

B. In-lab Measurement for CM Signal

2.4 Based on Fig. 4, construct the measurement setup for the differential amplifier. Use V+ = 5V for V_{CC}, V- = -5V for V_{EE}, and Wavegen 1 (W1) for V_{cm}. Connect GNDV+, GNDV-, and GNDW1 to a common ground line.

2.5 Connect Scope Ch. 1 Positive (1+) to V_E (the emitter of Q_2), Scope Ch. 2 Positive (2+) to V_o (the collector of Q_2). Connect Scope Ch. 1 Negative (1-) and Scope Ch. 2 Negative (2-) to the common ground.

2.6 **Quiescent (Q-) Point:** In WaveForms, choose Wavegen and set the type of Wavegen 1 (W1) to DC. Here we use Wavegen 1 (W1) as a DC voltage source. Set the DC voltage of Wavegen 1 (W1) to 0 V, and use the Voltmeter in WaveForms to measure the voltage V_{EQ2} at the emitter of Q_2 and V_{oQ2} at the collector of Q_2, respectively.

2.7 **Maximum Common-mode Voltage $V_{CM,max}$:** In WaveForms, click Workspace, open the provided script function workspace file "Lab2_Step2.7.dwf3work" and press Run. This script sweeps the DC voltage of Wavegen 1 (W1) from 4 V to 5 V with 0.1 V step and uses the Voltmeter in WaveForms to measure the voltages at V_E (the emitter of Q_2) and V_o (the collector of Q_2), respectively. Record the measured V_E and V_o in the sheet "Step 2.7" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

2.8 **Minimum Common-mode Voltage $V_{CM,min}$:** In WaveForms, click Workspace, open the provided script function workspace file "Lab2_Step2.8.dwf3work" and press Run. This script sweeps the DC voltage of Wavegen 1 (W1) from -2 V to -3 V with -0.1 V step and uses Voltmeter in WaveForms to measure the voltages at V_E (the emitter of Q_2) and V_o (the collector of Q_2), respectively. Record the measured V_E and V_o in the sheet "Step 2.8" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

C. Questions for Part 2:

For the differential amplifier designed, answer the following questions with simulated and measured data, and discuss any discrepancy between the simulation and measurement results.

Q5. (15 Points) Based on the simulation data obtained in Step 2.2, (1) what are the voltages of V_o and V_E, and I_{C2} of Q_2 when V_{CM} = 0V, (2) what is the input common-mode range (i.e., the voltage range of V_{CM} to maintain the same out voltage), and (3) what determines the upper and lower bounds of the input common-mode range? (5) Based on the measurement data obtained in Steps 2.7 and 2.8, verify the common-mode range by experimental data.

Q6. (10 Points) Based on the simulated data obtained in Step 2.3, what is the low-frequency voltage gain A_{cm} in dB for the common-mode signal?

Part 3: Differential Amplifier – Differential-mode (DM) Signal

A. Pre-lab Simulation for DM Signal

3.1 We want to analyze its characteristics for DC differential-mode signal V_{DM}, followed by the AC common-mode signal v_d. Here the voltage sources V_1 and V_2 in Fig. 5 provide both DC and AC voltages to the inputs of the differential amplifier.

3.2 **DC Characteristics:** Sweep the DC voltage V_1 from -0.25 V to 0.25V with 1 mV step, and simulate the collector currents I_{C1} and I_{C2} of Q_1 and Q_2, respectively. Record the simulated I_{C1} and I_{C2} in the sheet "Step 3.2" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

3.3 **Frequency Response:** Set the DC values of V_1 and V_2 = 0 V, and their AC amplitude 1 mV. For the differential-mode signal, set the phases of the AC signal V_1 and V_2 to be 0° and 180°, respectively, as shown in Fig. 5. In this setting, the differential-model signal $v_{id} = V_1 - V_2 = 1$ mV – (–1 mV) = 2 mV. Conduct AC analysis for V_o in DEC with Start Frequency = 100 Hz, Stop Frequency = 10 MHz, and Total Points Per Decade = 101. Choose REAL for magnitude unit and degree (DEG) for phase unit. Record the simulated magnitude and phase of V_o in the sheet "Step 3.3 of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

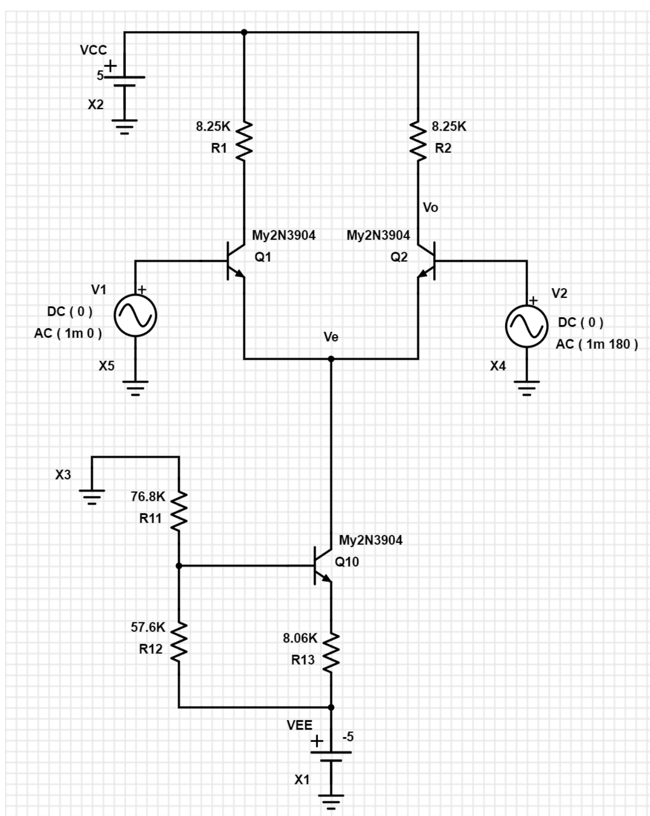

Fig. 5 Schematic diagram of the differential amplifier for differential-mode analysis

B. In-lab Measurement for DM Signal

3.4 Based on Fig. 5, construct the measurement setup for the differential amplifier. Use V+ = 5V for V_{CC}, V- = -5V for V_{EE}, Wavegen 1 (W1) for V_1 and Wavegen 2 (W2) for V_2. Connect GNDV+, GNDV-, GNDW1, and GNDW2 to a common ground line.

3.5 **DC Offset Voltage:** Due to the mismatch between Q_1 and Q_2, we need to balance their DC currents by applying offset voltage to Q_2 (or Q_1). To find the required offset voltage, connect Scope Ch. 1 Positive (1+) to the collector of Q_1 and Scope Ch. 2 Positive (2+) to V_o (i.e., the collector of Q_2). In WaveForms, click Workspace, open the provided workspace script "Lab2_Step3.5.dwf3work" and press Run. This script will set the offset voltage of Wavegen 1 (W1) to 0 V and gradually change the offset voltage of Wavegen 2 (W2) until the DC voltages V_{C1} at the collector of Q_1 and V_o at the collector of Q_2 to be about the same. Record the measured offset voltage for Q_2, V_{C1}, and V_{oQ2} in the sheet "Step 3.5" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx".

3.6 **Differential-mode Voltage Gain:** Connect Scope Ch. 1 Positive (1+) to Wavegen 1 (W1), Scope Ch. 2 Positive (2+) to V_o (the collector of Q_2). In WaveForms, click Workspace, open the provided workspace script "Lab2_Step3.6.dwf3work", set the W2Offset in the script to the value obtained in Step 3.5, and press Run. This script enables both Channel 1 (W1) and Channel 2 (W2) and sets their Type = Sine, Frequency = 100 Hz, Amplitude = 1 mV, Symmetry = 50%, Channel 1 (W1) Phase = 0°, Channel 2 (W2) Phase = 180°, Offset of Wavegen 1 (W1) = 0 V, and Offset of Wavegen 2 (W2) = W2Offset, respectively. This script returns the measured differential-mode voltage gain A_{vd} in dB.

3.7 **Using Scopes:** Display the measurement results using the Scope function in WaveForms. Use Y Cursors to set their upper and lower peak values and use the Ref function to calculate the difference. Record the measured peak-to-peak value of Scope Ch. 1 Positive (1+) and Scope Ch. 2 Positive (2+) in the sheet "Step 3.6" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx" to confirm the measured differential-mode voltage gain from the script. Copy and paste the screenshot of the measurement results to replace the one in the sheet "Step 3.6" of the Excel file "Lab 2 – Single-Stage Amplifier.xlsx" to support your calculation. Make sure to capture the date and time of your PC in the screenshot.

3.8 Disconnect the circuit from the power supply V_{CC}, but keep the rest of the differential amplifier connected. We will use it again in Lab 3 when we design a directly coupled multi-stage amplifier.

C. Questions for Part 3:

For the differential amplifier designed, answer the following questions with simulated and measured data, and discuss any discrepancy between the simulation and measurement results.

Q7. (10 Points) Based on the simulation data obtained in Step 3.2 and the description on page 618 of the textbook, (1) what is the input differential-mode range? (2) How do we determine the upper and lower bounds of the input differential-mode range?

Q8. (10 Points) (1) Based on the simulation data obtained in Step 3.3, what is the voltage gain A_d in dB for the differential-mode signal? (2) Estimate its upper 3-dB frequency f_{3dB} (i.e., the frequency at which the amplitude becomes $1/\sqrt{2}$ = 0.707 of its low-frequency value or the phase changes 45°) and calculate the gain-bandwidth product (GBW) in hertz (Hz). (3) Compare the upper 3-dB frequency f_{3dB} of this differential amplifier with that of the CE amplifier obtained in Q4. (4) Based on the measurement data obtained in Step 3.6, calculate the measured low-frequency differential voltage gain A_d in dB.

Q9. (10 Points) Based on the simulation data, what is the common-mode rejection ratio (CMRR) of the amplifier in dB?