THE LAST CLASS ACT!

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Enhanced Output-Impedance Current Mirror

- Use feedback to keep $V_{ds}$ across $Q_2$ stable

$$R_{out} \equiv g_m r_{ds1} r_{ds1} (1 + A)$$

- Limited by parasitic conductance between drain and substrate of $Q_1$
Simplified Enhanced Output-Impedance Mirror

- Rather than build extra opamps, use above
- Feedback amplifier realized by common-source amplifier of $Q_3$ and current source $I_{B_1}$
Simplified Enhanced Output-Impedance Mirror

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\[
2V_{\text{eff}} + V_{tn}
\]
Simplified Enhanced Output-Impedance Mirror

- Assuming output impedance of $I_{B1}$ is equal to $r_{ds3}$, loop gain will be $(g_{m3} r_{ds3})/2$, resulting in

$$r_{out} \approx \frac{g_{m1} g_{m3} r_{ds1} r_{ds2} r_{ds3}}{2}$$ (9)

- Circuit consisting of Q4, Q5, Q6, $I_{in}$, and $I_{B2}$ operates like a diode-connected transistor — results in accurate matching of $I_{out}$ to $I_{in}$

- Note that shown circuit is NOT wide-swing — requires output to be $2V_{eff} + V_{tn}$ above lower supply
Wide-Swing with Enhanced Output Impedance

- Add wide-swing to improve output voltage swing

\[ I_{in} \approx 7I_{bias} \]

- Q3 and Q7 biased at 4 times current density — \(2V_{eff}\)
- Requires roughly twice power dissipation
- Might need local compensation capacitors
Folded-Cascode Opamp

- Compensation achieved using load capacitor
- As load increases, opamp slower but more stable
- Useful for driving capacitive loads only
- Large output impedance (not useful for driving resistive loads)
- Single-gain stage but dc gain can still be quite large (say 1,000 to 3,000)
- Shown design makes use of wide-swing mirrors
- Simplified bias circuit shown
- Inclusion of Q12 and Q13 for improved slew-rate
**Folded-Cascode Opamp**

\[
A_V = \frac{V_{out}(s)}{V_{in}(s)} = g_{m1}Z_L(s) \tag{10}
\]

\[
A_V = \frac{g_{m1}r_{out}}{1 + sr_{out}C_L} \tag{11}
\]

- \(r_{out}\) is output impedance of opamp (roughly \(g_m r_{ds}^2/2\))
- For mid-band freq, capacitor dominates

\[
A_V \approx \frac{g_{m1}}{sC_L} \tag{12}
\]

\[
\omega_t = \frac{g_{m1}}{C_L} \tag{13}
\]
Folded-Cascode Opamp

- Maximizing gm of input maximizes freq response (if not limited by second-poles)
- Choose current of input stage larger than output stage (also maximizes dc gain)
- Might go as high as 4:1 ratio
- Large input gm results in better thermal noise
- Second poles due to nodes at sources of Q5 and Q6
- Minimize areas of drains and sources at these nodes with good layout techniques
- For high-freq, increase current in output stage
Folded-Cascode Opamp
Folded-Cascode Slew-Rate

- If Q2 turned off due to large input voltage

\[ SR = \frac{I_{D4}}{C_L} \]  \hspace{1cm} (14)

- But if \( I_{\text{bias}_2} > I_{D3} \), drain of Q1 pulled near negative power supply
- Would require a long time to recover from slew-rate
- Include Q12 (and Q13) to clamp node closer to positive power supply
- Q12 (and Q13) also dynamically increase bias currents during slew-rate limiting (added benefit)
- They pull more current through Q11 thereby increasing bias current in Q3 and Q4
Folded-Cascode Example

Design Goals

- \(+/-2.5\text{V power supply and 2mW opamp with 4:1 ratio of current in input stage to output stage}\)
- Set bias current in Q11 to be \(1/30\) of Q3 (or Q4)
- Channel lengths of \(1.6\text{um}\) and max width of \(300\text{um}\) with \(V_{\text{eff}}=0.25\) (except input transistors)
- Load cap = \(10\text{pF}\)

Circuit Design

\[
I_{\text{total}} = 2(I_{D1} + I_{D6}) = 2(4I_B + I_B) = 10I_B
\]  
(15)

\[
I_B = I_{D5} = I_{D6} = \frac{I_{\text{total}}}{10} = \frac{(2\text{mW})/5\text{V}}{10} = 40\ \mu\text{A}
\]  
(16)

\[
I_{D3} = I_{D4} = 5I_{D5} = 200\ \mu\text{A}
\]  
(17)
\[ I_{D1} = I_{D2} = 4I_{D5} = 160 \, \mu A \]  

(18)

- To find transistor sizing:

\[
\left( \frac{W}{L} \right)_i = \frac{2I_{Di}}{\mu_i C_{ox} V_{effi}^2}
\]  

(19)

Rounding to nearest factor of 10 (and limiting to 300μm width) results in

\[
\begin{array}{cccccc}
Q_1 & 300/1.6 & Q_6 & 60/1.6 & Q_{11} & 10/1.6 \\
Q_2 & 300/1.6 & Q_7 & 20/1.6 & Q_{12} & 10/1.6 \\
Q_3 & 300/1.6 & Q_8 & 20/1.6 & Q_{13} & 10/1.6 \\
Q_4 & 300/1.6 & Q_9 & 20/1.6 & & \\
Q_5 & 60/1.6 & Q_{10} & 20/1.6 & & \\
\end{array}
\]

- Widths of \( Q_{12} \) and \( Q_{13} \) were somewhat arbitrarily chosen to equal the width of \( Q_{11} \)

- Transconductance of input transistors
\[ g_{m1} = \sqrt{2^{1_{D1}} \mu_n C_{ox}(W/L)_1} = 2.4 \text{ mA/V} \quad (20) \]

- Unity-gain frequency

\[ \omega_t = \frac{g_{m1}}{C_L} = 2.4 \times 10^8 \text{ rad/s} \Rightarrow f_t = 38 \text{ MHz} \quad (21) \]

- Slew rate \textit{without} clamp transistors

\[ \text{SR} = \frac{I_{D4}}{C_L} = 20 \text{ V/\mu s} \quad (22) \]

- Slew rate \textit{with} clamp transistors

\[ I_{D12} + I_{D3} = I_{bias2} = 320 \mu A \quad (23) \]

\[ I_{D3} = 30I_{D11} \quad (24) \]

\[ I_{D11} = 6.6 \mu A + I_{D12} \quad (25) \]
• Solving above results in
\[ I_{D11} = 10.53 \, \mu A \]  
which implies
\[ I_{D3} = I_{D4} = 30I_{D11} = 0.32 \, mA \]
leading to slew-rate
\[ SR = \frac{I_{D4}}{C_L} = 32 \, V/\mu s \]

• More importantly, time to recover from slew-rate limiting is decreased.
Folded-Cascode Opamp

Q11

Q12

Q1

Q2

Q3

Q4

Q5

Q6

Q7

Q8

Q9

Q10

V_{in}

V_{B1}

V_{B2}

I_{bias1}

I_{bias2}

I_{bias3}

I_{bias4}

CL

V_{out}

6.66\mu A

300/1.6

10/1.6

20/1.6

200\mu A

40\mu A

40\mu A

40\mu A

320\mu A

300/1.6

300/1.6

60/1.6

60/1.6
Fully Differential Folded-Cascode Opamp

- Q1
- Q2
- Q3
- Q4
- Q5
- Q6
- Q7
- Q8
- Q9
- Q10
- Q11
- Q12
- V_{in}
- V_{out}
- I_{bias}
- V_{B1}
- V_{B2}
- V_{B3}
- V_{cntrl}
- CMFB circuit
Other Fully-Diff Opamps

These fully diff op-amps also need CMFB

Using 2 single-ended opamps

Rail-to-rail input common-mode range
Common-Mode Feedback Circuits

- Balanced signal on Vout does not affect Vctrl
- Does not depend on small-signal analysis
Common-Mode Feedback Circuits

\[ V_A = V_{CM} - (V_{eff1} + V_{t1}) \]
\[ V_{ref} = -(V_{eff1} + V_{t1}) \]

- Limited differential swing
- Should ensure CMFB loop is stable
Common-Mode Feedback Circuits

- Useful for switched-capacitor circuits
- Caps Cs set nominal dc bias at bottom of Cc
- Large output signal swing allowed
HAVE A GREAT SUMMER!!!!!!