ECEN326: Electronic Circuits
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Lecture 6: Operational Transconductance Amplifiers (OTAs)

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Announcements

- HW4 due today
- HW5 due 11/1
OpAmps and OTAs

- High voltage gain
- High input impedance
- Voltage source output (low impedance)

OpAmp

- High “voltage” gain
- High input impedance
- Current source output (high impedance)

OTA
Simple OTA

- Important Parameters
  - Transconductance
  - Output Resistance
  - Differential Gain
  - Common-Mode Input Range
From Lecture 3

\[ v_{Thev} = -g_{mn}r_{ON}(v_{in1} - v_{in2}) \text{ and } R_{Thev} = 2r_{ON} \]

To find \( i_{sc} \), we need to find \( i_p \) and \( i_n \)

\[ i_p = g_{m4}v_A \]

\[ v_A = \frac{1}{g_{m3}} \left( \frac{1}{r_{O3}} - g_{mn}r_{ON}(v_{in1} - v_{in2}) \right) \approx -\frac{g_{mn}}{2g_{m3}}(v_{in1} - v_{in2}) \]

\[ i_p = g_{m4}v_A = -\frac{g_{mn}}{2}(v_{in1} - v_{in2}) \]

\[ i_n = \frac{-g_{mn}r_{ON}(v_{in1} - v_{in2})}{2r_{ON} + \frac{1}{g_{m3}}} \approx -\frac{g_{mn}}{2}(v_{in1} - v_{in2}) \]

\[ i_{sc} = i_p + i_n = -g_{mn}(v_{in1} - v_{in2}) \]

\[ G_m = \frac{i_{sc}}{v_{in1} - v_{in2}} = -g_{mn} \]
Simple OTA Transconductance: Informal Virtual Ground Approach

- As the differential circuit is not purely symmetric, we cannot formally assume a virtual ground at node P.
- However, if the differential pair transistors M1 and M2 have high output resistance, a virtual ground can be approximated at node P to simplify the analysis.

\[ i_n = g_{m2}v_{in2} \]

Assuming an ideal current mirror load

\[ i_p = -g_{m1}v_{in1} \]

\[ i_{sc} = i_p + i_n = -g_{m1}v_{in1} + g_{m2}v_{in2} \]

\[ G_m = \frac{i_{sc}}{v_{in1} - v_{in2}} = -\frac{g_{m1}v_{in1} + g_{m2}v_{in2}}{v_{in1} - v_{in2}} = -g_{mn} \]
Simple OTA Output Resistance

\[ R_{out} = r_{Op} \parallel r_{On} \]

It is often useful to also use the output conductance

\[ G_{out} = \frac{1}{R_{out}} = g_{op} + g_{on} \]
Simple OTA Differential Gain

\[ A_v = -G_m R_{out} = -(-g_{mn}) (r_{On} \parallel r_{Op}) \]

\[ A_v = g_{mn} (r_{On} \parallel r_{Op}) = \frac{g_{mn}}{g_{op} + g_{on}} \]
Simple OTA Common-Mode Input Range

- Common-mode input range set by transistor saturation conditions
  - Low-end set by tail current source saturation
    \[ V_{icm} \geq V_{DSAT5} + V_{GS1} = \sqrt{\frac{2I_{SS}}{W}} + \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L_5}}} + V_{TH,n1} \]
  - High-end set by differential pair saturation
    \[ V_{icm} \leq V_{ocm} + V_{TH,n1} = V_{DD} - |V_{GS3}| + V_{TH,n1} = V_{DD} - \left( \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L_3}}} + |V_{TH,p3}| \right) + V_{TH,n1} \]

\[
\sqrt{\frac{2I_{SS}}{W}} + \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L_5}}} + V_{TH,n1} \leq V_{icm} \leq V_{DD} - \left( \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L_3}}} + |V_{TH,p5}| \right) + V_{TH,n1}
\]
Bipolar Simple OTA

• Following a similar procedure

\[
G_m = -g_{mn} \\
R_{out} = r_{On}||r_{Op} \\
A_v = g_{mn}(r_{On}||r_{Op}) = \frac{g_{mn}}{g_{on} + g_{op}}
\]

• Low-end \( V_{icm} \) set by keeping tail current source in active mode

\[
V_{icm} \geq V_{CE,sat} + V_{BE,on} \approx 0.3V + 0.7V = 1V
\]

• High-end \( V_{icm} \) set by keeping differential pair in active mode

\[
V_{CE1} = V_{CC} - V_{BE,on} - (V_{icm} - V_{BE,on}) \geq V_{CE,sat} \\
V_{icm} \leq V_{CC} - V_{CE,sat} \approx V_{CC} - 0.3V
\]
3 Current Mirror OTA

- While \( G_m \) has increased by the current mirror factor \( B \), the voltage gain remains the same due to the output resistance being reduced by \( B^{-1} \)

- Common-mode input range expression remains the same as the previous simple OTA

\[
\begin{align*}
i_p &= -B g_m v^+ \\
i_n &= B g_m v^- \\
i_{sc} &= i_p + i_n = -B g_m v^+ + B g_m v^- \\
G_m &= \frac{i_{sc}}{v^+ - v^-} = -B g_m \\
R_{out} &= \frac{r_{Op} \parallel r_{O1}}{B} = \frac{1}{B} \left( r_{Op} \parallel r_{O1} \right) \\
G_{out} &= B \left( g_{op} + g_{o1} \right) \\
A_v &= g_m \left( r_{Op} \parallel r_{O1} \right)
\end{align*}
\]
In order to improve the distortion performance, emitter resistors have been added in the input differential pair.

In order to improve the output resistance, emitter resistance has been added to all the current mirror/source transistors.

Assuming a 1:1 ratio for all the current mirrors, $G_m$ is set by the degenerated $G_m$ of the input transistors:

$$G_m = -\frac{\alpha}{r_{e1} + R_{E1}} \approx -\frac{1}{r_{e1} + R_{E1}}$$
Bipolar 3 Current Mirror OTA w/ Degenerated $G_m$ (Lab 7)

$$R_{out} \approx \left( g'_{m6} r_{o6} R'_{E3} + r_{o6} \right) \left( g'_{m8} r_{o8} R'_{E4} + r_{o8} \right)$$

$$g'_{m6} = g_{m6} \frac{r_{\pi6}}{r_{\pi6} + r_{e4} + R_{E2}} \approx g_{m6}, \quad R'_{E3} = R_{E3} \| (r_{\pi6} + r_{e4} + R_{E2}) \approx R_{E3} \| r_{\pi6}$$

$$g'_{m8} = g_{m8} \frac{r_{\pi8}}{r_{\pi8} + r_{e7} + R_{E4}} \approx g_{m6}, \quad R'_{E4} = R_{E4} \| (r_{\pi8} + r_{e7} + R_{E4}) \approx R_{E4} \| r_{\pi8}$$
Bipolar 3 Current Mirror OTA w/ Degenerated G_m (Lab 7)

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

- Low-end \( V_{icm} \) set by keeping tail current source in active mode

\[ V_{icm} \geq -V_{EE} + I_T R_{B3} + V_{CE,\text{sat}} + \frac{I_T}{2} R_{E1} + V_{BE,\text{on}} \]

- High-end \( V_{icm} \) set by keeping differential pair in active mode

\[ V_{CE1} = V_{CC} - \frac{I_T}{2} R_{E2} - V_{BE,\text{on}} - (V_{icm} - V_{BE,\text{on}}) \geq V_{CE,\text{sat}} \]

\[ V_{icm} \leq V_{CC} - \frac{I_T}{2} R_{E2} - V_{CE,\text{sat}} \]

- Maximum differential input amp. for good distortion

\[ |v_{id,\text{max}}| = I_T R_{E1} \]
Simulating the 3 Current Mirror OTA

- To simulate differential amplifiers, use voltage-controlled voltage sources (VCVS or “E” elements) to generate the differential input signal and monitor the current through the load resistor.

Note: This example is designed for 2X the Lab 7 Gm.

Single-ended input source

DC voltage source to set input DC level

2 VCVS to generate differential inputs

Monitor I(RL)
Simulating Transconductance

- Set Inputs E1 Gain=0.5 and E2 Gain=-0.5
- With input source AC=1, simply plot the load resistor current I(RL) to get the transconductance.

Gain=0.5  Gain=-0.5

Single-ended input source
DC=0
AC=1

DC voltage source to set input DC level

Monitor I(RL)
Simulating Transconductance

- $G_m = 2.01\text{mA/V}$
Simulating Differential $R_{\text{ind}}$

- The differential input resistance is equivalent to the differential input ($V_i$) divided by the input current, where $I$ use the base current of $Q1$ or $I_B(Q1)$
- $R_{\text{ind}} = 159\, k\Omega$
Simulating THD

- Set input source to differential input amplitude spec
  - For Lab 7, that is 2V
- Check the THD at 3 different common-mode points
  - $V_{CM,\text{min}}$, $V_{CM,\text{max}}$

$V_{CM}=0V$

$V_{CM}=-2V$

$V_{CM}=2V$
Simulating Output Resistance

- Ground input source and apply an AC-coupled voltage stimulus at output
- With output source AC=1, plot the ratio of V(Vout) over the current through the coupling capacitor
Simulating $R_o$

- The output resistance is equivalent to the output stimulus $V(V_{out})$ divided by the output current, which is equal to the current through the output capacitor $I(C5)$
- $R_o = 25.4k\Omega$