Başkent University
Department of Electrical and Electronics Engineering
EEM 311 Electronics II
Experiment 8

INTRODUCTION TO OPAMPs

Aim:

The aim of this experiment is to familiarize the student with the biasing and operation of a BJT differential pair amplifier.

Theory :

The typical(basic) BJT differential pair amplifier which is in Fig.1 consists of a pair of transistors coupled at the emitters to a current source, having equal resistances in each collector and signal sources in each base. The amplifier has several variations on this basic configuration. Differential amplifiers generate an output signal proportional to the difference between two independent input signals. Differential amplifier is the first stage of all the operational amplifiers and many other analog integrated circuits.

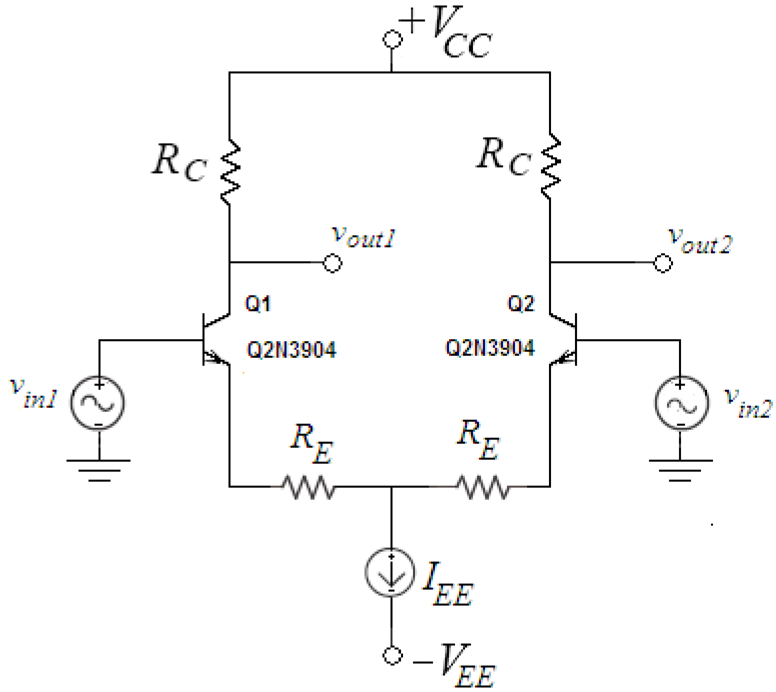

figure1

DC Analysis of Differential Amplifier

The operating point current I_{EE} is set using a current mirror. Since the emitters of transistors Q_1 and Q_2 are connected together through a equal resistors and their bases are grounded (at DC condition i.e. $v_{in1} = v_{in2} = 0$), V_{BE} is same for Q_1 and Q_2; therefore $I_{C1} = I_{C1} \approx I_{EE}/2$ and they will have same values of $r_\pi=\beta_o V_T / I_C$, $g_m = I_C/V_T$ and $r_o = V_A/I_C$. Note that in the active region of operation the collector current does not depend on the collector resistance R_C, just depends on V_{BE} (and in turns I_B).

AC Analysis of Differential Amplifier

The following terms are general and applied to any differential amplifier:

Differential Mode Input :

$$v_{idm} = v_{in1} - v_{in2}$$

Common Mode Input :

$$v_{icm} = \frac{v_{in1} + v_{in2}}{2}$$

Differential Mode Output :

$$v_{odm} = v_{out1} - v_{out2}$$

Common Mode Output :

$$v_{ocm} = \frac{v_{out1} + v_{out2}}{2}$$

If $-v_{in2} = v_{in1} = v_{in}$, the differential amplifier circuit in Fig.1 becomes ***pure differential mode circuit*** since common mode input will be zero. The small signal AC equivalent circuit of the pure differential mode circuit is :

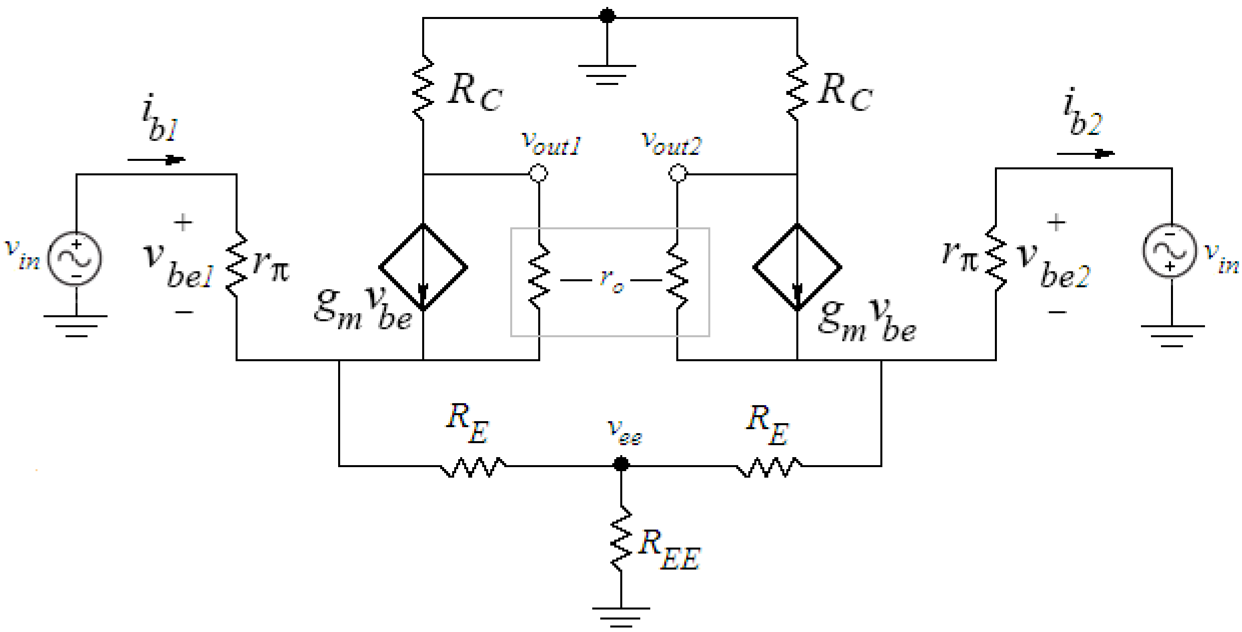

figure2

NOTE : For a purely differential-mode input voltage: voltage at the node v_{ee} is zero therefore $i_{b2} = i_{b1} = i_b$ and $-v_{be2} = v_{be1} = v_{be}$.

Assuming that $r_o >> R_C$, the output voltages(collector voltages) are ;

$$v_{out1} = -g_m v_{be1} R_C = -g_m i_b r_\pi R_C \quad and \quad v_{out2} = -g_m v_{be2} R_C = g_m i_b r_\pi R_C$$

the base currents are :

$$i_{b1} = i_{b2} = i_b = \frac{v_{in}}{r_\pi (1 + g_m R_E)}$$

Small Signal Differential Mode Voltage Gain for differential Output is :

$$A_{vdm-diff} = \frac{v_{odm}}{v_{idm}} = \frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}} = \frac{-g_m \dfrac{v_{in}}{r_\pi (1 + g_m R_E)} r_\pi R_C - g_m \dfrac{v_{in}}{r_\pi (1 + g_m R_E)} r_\pi R_C}{2v_{in}} = -\frac{g_m R_C}{(1 + g_m R_E)}$$

If either v_{out1} or v_{out2} alone is used to as the output, ***small signal single ended differential mode voltage gain*** is

$$A_{vdm-se1} = \frac{v_{out1}}{v_{idm}} = -\frac{g_m R_C}{2(1 + g_m R_E)} \quad or \quad A_{vdm-se2} = \frac{v_{out2}}{v_{idm}} = \frac{g_m R_C}{2(1 + g_m R_E)}$$

depending on which output is selected.

The differential-mode input resistance R_{idm} represents the small signal resistance presented to the full differential-mode input voltage appearing between the two bases of the transistors and is defines as:

$$R_{idm} = \frac{v_{idm}}{i_{b1}}$$

If $v_{in2} = v_{in1} = v_{in}$, the differential amplifier circuit in Fig.1 becomes ***pure common mode circuit*** since differential mode input will be zero. The small signal AC equivalent circuit of the pure common mode circuit is :

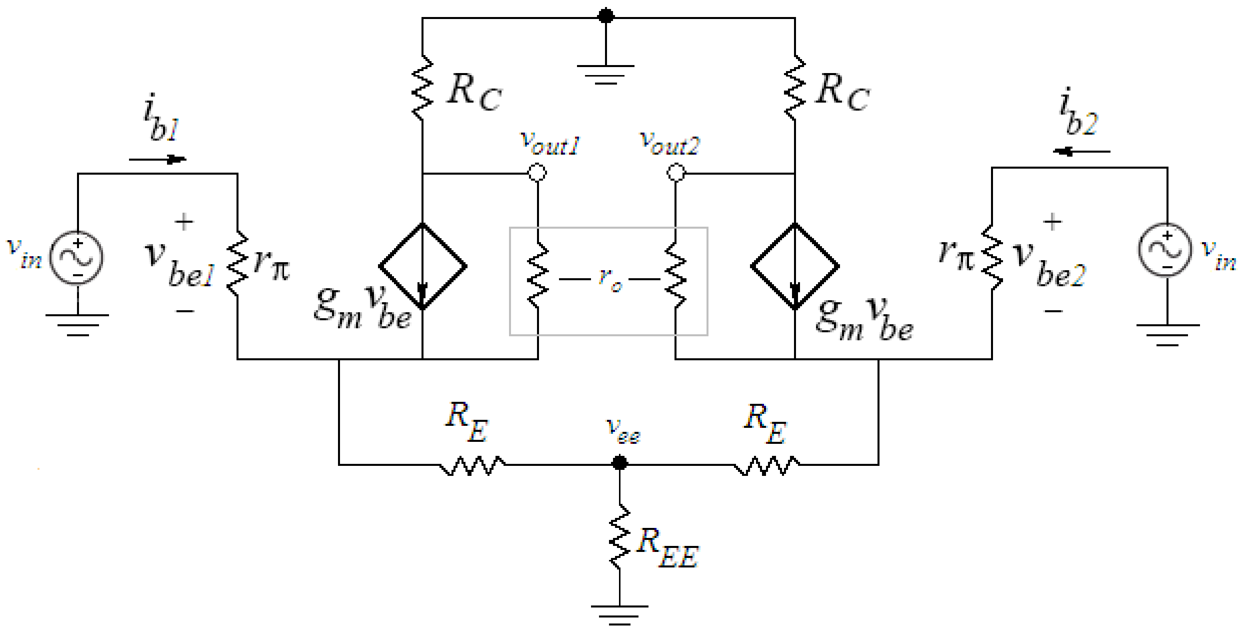

figure3

NOTE: For a purely common-mode input voltage both sides of the amplifier are completely symmetrical: therefore $i_{b2} = i_{b1} = i_b$ and $v_{be2} = v_{be1} = v_{be}$.

Assuming that $r_o >> R_C$, the output voltages(collector voltages) are ;

$$v_{out1} = v_{out2} = -g_m v_{be} R_C = -g_m i_b r_\pi R_C$$

the base currents are:

$$i_{b1} = i_{b2} = i_b = \frac{v_{in}}{r_\pi (1 + g_m R_E + g_m R_{EE})}$$

Because the output voltages are equal ***Small Signal Common Mode Voltage Gain for differential Output*** is zero:

$$A_{vcm-diff} = \frac{v_{odm}}{v_{icm}} = \frac{v_{out1} - v_{out2}}{\frac{v_{in1} + v_{in2}}{2}} = 0$$

However ***small signal single ended common mode voltage gain*** is not zero and as $v_{out1} = v_{out2}$: the common mode voltage gain at output1 is equal to common mode voltage gain at output2:

$$A_{vcm-se1} = A_{vcm-se2} = \frac{v_{out1}(v_{out2})}{v_{icm}} = \frac{-g_m \dfrac{v_{in}}{r_\pi(1+g_mR_E+2g_mR_{EE})} r_\pi R_C}{v_{in}} = -\frac{g_mR_C}{(1+g_mR_E+2g_mR_{EE})}$$

***Note:** The R_{EE} is the incremental resistance of the current source I_{EE} which is ideally infinity, but in practical circuits is not infinitely high.

Common-Mode Rejection Ratio (CMRR) is a figure of merit for any differential amplifier. It is defined as follows:

For single-ended outputs :

$$CMRR = \frac{A_{vdm-se}}{A_{vcm-se}} = \frac{\dfrac{g_mR_C}{2(1+g_mR_E)}}{\dfrac{g_mR_C}{(1+g_mR_E+2g_mR_{EE})}} = \frac{(1+g_mR_E+2g_mR_{EE})}{2(1+g_mR_E)} = \frac{(1/g_m+R_E+2R_{EE})}{2(1/g_m+R_E)} \cong \frac{R_{EE}}{(1/g_m+R_E)}$$

since $2R_{EE} >> 1/g_m + R_E$.

If the output is taken differentially from *vout1* to *vout2:*

$$CMRR = \frac{A_{vdm-diff}}{A_{vcm-diff}} = \infty$$

The function of a differential amplifier is to enhance the difference between the inputs and to suppress the common-mode component. This desirable characteristic is used to attenuate unwanted presences in the input signal such as noise from a coaxial cable or from an audio cable. Therefore, for a good Differential amplifier, CMRR should be as large as possible (common-mode gain should be as small as possible).

The common-mode input resistance R_{icm} is determined by the total signal current being supplied from the common mode source:

$$R_{icm} = \frac{v_{icm}}{2i_b}$$

Preliminary Work:

Review the sections 5.13, 15.3.1 through 15.3.9 from the Course Book.

In preliminary work you will design differential amplifier circuit in Fig.5 using the tansistor 2N3904 and following values ;

V_{CC}	V_{EE}	R_A	R_B	R_E
15 V	-15 V	2.2 kΩ	2.2 kΩ	250 Ω

Assume the 2N3904 has a $\beta = 100$, $V_{BE(ON)}$ = 0.7V and V_A = 100V. Use the emission coefficient as n = 1. (You can download data sheet 2N3904.pdf from course web page). The Pin Diagram of the 2N3904 is in Fig.4

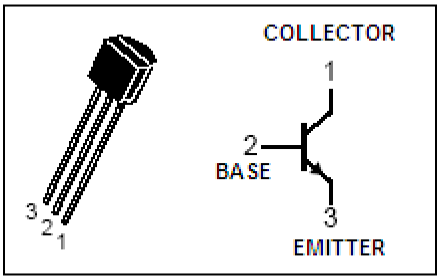

figure4

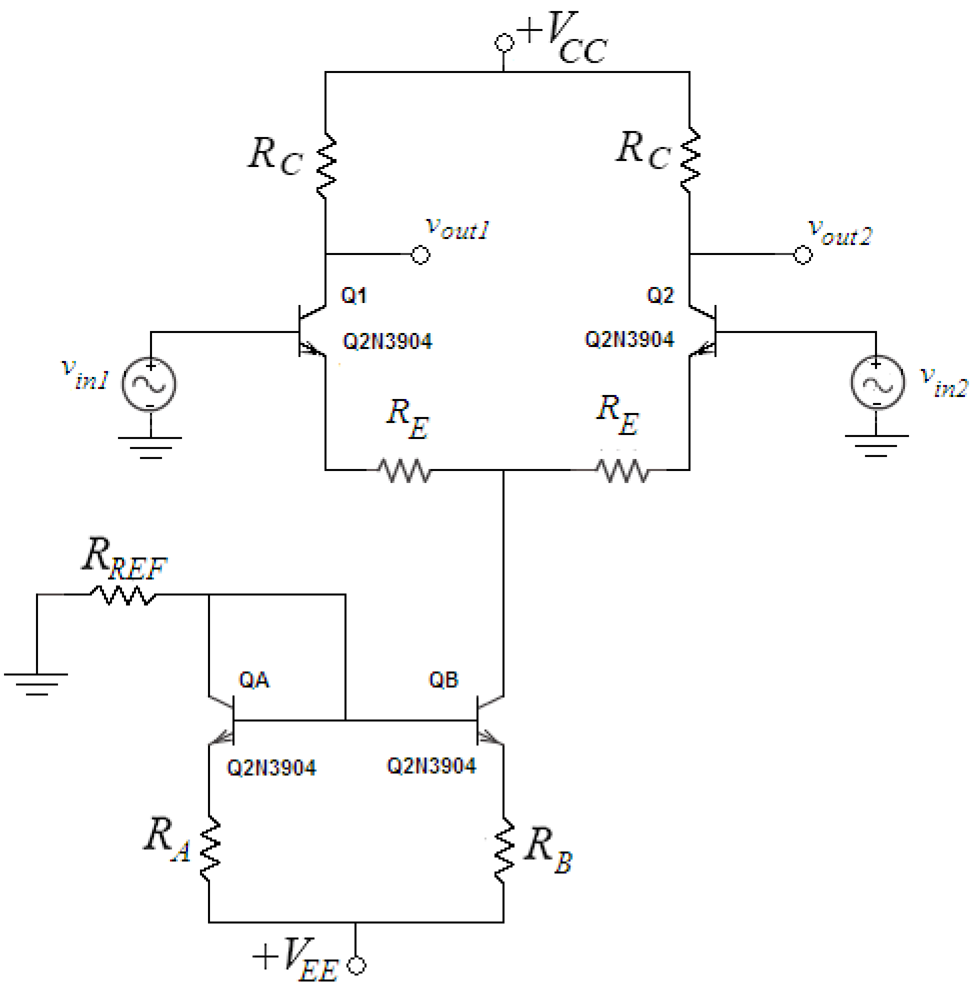

figure5

1. For the circuit of Fig.5, solve for R_{REF} and R_C's such that $I_{CQA,B}$ is approximately equal to 2 mA and $V_{CE1,2}$ = 6V. Assume $I_{CQ1,2} = 0.5I_{CQA,B}$, and the transistors are matched and operating in the active region. (Use only **Standard Resistor Values**)

2. Using the equations in the theory and information from Problem 1, Find the,

a. Small signal differential mode voltage gain for differential output $A_{vdm\text{-}diff}$

b. Small signal single ended differential mode voltage gains $A_{vdm\text{-}se1}$ and $A_{vdm\text{-}se2}$

c. Small signal single ended common mode voltage gain $A_{vcm\text{-}se1}$

d. CMRR (Common-Mode Rejection Ratio)

for the circuit in Fig.5.

3. Derive equations for the R_{idm} and R_{icm}, find their values.(Show all your steps clearly)

Verify your design using PSpice. You will need to use a model for the 2N3904 transistor. The models can be found in the bipolar.lib library.

a. Form your circuit in Fig.5 in Pspice with the given values in Table1 and using the R_C and R_{REF} values calculated at preliminary work part1. Ground the both v_{in1} and v_{in2}

b. Bias simulation. Simulate the circuit. Do a BIAS simulation and find the DC **voltages V_{CE1}, V_{CE2} and currents I_{CQ1}, I_{CQ2}, I_{CQA} and $I_{CQ,B}$.** Check whether your design is correct or not. If it is not design again!!

c. Next, do a transient simulation.

Apply a sinusoidal source(V_{sin}) of 1 kHz frequency and amplitude of 50mV at the base of Q1 and apply a sinusoidal source(V_{sin}) of 1 kHz frequency and amplitude of -50mV at the base of Q2 (i.e. v_{in1}= 50mVp-p, v_{in2}= -50mVp-p). Measure **v_{in1}, v_{out1}, v_{out2} , $v_{odm} = v_{out1} - v_{out2}$** and **$v_{idm} = v_{in1} - v_{in2}$**. Calculate **the $A_{vdm\text{-}diff}$, $A_{vdm\text{-}se1}$ and $A_{vdm\text{-}se2}$**

Apply a sinusoidal source (V_{sin}) of 1 kHz frequency and amplitude of 4V at the base of Q1 and Q2 (i.e. $v_{in1} = v_{in2}$ =4Vp-p). **Measure v_{out1}, v_{out2}, and $v_{icm} = (v_{in1}+v_{in2})/2$.** Calculate the **$A_{vcm\text{-}se1}$ and $A_{vcm\text{-}se2}$**

d. Summarize the **simulation results in table form** and hand it in together with the calculations and the **simulation print-outs.** Label each graph clearly.

4. Read the experiment.

Experimental Work:

Before constructing the circuit, verify the values of the resistors that you are going to use by measuring their resistances with a multimeter. Make sure that all resistors are within 2% of their marked values. This will assure that your current measurements are accurate.

*****Oscilloscope channels should be AC coupling for entire experiment*****

Construct the amplifier circuit in Fig.6 using the R_C and R_{REF} (Use 10kΩPOT for R_{REF}) values calculated in preliminary work and the following values :

V_{CC}	V_{EE}	R_A	C	R_B	R_{POT}
15 V	-15 V	2.2 kΩ	100 µF	2.2 kΩ	500 Ω

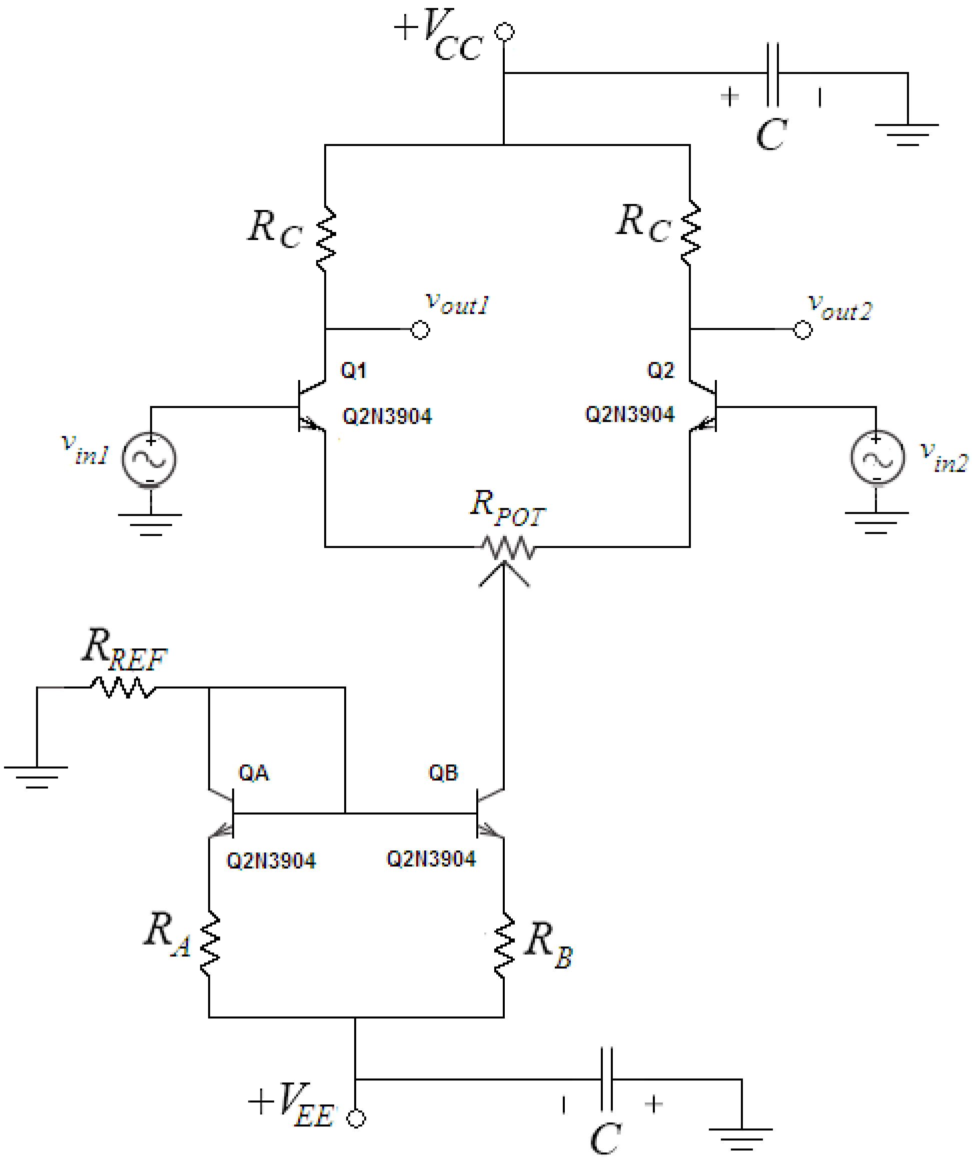

figure6

Note: Bypass capacitors are used to reduce noise.

1. Ground both v_{in1} and $v_{in2.}$ Measure I_{CQA}, I_{CQB}, V_{CE1}, and V_{CE2}. If $V_{CE1,2}$ is not equal to approximately 6V, but $I_{CQA,B}$ = 2mA and $V_{BE1,2} \approx 0.7$V, adjust R_{POT} until $V_{CE1,2}$ is almost 6V. Due to the differences in resistors R_C and the differences in β, the potentiometer is necessary to balance the differential pair. Record the aforementioned bias voltages and currents and momentarily take out the potentiometer R_{POT} and measure the resistance on each side. Also, measure and record the value of $I_{CQ1,2}$ and $V_{C1,2}$.

I_{CQA} = $\qquad$ I_{CQB} =

V_{CE1} = $\qquad$ V_{CE2} =

I_{CQ1} = $\qquad$ I_{CQ2} =

V_{C1} = $\qquad$ V_{C2} =

2. Apply a small signal input of 100mVp-p with a frequency of 1kHz at the base of Q. Leave v_{in2} grounded. Measure and record the single-ended output voltages v_{out1} and v_{out2} and calculate the differential circuit single ended gain. Note which is in phase and which is out of phase with v_{in1}.

v_{out1} =

v_{out2} =

$A_{vdm\text{-se1}}$ = $\qquad$ $A_{vdm\text{-se2}}$ =

3. Now connect the small signal input of 100mVp-p with a frequency of 1kHz to v_{in2} and ground v_{in2}. Now measure and record the single-ended output voltages v_{out1} and v_{out2} and calculate the differential circuit single ended gain. Note which is in phase and which is out of phase with v_{in2}.

v_{out1} =

v_{out2} =

$A_{vdm\text{-se1}}$ = $\qquad$ $A_{vdm\text{-se2}}$ =

4. For Laboratory 2 Using the same circuit from Step 2, connect channel 1 of the oscilloscope to v_{out1} and channel 2 of the oscilloscope to v_{out2}. Make sure that the volts/division adjustments are the same for both channels. Press the **Math** key to open the Math menu. Press the **CH1-CH2** softkey to have the oscilloscope subtract v_{out2} from v_{out1}. Now measure and record the differential mode output v_{odm}=v_{out1}-v_{out2}. This will allow for the calculation of the differential voltage gain:

$$A_{vdm-diff} = \frac{v_{odm}}{v_{idm}} = \frac{v_{out1} - v_{out2}}{v_{in}}$$

$v_{out1} - v_{out2}$ = $\qquad$ $A_{vdm\text{-diff}}$ =

4. For Laboratory 1 Using the same circuit from Step 2, connect channel 1 of the oscilloscope to v_{out1} and channel 2 of the oscilloscope to v_{out2}. Make sure that the volts/division adjustments are the same for both channels. Pull the position y button to get the inverse of the signal at channel 2 then turn the mode to add to have the oscilloscope subtract v_{out2} from v_{out1}. Now measure and record the differential mode output $v_{odm}=v_{out1}-v_{out2}$. This will allow for the calculation of the differential voltage gain:

$$A_{vdm-diff} = \frac{v_{odm}}{v_{idm}} = \frac{v_{out1} - v_{out2}}{v_{in}}$$

v_{out1} - v_{out2} =

$A_{vdm\text{-diff}}$ =

5. Now connect a sinusoidal input (8.0Vp-p @1kHz) to both v_{in1} and v_{in2}, this connection will allow for common-mode measurements. Measure and record the single-ended common-mode output voltages at v_{out1} and v_{out2} and calculate the common mode circuit single ended gain.

v_{out1} =
v_{out2} =

$A_{vcm\text{-se1}}$ =

$A_{vcm\text{-se2}}$ =

6. Using the data obtained for the single-ended common-mode gain and the differential circuit single-ended gain (either measurement), calculate the Common Mode Rejection Ratio (CMRR) for the differential pair amplifier. Compare this with the calculated value in the Preliminary work.

CMRR =

7. Did the calculated bias currents and voltages correspond to the measured values obtained in the experiment? Note any differences and note what the different resistances were on each side of the resistor R_{POT}, were the resistor values drastically different (more than 100Ω apart.)?

8. Did the voltage gains for each circuit at 1kHz correspond to the calculated values from the Preliminary work? Note any differences.

Experiment Instruments:	**Experiment Components:**
• Breadboard • Oscilloscope • Signal Generator • Multimeter • DC Power Source	4 2N3904 2 2.2 kΩ 1 500Ω POT 1 10k POT 2 100 μF

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Experiment Results

Part1	I_{CQA} = I_{CQB} = V_{CE1} = V_{CE2} = I_{CQ1} = I_{CQ2} = V_{C1} = V_{C2} =	
Part2	v_{out1} = v_{out2} =	
Part3	v_{out1} = v_{out2} =	
Part4	v_{out1} - v_{out2} =	
Part5	v_{out1} = v_{out2} =	
Part6	CMRR =	