

# McMaster University

## Electrical and Computer Engineering Department

### EE3EJ4 Electronic Devices and Circuits II - Fall 2023



## Lab. 2 Single-Stage Amplifiers

### Lab Report Due on Oct. 8, 2023

**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 a 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

#### Information of Components:

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 no longer have to change the circuit connection.

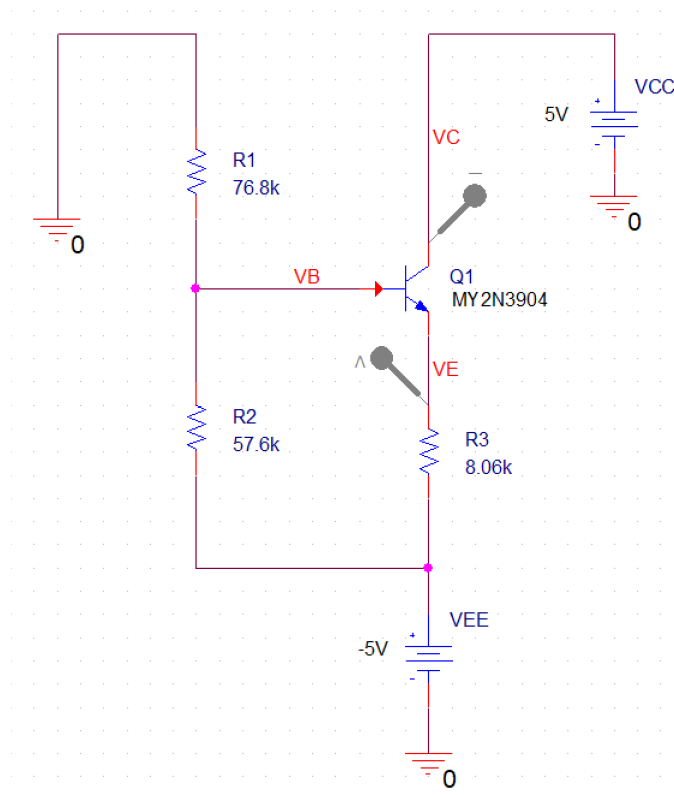
## **Part 1: Common-emitter (CE) Amplifier**

### **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 characterizing the output resistance  $R_o$  of a current sink, followed by the design of a CE amplifier.



### **A. SPICE Simulation – Constant Current Sink**

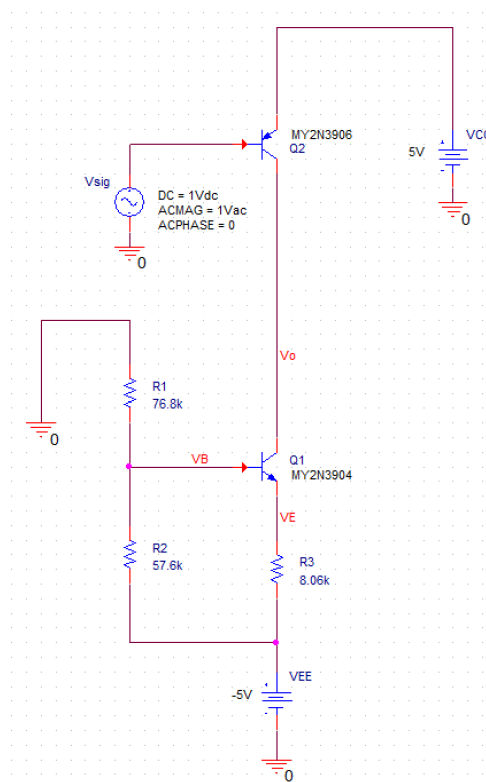
- 1.1 To characterize the output resistance of a current sink, construct the current sink in [PSpice](#) with resistance values and supply voltages, as shown in Fig. 1.
- 1.2 **DC Characteristics:** Sweep  $V_{CC}$  from -3.9V to -0.6V with a 0.3V step and measure the emitter voltage  $V_E$  and the collector  $I_C$ . In the PSpice simulator window, (1) Edit -> Select All, and (2) Edit -> Copy. Open Excel and paste the data into an Excel sheet. 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  $R_o = \frac{\partial V_{CC}}{\partial I_o}$ , where  $I_o$  is the collector current  $I_C$  of Q1.



**Fig. 1** The schematic diagram for the constant current sink

## B. SPICE Simulation – CE Amplifier

- 1.4 Construct the CE amplifier, as shown in Fig. 2, using a PNP-BJT 2N3906 and the current sink 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. Double-click  $V_{sig}$  in Schematic to open the Property Editor and click Pivot to show the property items vertically. Click the blank field beside the ACPHASE and enter 0 in the data entry field between the New Property tag and the property table. Click on the Display tag and choose Name and Value for ACPHASE. Click  to save the property.
- 1.5 **Quiescent (Q-) Point:** Set the DC voltage of  $V_{sig} = 4.39\text{V}$  and measure the resulting DC voltage at  $V_o$  as  $V_{o1}$ . Set the DC voltage of  $V_{sig} = 4.41\text{V}$  and 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 a 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  $V_o \approx 0\text{V}$ .
- 1.7 **Frequency Response:** Set the DC value of  $V_{sig} = V_{BQ2}$  and the AC amplitude of  $V_{sig} = 1\text{ mV}$ . Conduct AC sweep for  $V_o$  in Logarithmic with Start Frequency = 100 Hz, End Frequency = 1 MegHz, and Points/Decade = 101. In the simulator window, click the Add Trace icon , choose Plot Window Templates under Functions or Macros, select Bode Plot – dual Y axes(1), select V( $V_o$ ) in Simulation Output Variables, and press OK. Record the simulated magnitude  $|V_o|$  and phase  $\angle V_o$  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. AD2 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 the 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 a 0.3V voltage step, and measures the base voltage  $V_B$  and the emitter voltage  $V_E$  of  $Q_1$ . 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  $V_{CC}$  data, the second row is the  $V_B$  data, and the third row is the  $V_E$  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  $Q_1$  as follows.

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

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

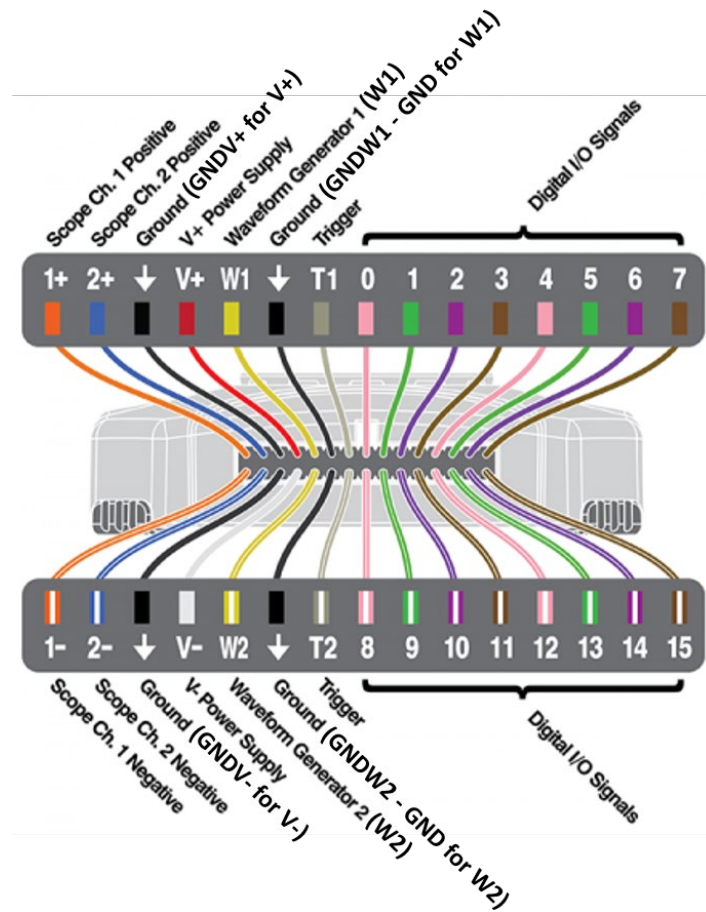
$$I_{B1} = I_{R1} - I_{R2}, \quad (3)$$

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

and

$$I_o = I_{C1} = I_{E1} - I_{B1}. \quad (5)$$

- 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. AD2 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 a 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  $V_o \approx 0V$ .
- 1.17 **Quiescent (Q-) Point:** 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  $Q_1$ ). Set W1 to the  $V_{BQ2}$  obtained in Step 1.16. Use a Voltmeter in WaveForms to measure the base voltage  $V_B$  and the emitter voltage  $V_E$  of  $Q_1$ . 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 =  $0^\circ$ .
- 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 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 to design a directly coupled operational amplifier.

### E. Questions for Part 1

For the common emitter (CE) 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  $V_{CC}$  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  $Q_2$  under these two conditions and explain/justify the results obtained qualitatively.

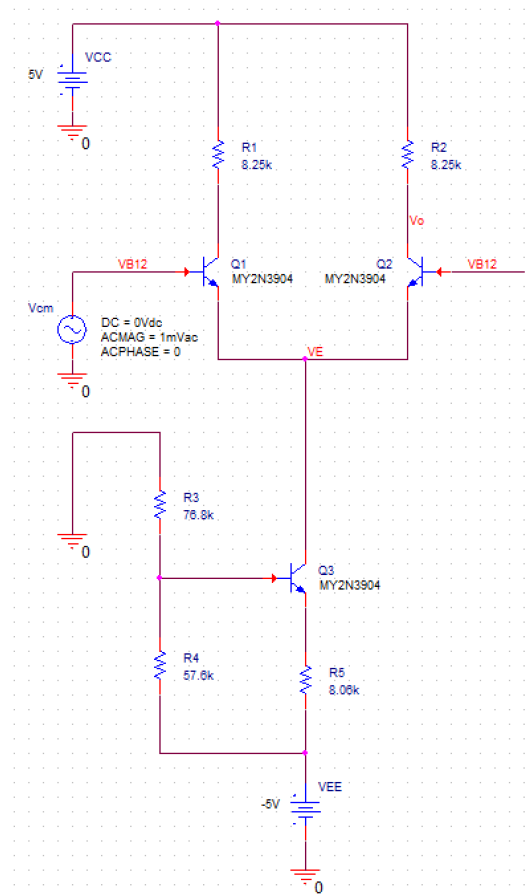
**Q3. (15 Points)** Based on the simulation data obtained in Step 1.6, (1) plot the simulated DC  $V_o$  vs.  $V_{sig}$  characteristics. Discuss/justify the simulated characteristics. (2) For the circuit to work as an amplifier, find the DC input range for  $V_{sig}$  and the output voltage range for  $V_o$ . (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  $45^\circ$ ) 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.

## **Part 2: Differential Amplifier - Common-mode (CM) Signal**

### **A. SPICE Simulation - CM Signal**

- 2.1 As shown in Fig. 4, construct the differential amplifier using two NPN-BJT 2N3904 (Q1 and Q2), two 8.25 k $\Omega$  resistors (R1 and R2), 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 a 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 sweep for  $V_o$  in Logarithmic with Start Frequency = 0.1 Hz, End Frequency = 1 MegHz, and Points/Decade = 101. In the simulator window, click the Add Trace icon , choose Plot Window Templates under Functions or Macros, select Node Plot – dual Y axes(1), select V(Vo) in Simulation Output Variables, and press OK. Record the simulated magnitude  $|V_o|$  and phase  $\angle V_o$  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. AD2 Measurement - 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  $Q_2$ ) and 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 a 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 a -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? (4) Based on the measurement data obtained in Steps 2.7 and 2.8, verify the common-mode range by experimental data.

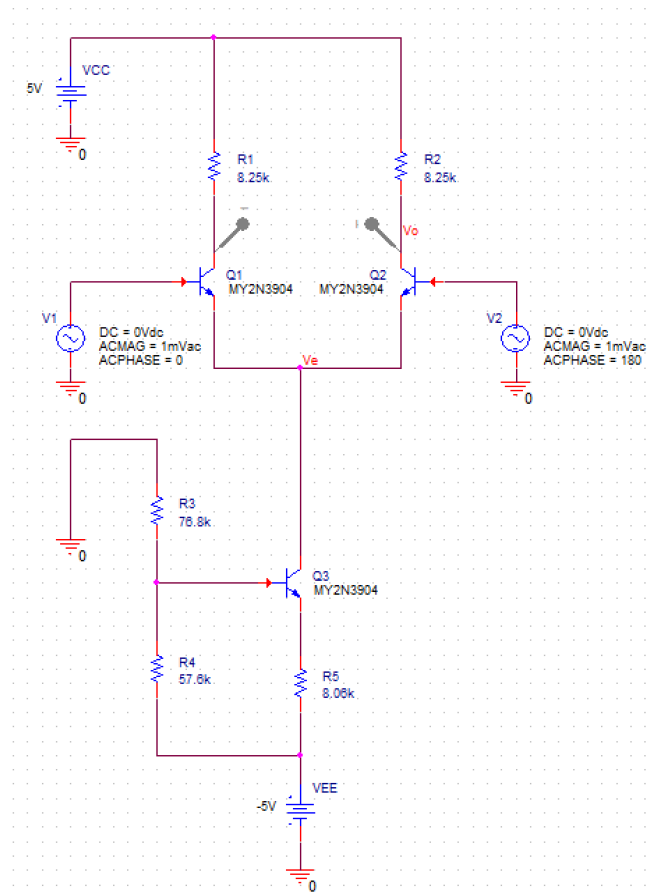
**Q6. (10 Points)** Based on the simulated data obtained in Step 2.3, what is the low-frequency voltage gain  $A_{cm}$  in dB for the common-mode signal?



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

#### **A. SPICE Simulation - DM Signal**

- 3.1 We want to analyze its characteristics for the DC differential-mode signal  $V_{DM}$ , followed by the AC differential-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. Set the DC values of  $V_1$  and  $V_2 = 0$  V.
- 3.2 **DC Characteristics:** Sweep the DC voltage of  $V_1$  from -0.25 V to 0.25V with a 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 AC magnitudes of  $V_1$  and  $V_2$  to 1 mV. For the differential-mode signal, set the phases of the AC signal  $V_1$  and  $V_2$  to be  $0^\circ$  and  $180^\circ$ , respectively, as shown in Fig. 5. In this setting, the differential-mode signal  $v_{id} = V_1 - V_2 = 1 \text{ mV} - (-1 \text{ mV}) = 2 \text{ mV}$ . Conduct AC sweep for  $V_o$  in Logarithmic with Start Frequency = 100 Hz, End Frequency = 10 MegHz, and Points/Decade = 101. In the simulator window, click the Add Trace icon , choose Plot Window Templates under Functions or Macros, select Bode Plot – dual Y axes(1), select V( $V_o$ ) in Simulation Output Variables, and press OK. Record the 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. AD2 Measurement - 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  $V_{C1}$  (collector voltage of  $Q_1$ ) and  $V_o$  (collector voltage of  $Q_2$ ) are 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 =  $0^\circ$ , Channel 2 (W2) Phase =  $180^\circ$ , 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 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 to 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 in Section 9.2.3 Large-Signal Operation of the textbook, (1) what are the DC and AC input differential-mode ranges? (2) How do we determine the upper and lower bounds of these input differential-mode ranges?

**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  $45^\circ$ ) 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?