Announcements & Agenda

- HW4 due Wednesday 10/31
- Exam 2 Friday 11/2
- Simple OTA Review
- Three Current Mirror OTA Parameters
- Three Current Mirror OTA w/ Cascode Output
Operational Transconductance Amplifier

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

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

DC Gain \( A_v = G_m R_{out} = \frac{g_{m1}}{g_{o2} + g_{o6}} = \frac{2}{\lambda_n + \lambda_p} \sqrt{\frac{KP_n W}{I_{TAIL} L_1}} \)

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

Non-Dominant Pole \( \omega_{p2} = \frac{g_{m6}}{C_M} \approx \frac{g_{mg}}{2C_{gs6}} \)

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

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

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

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

(a) (b)

SINGLE-ENDED

(c) (d)

FULLY-DIFFERENTIAL
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 \( G_m = B g_{m1} = B \sqrt{\frac{K P_n}{L_1}} I_{TAIL} \)

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

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

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

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

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

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

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

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 \( GBW = \frac{G_m}{C_L} = \frac{B \sqrt{K P_n W}}{L_1 C_L} \)

Slew Rate \( SR = \frac{B I_{tail}}{C_L} \)
Output Noise Current $i_{on}^2 = 2\left(\frac{8}{3}kT\right)\left(B^2g_{m1} + B^2g_{mp} + Bg_{mp} + g_{mn}\right)$

Input Noise Voltage $v_{in}^2 = 2\left(\frac{8}{3}kT\right)\left(\frac{1}{g_{m1}}\right)\left(1 + \frac{g_{mp}}{g_{m1}}\left(1 + \frac{1}{B}\right) + \frac{g_{mn}}{B^2g_{m1}}\right)$
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 $V_Y$

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

$\Rightarrow \omega_{PND} = \frac{g_{m1} + g_{mb11}}{C_{PY}}$

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

$\Rightarrow$ Transfer function

$$\frac{vout}{vin} = \left( -\frac{g_{m1}}{g_{out}} \right) \left( \frac{1}{1 + s \frac{C_{out}}{g_{out}}} \right) \left( \frac{1}{1 + s \frac{C_{PY}}{g_{m1} + g_{mb11}}} \right)$$
Small Signal Analysis: Noise Level

Input referred Noise:

\[ \frac{i_{d1}}{v_{n11}} = \left( -\frac{g_{m11}}{1 + g_{m11}Z_{01}} \right) \]

\[ v_{eqin,11}^2 = \frac{\left( \frac{g_{m11}}{1 + g_{m11}Z_{01}} \right)^2}{\frac{g_{m1}}{2} - \frac{1}{Z_{01}^2}} v_{n,11}^2 \]

For \( g_{m11}Z_{01} \gg 1 \)

\[ v_{eqin,11}^2 = \frac{1}{\frac{g_{m1}}{2}Z_{01}^2} v_{n,11}^2 \]

In general \( Z_{01} = R_{01} \parallel 1/sC_{01} \)

\[ \frac{(g_{m11}/g_{m1})^2 V_{n,11}}{2} \]

\[ \frac{(g_{01}/g_{m1})^2 V_{n,11}}{2} \]

\[ g_{m11}Z_{01} \ll 1 \]

\[ g_{m11}Z_{01} \gg 1 \]

\[ \frac{g_{m11}}{g_{m1}} \]

\[ \frac{g_{01}}{C_{01}} \]

\[ \omega \text{ (rad/sec)} \]

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

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

Output Conductance \( g_{out} = \frac{g_{on}}{g_{mcn} r_{onen}} + \frac{g_{op}}{g_{mcp} r_{ocp}} \approx \frac{BI_{TAIL}}{2 g_{me} r_{oc}} \left( \lambda_n + \lambda_p \right) \)

DC Gain \( A_v = G_m R_{out} = \frac{B g_{m1} g_{mc} r_{oc}}{g_{on} + g_{op}} = \frac{2 \sqrt{K P_n W}}{\lambda_n + \lambda_p} \left( g_{mc} r_{oc} \right) \)

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

Slew Rate \( SR = \frac{BI_{tail}}{C_L} \)
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 \( v_{in}^2 = 2 \left( \frac{8}{3} kT \right) \left( \frac{1}{g_{m1}} \right) \left( 1 + \frac{g_{mp}}{g_{m1}} \left( 1 + \frac{1}{B} \right) + \frac{g_{mn}}{B^2 g_{m1}} \right) \)

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

\[ A_v \approx \frac{B g_{m1} R_{out}}{2} \frac{1}{1 + s (1 + B) C_{GSP} g_{mP}} \left[ 1 + s \left( \frac{1 + \Delta}{(1 + \Delta) C_{GSCP} g_{mcp}} + \frac{1}{1 + s \left( \frac{1}{1 + \Delta} C_{GSCN} g_{mcn}} + \frac{1}{1 + s \frac{2 C_{GSN}}{g_{mN}}}}\right) \right] \]

Phase Margin is limited
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