High Gain

- Goal of opamp design – High gain
- Previous opamps do not have very high gain
- Example – 5T Opamp
  - Gain = \(-g_{m1}r_{o2}\parallel r_{04}\)
  - Subthreshold operation – |Gain| \(\approx 650\)
  - Above threshold operation – |Gain| \(\approx 50\)
- Need much higher gain
  - Cascade structures provide high gain
  - Cascade of multiple amplifiers
Telescopic Opamps

\[ A_v = g_{m1} \left( r_{o2} g_{x4} r_{o4} \parallel r_{o8} g_{x6} r_{o6} \right) \]

Approximately the square of the original gain

This is a high-speed opamp design

Major Drawback
- Very limited allowable signal swing
- Must ensure all transistors stay in saturation
- Limited signal swing at both the input and the output
Telescopic Opamps – Single-Ended Output

- Increased output signal swing
- Requires an additional bias
Unity-Gain Feedback Connection

- Another major drawback to the telescopic opamp is the very limited range for unity-feedback connections
- Therefore, this opamp is rarely used as a unity-gain buffer
- Often used in switched-capacitor circuits, where the output is fed back to the input only for short durations of time

For M₂ and M₄ to stay in saturation

\[ V_{out} \leq V_x + V_{T2} = V_{b1} - V_{gs4} + V_{T2} \quad \text{for } M_2 \]
\[ V_{out} \geq V_{b1} - V_{T4} \quad \text{for } M_4 \]

\[ V_{b1} - V_{T4} \leq V_{out} \leq V_{b1} - V_{gs4} + V_{T2} \]

Voltage range for \( V_{out} \)

\[ V_{max} - V_{min} = V_{T4} - V_{gs4} + V_{T2} = V_{T2} - V_{ov4} \]

Always less than a threshold voltage
Folded Cascode Structure

Used in opamps to increase input/output voltage ranges

- $I_{\text{ref1}}$ is typically greater than $I_b$ to improve response after slewing
- Burns more power than the telescopic version

\[ I_{\text{ref3}} = \frac{I_b}{2} + I_{\text{ref1}} \]
Folded Cascode Opamp

\[ V_{i1} \rightarrow M_1 \rightarrow M_2 \rightarrow V_{i2} \]

\[ V_b \rightarrow M_b \]

\[ V_{o1} \rightarrow M_5 \rightarrow M_6 \rightarrow V_{o2} \]

\[ V_{b1} \rightarrow M_3 \rightarrow M_4 \]

\[ V_{b2} \rightarrow M_7 \rightarrow M_8 \]

\[ V_{b3} \rightarrow M_9 \rightarrow M_{10} \]

\[ V_{out} \rightarrow M_5 \rightarrow M_6 \]

\[ V_{out} \rightarrow M_3 \rightarrow M_4 \]
Differential Gain of the Folded Cascode Opamp

- Resistance looking into the source of $M_7$ is much less than $r_{o1} || r_{09}$
- Virtually all current flowing out of $M_1$ will flow into the source of $M_7$

$$A_v = g_{m1} \left[ (r_{o8} g_{x8} (r_{o10} || r_{o2})) || r_{o6} g_{x6} r_{o4} \right]$$

[Slightly] reduced gain from telescopic amplifier

ICMR

\[
V_{gs1} + V_{sat,b} \quad \text{to} \quad V_{dd} - V_{sat,9} - V_{sat,1} + V_{gs1} = V_{dd} - V_{ov,9} + V_{T1}
\]

Can use pFET inputs for operation to ground

Output range

$$2V_{sat} \quad \text{to} \quad V_{dd} - 2V_{sat}$$
Folded Cascode Summary

Comparison to Telescopic Opamp
• Larger input/output swings
• Can be used in unity-gain configuration
• One less voltage is required to be set
  • Do not need to worry about the CM voltage
• Decreased voltage gain
• Increased power consumption (plus, $I_g$ should be $\sim1.2$-$1.5$ times $I_b$)
• Lower frequency of operation
• More noise

Overall, the folded cascode opamp is a good, widely used opamp
Two-Stage Opamp

- Cascade of two amplifier stages
  - First stage – Differential amplifier
  - Second stage – High-gain amplifier
**Two-Stage Opamp (Single-Ended Output)**

- Cascade of two amplifier stages
  - First stage – Differential amplifier
  - Second stage – High-gain amplifier (CS Amp)

\[
A_{v1} = -g_{m1}r_{o2} \parallel r_{o4} \\
A_{v2} = -g_{m5}r_{o5} \parallel r_{o6} \\
A_v = (g_{m1}r_{o2} \parallel r_{o4})(g_{m5}r_{o5} \parallel r_{o6})
\]

- Large output swing (\(V_{\text{sat},6}\) to \(V_{dd} - V_{\text{sat},5}\))
- ICMR same as 5T opamp
- Unity-gain configuration sets a minimum voltage to \(V_{gs1} - V_{\text{sat},b}\)
- Can include cascodes, as well
- Adding an amplifier stage adds a pole
- Typically requires compensation to remain stable
If $F(s)=1$, then unity gain feedback
Opamp Poles

- Several poles in an opamp
- Typically, one pole dominates
  - Dominant pole is closest to the origin (Re-Im Plot)
  - Dominant pole has the largest time constant
- Dominant pole is often associated with the output node in an unbuffered opamp
  - Large Rout and load capacitance

Gain Bandwidth, GB

\[ GB = A_{v,dc} \omega_{-3dB} \]

\[ = \left(-G_m R_{out}\right) \left(\frac{-1}{R_{out}C_{out}}\right) \]

\[ = \frac{G_m}{C_{out}} \]
Multiple Poles

- For multi-pole systems, other poles may be close enough to the dominant pole to affect stability
- Typically two poles are of primary concern
- Typically, for a two-stage, unbuffered opamp
  - Pole at output of stage 1
  - Pole at output of stage 2
  - Dominant pole is usually associated with a large load capacitance (i.e. output node)
Multiple Poles

\[ V_{in} \xrightarrow{G_m V_{in}} V_x \xrightarrow{R_{out1}} C_{out1} \xrightarrow{G_{m2} V_x} V_{out} \]

\[ p_1 = \frac{-1}{R_1 C_1} \]

\[ p_2 = \frac{-1}{R_2 C_2} \]

\( p_2 \) typically dominates because of the load capacitance.
Multiple Poles

$|H(j\omega)|_{dB}$

$A_{v,dc}$

Unity Gain

Phase of $-180^\circ$

$log(\omega)$

$log(\omega)$

$-90^\circ$

$-180^\circ$

$arg(H(j\omega))$
Negative Feedback

In negative feedback configuration, if

\[ |H(j\omega)| \geq 1 \text{ and } \angle H(j\omega) = -180^\circ \]

Then, combined with subtraction (-180 °) at the input

- Results in -360 ° phase shift
- This is addition (positive feedback)
  - Since the gain is > 1 at this frequency, the output will grow without bound
  - Therefore, this system is unstable at this frequency

- For stability, must ensure that

\[ |H(j\omega)| < 1 \text{ for } \omega \text{ where } \angle H(j\omega) = -180^\circ \]
Phase Margin

• Typically, we like to design to provide a margin of error
  – These conditions (magnitude and phase) can deviate from their designed values due to processes like noise and temperature drift

• Phase margin
  – A measure of how far away from a complete 360° phase shift
  – Phase margin = 180° - arg(H(j\omega))
  – Measure at \omega where |H(j\omega)| = 1

• Typical designs call for Phase margins of greater than 45°
  – Often higher, e.g. 60° - 90°
Miller Compensation

- Need to spread the poles apart
- Add a capacitor from input to output of stage 2
Miller Compensation

\[
\frac{V_{out}(s)}{V_{in}(s)} = \frac{G_{m1}G_{m2}R_1R_2(1 - sC_2/G_{m2})}{s^2R_1R_2(C_1C_2 + C_cC_1 + C_cC_2) + s[R_1(C_1 + C_c) + R_2(C_2 + C_c) + G_{m2}R_1R_2C_c] + 1}
\]

\[
p_1 \approx -\frac{1}{G_{m2}R_1R_2C_c}
\]

\[
p_2 \approx -\frac{G_{m2}C_c}{C_1C_2 + C_2C_c + C_1C_c} \approx -\frac{G_{m2}}{C_2}
\]

If \( C_2 >> C_1 \) and \( C_c > C_1 \)
Miller Compensation

\[ |H(j\omega)|_{dB} \]

\[ A_{v,dc} \]

\[ \arg(H(j\omega)) \]

\[ \omega_2 \text{ should be } \geq \text{GB} \]

\[ \log(\omega) \]

\[ \log(\omega) \]

Phase Margin

\[ GB \approx \frac{G_{m1}}{C_c} \]
## Opamp Comparison

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