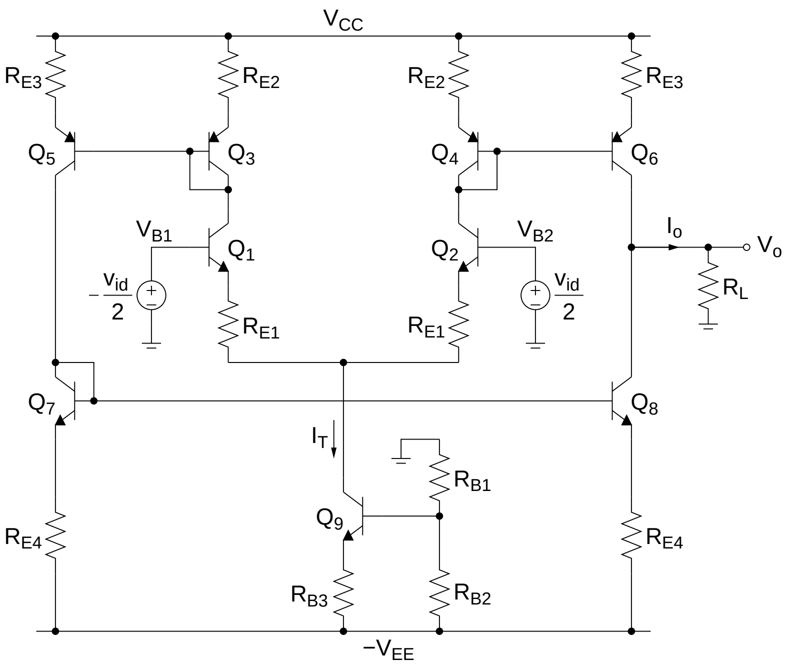
ECEN 326 Lab 7
Design of a BJT Operational Transconductance Amplifier

Circuit Topology

The operational transconductance amplifier (OTA) schematic that will be designed in this lab is shown in Fig. 1.



Matching transistors:
$Q_1 = Q_2$
$Q_3 = Q_4$
$Q_5 = Q_6$
$Q_7 = Q_8$

	NPN 2N3904	**PNP** 2N3906
β	140	180
V_A	75 V	20 V

Figure 1: Operational transconductance amplifier (OTA) schematic.

DC Biasing and Large-Signal Analysis:

Assuming $I_{B9} \ll I_{R_{B2}}$, the tail current source (I_T) can be calculated from

$$I_T \approx \frac{\frac{R_{B2}}{R_{B1}+R_{B2}} V_{EE} - 0.7}{R_{B3}} \tag{1}$$

Collector currents of $Q_1 - Q_4$ for $V_{id} = 0$ can be found as

$$I_{C1-C4} \approx \frac{I_T}{2} \tag{2}$$

If the ratio of I_5 to I_3 is less than an order of magnitude, then $V_{EB5} \approx V_{EB3}$, therefore,

$$I_{C5} R_{E3} = I_{C3} R_{E2} \quad \Rightarrow \quad \frac{I_{C5}}{I_{C3}} \approx \frac{R_{E2}}{R_{E3}} \tag{3}$$

An OTA is commonly used in the open-loop configuration. For proper operation, the maximum differential input amplitude $|v_{id,max}|$ needs to be determined. With emitter degeneration resistors R_{E1}, $|v_{id,max}|$ can be approximately found as

$$|v_{id,max}| = I_T R_{E1} \tag{4}$$

A more accurate limit can be defined by a maximum distortion specification. It is also necessary to determine what range of common-mode input voltages will allow all transistors in the input stage to remain in the active region. Defining the minimum collector-emitter voltage for the active operation as $V_{CE,sat}$, the range of V_{CM} can be approximately given by

$$V_{CC} - I_T R_{E2} - V_{CE,sat} > V_{CM} > -V_{EE} + I_T R_{B3} + V_{CE,sat} + I_T R_{E1} + V_{BE,on} \tag{5}$$

AC Small-Signal Analysis:

Since the circuit is not symmetrical, half-circuit concepts will not be useful. Figure 2 shows the AC small-signal equivalent circuit to determine the equivalent transconductance

$$G_m = \frac{-i_{sc}}{v_{id}} \tag{6}$$

where the output resistances (r_o) of transistors are assumed to be infinite.

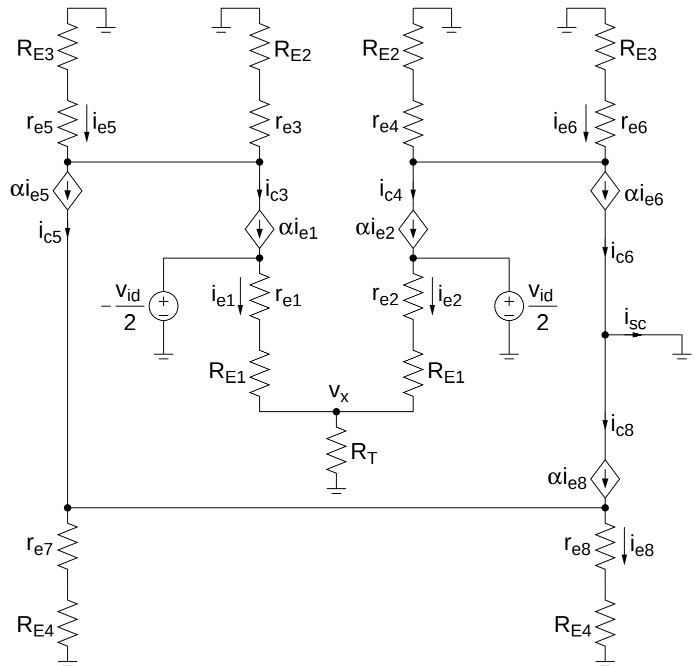


Figure 2: Small-signal circuit of the OTA.

KCL at v_x yields

$$\frac{v_x}{R_T} + \frac{v_x - \left(-\frac{v_{id}}{2}\right)}{r_{e1} + R_{E1}} + \frac{v_x - \left(\frac{v_{id}}{2}\right)}{r_{e2} + R_{E1}} = 0 \tag{7}$$

Since Q_1 and Q_2 are identical, $r_{e1} = r_{e2}$, resulting in

$$\frac{v_x}{R_T} + \frac{v_x}{r_{e1} + R_{E1}} + \frac{v_x}{r_{e2} + R_{E1}} = 0 \;\Rightarrow\; v_x = 0 \tag{8}$$

Therefore, v_x is a virtual AC ground for differential input signals. The collector current of Q_6 can be found as follows:

$$i_{c4} = \alpha i_{e2} \approx \frac{v_{id}/2}{R_{E1} + r_{e2}} \tag{9}$$

$$i_{c6} \approx \frac{i_{c4}(R_{E2} + r_{e4})}{R_{E3} + r_{e6}} = \frac{v_{id}}{2}\,\frac{1}{R_{E1} + r_{e2}}\,\frac{R_{E2} + r_{e4}}{R_{E3} + r_{e6}} \tag{10}$$

Similarly, i_{c5} and i_{c8} can be found as

$$i_{c5} \approx -\frac{v_{id}}{2}\,\frac{1}{R_{E1} + r_{e1}}\,\frac{R_{E2} + r_{e3}}{R_{E3} + r_{e5}} \tag{11}$$

$$i_{c8} \approx i_{c5}\frac{R_{E4} + r_{e7}}{R_{E4} + r_{e8}} \tag{12}$$

Since Q_7 and Q_8 are identical, $r_{e7} = r_{e8}$, which yields

$$i_{c8} \approx -\frac{v_{id}}{2} \frac{1}{R_{E1} + r_{e1}} \frac{R_{E2} + r_{e3}}{R_{E3} + r_{e5}} \tag{13}$$

The short-circuit output current (i_{sc}) can be determined as

$$i_{sc} = i_{c6} - i_{c8} = \frac{v_{id}}{2} \frac{1}{R_{E1} + r_{e2}} \frac{R_{E2} + r_{e4}}{R_{E3} + r_{e6}} - \left(-\frac{v_{id}}{2} \frac{1}{R_{E1} + r_{e1}} \frac{R_{E2} + r_{e3}}{R_{E3} + r_{e5}} \right) \tag{14}$$

Using the matching data, $r_{e2} = r_{e1}$, $r_{e4} = r_{e3}$, $r_{e6} = r_{e5}$,

$$i_{sc} = v_{id} \frac{1}{R_{E1} + r_{e2}} \frac{R_{E2} + r_{e4}}{R_{E3} + r_{e6}} \tag{15}$$

$$\tag{16}$$

$$G_m = -\frac{1}{R_{E1} + r_{e2}} \frac{R_{E2} + r_{e4}}{R_{E3} + r_{e6}} \tag{17}$$

The differential input resistance can be found as

$$R_{id} = 2(\beta + 1)(r_{e2} + R_{E1})$$

The output resistance can be expressed as

$$R_o \approx (g'_{m6} r_{o6} R'_{E3} + r_{o6}) \parallel (g'_{m8} r_{o8} R'_{E4} + r_{o8}) \tag{18}$$

$$g'_{m6} = g_{m6} \frac{r_{\pi 6}}{r_{\pi 6} + r_{e4} + R_{E2}}, \quad R'_{E3} = R_{E3} \parallel (r_{\pi 6} + r_{e4} + R_{E2}) \tag{19}$$

$$g'_{m8} = g_{m8} \frac{r_{\pi 8}}{r_{\pi 8} + r_{e7} + R_{E4}}, \quad R'_{E4} = R_{E4} \parallel (r_{\pi 8} + r_{e7} + R_{E4}) \tag{20}$$

We may construct an equivalent small-signal model for the OTA as shown in Fig. 3.

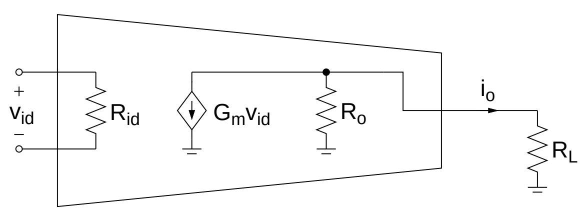


Figure 3: Equivalent small-signal model of the OTA.

Calculations and Simulations

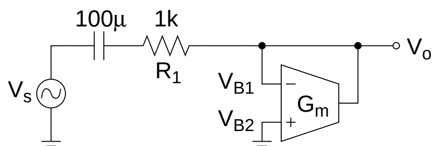
Design an OTA with the following specifications:

$V_{CC} = V_{EE} = 5\ V$	$G_m = 1mA/V$	Operating frequency: 1 kHz
$\lvert v_{id,max} \rvert \geq 2V$	$V_{CM,max} - V_{CM,min} \geq 4V$	$I_{supply} \leq 5mA$

1. Show all your calculations and final component values.
2. Calculate R_{id} and R_o for your design.
3. Verify your results using a circuit simulator (use 2N3904 and 2N3906 transistors). Submit all necessary simulation plots showing that the specifications are satisfied. Also provide the circuit schematic with DC bias points annotated.

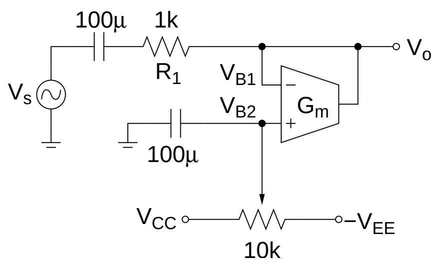
Measurements

1. Construct the OTA you designed.
2. Set $V_{id} = 0$ and record all DC quiescent voltages and currents.
3. Measure I_{supply} and the short-circuit output current while $V_{id} = 0$.
4. Apply differential input signals to the OTA.
5. Connect a $1k\Omega$ resistor between the output node and ground and measure G_m.
6. Increase the input amplitude until nonlinearity occurs. Measure the width of the input linear range ($|v_{id,max}|$).
7. Ground V_{B2} and the output node, and measure the differential input resistance R_{id} at V_{B1}.
8. Using the circuit setup below, measure the transconductance (G_m) of your OTA.



$$\frac{V_o}{V_s} = \frac{1/G_m}{R_1 + (1/G_m)}$$

9. Connect the OTA as shown in the figure below and set the amplitude of V_s to $|v_{id,max}|$. While monitoring V_o vs. V_s, vary the potentiometer in both directions until nonlinearity occurs. Measure and record the DC voltage at V_{B2} at the two settings of the potentiometer where distortion occurs. Record these two measurements as $V_{CM,max}$ and $V_{CM,min}$.



$$\frac{V_o}{V_s} = \frac{1/G_m}{R_1 + (1/G_m)}$$

Report

1. Include calculations, schematics, simulation plots, and measurement plots.
2. Prepare a table showing calculated, simulated and measured results.
3. Compare the results and comment on the differences.

Demonstration

1. Construct the OTA you designed on your breadboard and bring it to your lab session.
2. Your name and UIN must be written on the side of your breadboard.
3. Submit your report to your TA at the beginning of your lab session.
4. Apply differential input signals to the OTA, connect a $1k\Omega$ resistor between the output node and ground, and measure G_m.
5. Measure $|v_{id,max}|$, $V_{CM,max}$ and $V_{CM,min}$.