Announcements

• HW4 Due Friday 10/22
Agenda

- Simple OTA Review
- Three Current Mirror OTA Parameters
- Three Current Mirror OTA w/ Cascode Output
OpAmps and OTAs

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

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

Transconductance \( G_m = g_m = \sqrt{\frac{Kp}{L_1}} \frac{W}{I_{TAIL}} \)

Output Conductance \( g_{out} = g_{o2} + g_{o6} = \frac{I_{TAIL}}{2} (\lambda_n + \lambda_p) \)

DC Gain \( A_v = G_m R_{out} = \frac{g_m}{g_{o2} + g_{o6}} = \frac{2}{\lambda_n + \lambda_p} \)

Dominant Pole \( \omega_{p1} = \frac{g_{o2} + g_{o6}}{C_L} \)

Non-Dominant Pole \( \omega_{p2} = \frac{g_{m6}}{C_M} \approx \frac{g_{mg}}{2C_{gss}} \)

Output Noise Current \( i_{on}^2 = 2 \left( \frac{8}{3} kT \right) \left( g_{m1} + g_{m6} \right) \)

Input Noise Voltage \( v_{in}^2 = 2 \left( \frac{8}{3} kT \right) \left( g_m \right) \left( 1 + \frac{g_{m6}}{g_{m1}} \right) \)

GBW \( = \frac{G_m}{C_L} = \sqrt{\frac{Kp}{L_1}} \frac{W}{I_{TAIL}} \frac{C_L}{C_L} \)

Slew Rate \( SR = \frac{I_{tail}}{C_L} \)
Basic Operational Transconductance Amplifier Topologies

(a) SINGLE-ENDED

(b)

(c) FULLY-DIFFERENTIAL

(d)
3 Current Mirror OTA

- Relative to Simple OTA
  - Factor of “B” increase in $G_m$, GBW, and SR
  - Same $A_v$
  - Slightly higher noise
  - Lower frequency non-dominant pole and third pole
  - $(B+1)$ times the power
OTA based on 3 current mirrors

Transconductance \( G_m = B g_{m1} = B \sqrt{\frac{K P_n W}{L_1}} I_{TAIL} \)

Output Conductance \( g_{out} = g_{on} + g_{op} = \frac{B I_{TAIL}}{2} (\lambda_n + \lambda_p) \)

DC Gain \( A_v = G_m R_{out} = \frac{B g_{m1}}{g_{on} + g_{op}} = \frac{2 \sqrt{\frac{K P_n W}{I_{TAIL} L_1}}}{\lambda_n + \lambda_p} \)

Dominant Pole \( \omega_{p1} = \frac{g_{on} + g_{op}}{C_L} \)

Non-Dominant Pole \( \omega_{p2} \approx \frac{g_{mp}}{C_{Mp}}(1 + B)C_{gsp} \)

Gain-Bandwidth \( GBW = \frac{G_m}{C_L} = \frac{B \sqrt{K P_n W I_{TAIL}}}{L_1 C_L} \)

Slew Rate \( SR = \frac{B I_{tail}}{C_L} \)
OTA based on 3 current mirrors

Transconductance $G_m = B g_{m1} = B \sqrt{K P_n \frac{W}{L_1}} \frac{I_{TAIL}}{L_1}$

Output Conductance $g_{out} = g_{on} + g_{op} = \frac{B I_{TAIL}}{2} (\lambda_n + \lambda_p)$

DC Gain $A_v = G_m R_{out} = \frac{B g_{m1}}{g_{on} + g_{op}} = \frac{2 \sqrt{K P_n W}}{\lambda_n + \lambda_p}$

Dominant Pole $\omega_{p1} = \frac{g_{on} + g_{op}}{C_L}$

Non-Dominant Pole $\omega_{p2} = \frac{g_{mp}}{C_{Mp}} \approx \frac{g_{mp}}{(1 + B) C_{gsp}}$

Gain-Bandwidth $GBW = \frac{G_m}{C_L} = \frac{B \sqrt{K P_n W}}{L_1} \frac{I_{TAIL}}{C_L}$

Slew Rate $SR = \frac{B I_{tail}}{C_L}$
3 Current Mirror OTA Noise

Output Noise Current \( i_{on}^2 = 2 \left( \frac{8}{3} kT \right) \left( B^2 g_{m1} + B^2 g_{mp} + B g_{mp} + g_{mn} \right) \)

Input Noise Voltage \( v_{in}^2 = 2 \left( \frac{8}{3} kT \right) \left( \frac{1}{g_{m1}} \right) \left( 1 + \frac{g_{mp}}{g_{m1}} \left( 1 + \frac{1}{B} \right) + \frac{g_{mn}}{B^2 g_{m1}} \right) \)
3 Current Mirror OTA w/ Cascode Output

- Relative to 3 Current Mirror OTA
  - Same $G_m$, GBW, and SR
  - $A_v$ increased by cascode $g_{mc}r_{oc}$ factor
  - Approximately same noise
  - Introduce two additional cascode non-dominant poles
  - Same power
Small Signal Analysis: Common-source Cascode Amplifier

AC analysis:

POLE AT $V_Y$

$\supset$ Non-dominant pole: $\approx$

$\omega_{PND} = \frac{g_{m1} + g_{mb1}}{C_{PY}}$

$\supset$ Dominant pole at $1/ R_{OUT} C_{OUT}$

$\supset$ Transfer function

$$\frac{V_{out}}{V_{in}} = \left( - \frac{g_{m1}}{g_{out}} \right) \left( \frac{1}{1 + s \frac{C_{out}}{g_{out}}} \right) \left( \frac{1}{1 + s \frac{C_{PY}}{g_{m1} + g_{mb1}}} \right)$$

Small signal circuit
Small Signal Analysis: Noise Level

For \(gm_{11}Z_{01} >> 1\)

\[
\begin{eqnarray*}
(V_{n,11})^2 & = & (g_{m11}/g_{m1})^2 V_{n,11}^2 \\
(g_{m11}Z_{01} << 1) & & \\
(g_{m11}Z_{01} >> 1) & & (g_{m1}/g_{m1})^2 V_{n,11}^2 \\
g_{m11}Z_{01} & = & g_{01}/C_{01} \\
\omega \text{ (rad/sec)} & &
\end{eqnarray*}
\]

\[
\begin{eqnarray*}
\frac{i_{d11}}{V_{n,11}} & = & \left( -\frac{g_{m11}}{1 + g_{m11}Z_{01}} \right) \\
V_{eqin,11}^2 & = & \left( \frac{g_{m11}}{1 + g_{m11}Z_{01}} \right)^2 V_{n,11}^2 \\
\text{For } g_{m11}Z_{01} >> 1 & & \\
\text{For } g_{m11}Z_{01} << 1 & & \\
\end{eqnarray*}
\]

- Cascode transistor noise can generally be neglected
OTA based on 3 current mirrors using cascode transistors

Transconductance \( G_m = Bg_{m1} = B \sqrt{KP_n \frac{W}{L_1} I_{TAIL}} \)

Output Conductance \( g_{out} = g_{on} + g_{op} \approx \frac{BI_{TAIL}}{2g_{mc}r_{oc}} (\lambda_n + \lambda_p) \)

DC Gain \( A_v = G_m R_{out} = \frac{Bg_{m1}g_{mc}r_{oc}}{g_{on} + g_{op}} = \frac{2}{\lambda_n + \lambda_p} \left( \frac{KP_n}{I_{TAIL}} \right) \frac{W}{L_1} (g_{mc}r_{oc}) \)

Dominant Pole \( \omega_{p1} = \frac{g_{on} + g_{op}}{g_{mc}r_{oc}C_L} \)

Non-Dominant Pole \( \omega_{p2} = \frac{g_{mp}}{C_{Mp}} \approx \frac{g_{mp}}{(1+B)C_{gsp}} \)

Gain-Bandwidth \( GBW = \frac{G_m}{C_L} = \frac{B}{\sqrt{KP_n \frac{W}{L_1} I_{TAIL}}} \)

Slew Rate \( SR = \frac{BI_{tail}}{C_L} \)

Current\( = (1+B)I_{TAIL} \)
3 Current Mirror OTA Noise

\[ i_{on}^2 = 2\left(\frac{8}{3}kT\right)\left(B^2g_{m1} + B^2g_{mp} + Bg_{mp} + g_{mn}\right) \]

\[ v_{in}^2 = 2\left(\frac{8}{3}kT\right)\left(\frac{1}{g_{m1}}\right)\left(1 + \frac{g_{mp}}{g_{m1}}\left(1 + \frac{1}{B}\right)\right) + \frac{g_{mn}}{B^2g_{m1}} \]

- Cascode transistor contribution can be neglected
- Approximately equal to 3 current mirror OTA noise
OTA based on 3 current mirrors using cascode transistors

\[
\begin{align*}
A_V & \approx \frac{B g_{m1} R_{out}}{2} \left[ \frac{1}{1 + s \left( \frac{(1+B)C_{GSP}}{g_{mP}} \right)} \left[ 1 + \frac{1}{1 + s \left( \frac{(1+\Delta)C_{GSCP}}{g_{mCP}} \right)} + \left( \frac{1}{1 + s \left( \frac{(1+\Delta)C_{GSCN}}{g_{mCN}} \right)} \right) \right] \right] \\
\text{Phase Margin is limited}
\end{align*}
\]
OTA based on 3 current mirrors using cascode transistors

Excess Phase is defined as (phase at 0 - phase at $\omega_u$)

Phase Margin = (180 – excess phase)

Gain margin = Gain measured at 180° excess phase
Next Time

- Folded Cascode OTA
- Two Stage Miller OTA