ECEN 326 LAB 7
Design of a BJT Operational Transconductance Amplifier

1 Circuit Topology

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

![Schematic Diagram](image)

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

<table>
<thead>
<tr>
<th></th>
<th>NPN</th>
<th>PNP</th>
</tr>
</thead>
<tbody>
<tr>
<td>β</td>
<td>140</td>
<td>180</td>
</tr>
<tr>
<td>$V_A$</td>
<td>75 V</td>
<td>20 V</td>
</tr>
</tbody>
</table>

DC Biasing and Large-Signal Analysis:
Assuming $I_{B9} \ll I_{R_{B2}}$, the tail current source ($I_T$) can be calculated from

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

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

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

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

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

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

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

$$V_{CC} - I_T R_{E2} - V_{CE,sat} > V_{CM} > -V_{EE} + I_T R_{E3} + V_{CE,sat} + I_T R_{E1} + V_{BE,on} \quad (5)$$

**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

$$G_m = \frac{-i_{sc}}{v_{id}} \quad (6)$$

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

![Small-signal circuit of the OTA.](image)

KCL at $v_x$ yields

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

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

$$\frac{v_x}{R_T} + \frac{v_x}{r_{e1} + R_{E1}} + \frac{v_x}{r_{e2} + R_{E1}} = 0 \Rightarrow v_x = 0 \quad (8)$$

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

$$i_{c6} = \alpha i_{c2} \approx \frac{v_{id}/2}{R_{E1} + r_{e2}} \quad (9)$$

$$i_{c6} \approx \frac{i_{e4} (R_{E2} + r_{e4})}{R_{E3} + r_{e6}} = \frac{v_{id}}{2} \frac{1}{R_{E1} + r_{e2}} \frac{R_{E2} + r_{e4}}{R_{E3} + r_{e6}} \quad (10)$$
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, \(r_{e2} = r_{e1}, r_{e4} = r_{e3}, r_{e6} = r_{e5}\),

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

\[
G_m = -\frac{1}{R_{E1} + r_{e2}} \frac{R_{E2} + r_{e4}}{R_{E3} + r_{e6}} \tag{16}
\]

The differential input resistance can be found as

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

The output resistance can be expressed as

\[
R_o \approx (g_{m6} r_{e6} R'_{E3} + r_{e6}) \parallel (g_{m8} r_{e8} R'_{E4} + r_{e8}) \tag{18}
\]

\[
g_{m6} = g_{m6} \frac{r_{e6}}{r_{e6} + r_{e4} + R_{E2}}, \quad R'_{E3} = R_{E3} \parallel (r_{e6} + r_{e4} + R_{E2}) \tag{19}
\]

\[
g_{m8}' = g_{m8}' \frac{r_{e8}}{r_{e8} + r_{e7} + R_{E4}}, \quad R'_{E4} = R_{E4} \parallel (r_{e8} + r_{e7} + R_{E4}) \tag{20}
\]

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.](image)

### 2 Pre-Lab

Design an OTA with the following specifications:

\[
V_{CC} = V_{EE} = 5 \, \text{V} \quad G_m = 1 \, \text{mA/V} \quad \text{Operating frequency: } 1 \, \text{kHz}
\]

\[
|v_{id,max}| \geq 2 \, \text{V} \quad V_{CM,max} - V_{CM,min} \geq 4 \, \text{V} \quad I_{supply} \leq 5 \, \text{mA}
\]

1. Show all your calculations and final component values.
2. Calculate $R_{id}$ and $R_o$ for your design.

3. Verify your results using PSPICE (use Q2N3904 and Q2N3906 transistors). Submit all necessary simulation plots showing that the specifications are satisfied. Also provide the circuit schematic with DC bias points annotated.

4. Be prepared to discuss your design at the beginning of the lab period with your TA.

3 Lab Procedure

1. Construct the OTA you designed in the pre-lab.

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. Using a 1:1 center-tapped transformer, apply differential input signals to the amplifier as shown below:

5. Connect a $1k\Omega$ resistor between the output node and ground. Using the XY mode of the scope, monitor $V_o$ vs. $V_{B1}$. Measure the slope and calculate the resulting $G_m$.

6. Increase the input amplitude until nonlinearity occurs. Measure and record the width of the input linear range ($|v_{id,max}|$).

7. Disconnect the transformer, 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 and record the transconductance ($G_m$) of your OTA.

9. Connect the OTA as shown in the figure below and set the amplitude of $V_s$ to $|v_{id,max}|$. Using the XY mode of the scope, monitor $V_o$ 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 $V_{CM,min}$.

10. Prepare a data sheet showing your simulated and measured values.

11. Be prepared to discuss your experiment with your TA. Have your data sheet checked off by your TA before leaving the lab.