Outline

- Introduction
- Need for high gain
- Gain enhancement methods
  - Cross-coupled current mirror
  - Regulated current source
- Design methodology for high-gain op-amp
- Simulation Results
- Summary
Sensors

Healthcare Monitoring
Sensors

Structural Monitoring
Sensors

Weather & Agricultural Monitoring
...even in the iPhone

Accelerometer

Capacitive touch sensor

CCD sensors
The Role of Amplifiers

Circuitry for Signal Conditioning/Processing/Transmission

Signal amplification required

Sensor 
Produces low-level signal
Target Design Specifications

- **Gain:** >120 dB
- **Noise:** < 10nV/sqrt(Hz)
- **GBW:** Configurable
  - high speed
  - low speed
- **Power Consumption:** Low but variable
The Need for High Gain

\[ A = \frac{a}{1 + af} \]

\[ A \approx \frac{1}{f} \quad \text{for} \quad af \gg 1 \]

\[ \frac{dA}{A} = \frac{da}{a} \left( \frac{1}{1 + af} \right) \quad \rightarrow \text{desensitization} \]
Classical Miller Amplifier
Classical Miller Amplifier

Gain Required

> 120 dB
Gain Enhancement: Options

- Modify first stage
  - Cascode load
  - Folded-cascode
  - Cross-coupled current mirror
  - Regulated current source
Gain Enhancement: Options

- Modify first stage
  - Cascode: Reduced voltage headroom
  - Folded-cascode
  - Cross-coupled current mirror
  - Regulated current source
Gain Enhancement: Options

- Modify first stage
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Gain Enhancement: Cross Coupled Load
Cross Coupled Current Mirror Load

\[ G = A \left( \frac{1}{1 - \eta} \right) \]

- **Loop Gain**

\[ \eta = \frac{\Delta I_3}{\Delta I_{10}} = \frac{G_{m9}}{G_{m3}} \]

- **Effective Transconductance**

\[ G_m = \frac{G_{m1}}{1 - \eta} \]
Cross Coupled Load: Stability Issues

If $\eta \to 1$, amplifier can become unstable

If $\eta \to 0$, no gain improvement

Critical value of $\eta$ needs to be chosen
Cross Coupled Load: Stability Issues

\[ \frac{1}{1 - \eta} = \frac{1}{1 - (1 - 3\sigma)} = \frac{1}{3\sigma} \]

\[ \eta = \frac{G_{m9}}{G_{m3}} \approx \sqrt{\frac{I_{F3}}{I_{F9}}} \]

- 1/3\sigma: max. possible gain enhancement

- Susceptible to instability due to mismatch

\[ \sigma_{\eta}^2 = \frac{1}{4} \eta^2 (\sigma_{ID3}^2 + \sigma_{ID9}^2) + \sigma_{I_{spec3}}^2 + \sigma_{I_{spec9}}^2 \]

- Very carefully matched design required
Gain Enhancement: Options

- Modify first stage
  - Cascode: Reduced voltage headroom
  - Folded-cascode: Higher power consumption
  - Cross-coupled current mirror: Susceptible to instability
  - Regulated current source
Gain Enhancement: Options

- Modify first stage
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Gain Enhancement: Regulated Current Source
Gain Enhancement: Regulated Current Source
Regulated Current Source

\[ V_x \text{ tracks } V_y \]

\[ R_{out} \approx -1/g_{os} \]
Regulated Current Source

\[ R_{up} \approx -\frac{1}{g_{dsM3}} \]

\[ R_{dn} = \frac{1}{g_{dsM4}} \]

\[ R_{out} \to \infty \]
Regulated Current Source: Stability issues
Instability: A Detour

![Circuit Diagram]

![Frequency Response Graph]

- $f_1$, $f_2$, GBW, PM$\sim$0
Compensation

\[ v_{in} \quad g_{ml} \quad C_l \quad R_l \quad g_{ml} \quad C_{ll} \quad R_{ll} \quad v_{out} \]

\[ C_c \]

\[ \text{dB} \]

\[ f_1 \quad f_2 \quad \text{GBW} \quad f'_2 \]

\[ 0 \quad -90 \quad -180 \quad \text{deg} \quad \text{PM}=70 \]
Compensation

\[ f'_2 \geq 3 \times \text{GBW} \]
Compensation

\[ f'_2 \geq 3 \times \text{GBW} \]

\[ \frac{g_{\text{mlI}}}{g_{\text{ml}}} \geq 3 \times \frac{C_{\text{II}}}{C_c} \]
Regulated Current Source: Stability issues

\[
A(s) = \frac{A_0}{1 + sC_z/g_{oa}}
\]

\[
H_{OL}(s) = \frac{A_0 g_{m12}(g_{o4} - g_{o3})}{g_{ds12}(g_{ds12} + g_{o4})} \cdot \frac{1 + s(C_x - C_y)/(g_{o4} - g_{o3})}{(1 + s/p_x)(1 + s/p_y)(1 + s/p_z)}
\]

where \( p_x = (g_{o3} + g_{ds12})/C_x \), \( p_y = (g_{ds12} + g_{o3})/C_y \) and \( p_z = g_{oa}/C_z \).
Regulated Current Source: Stability issues

Frequency Response of Regulated Current Source Load

- M0 (65.77 MHz, 0 dB)
- M1 (95.77 MHz, -397.4°)

Gain (dB) vs. Frequency (Hz)
Regulated Current Source: Stability issues

\[ H_{OL}(s) = \frac{A_0 g_{m12}(g_{o4} - g_{o3})}{(g_{ds12} + g_{o3})(g_{ds12} + g_{o4})} \cdot \frac{(1 - s/z_1)(1 + s/z_2)}{(1 + s/p_x')(1 + s/p_y)(1 + s/p_z')} \]

where
- \( p_x' = g_{m12}/(C_x + C_y) \),
- \( p_z' = g_{oa}g_{ds12}/g_{m12}C_c \),
- \( z_1 = (g_{o4} - g_{o3})g_{m12}/C_c (g_{m12} + g_{o4}) \) and
- \( z_2 = g_{m12}/C_x \).
Regulated Current Source: Stability issues
Regulated Current Source: Stability issues

For stability:

\[ p_z \gg GBW_{main} \]

\[ \frac{g_o a g_{ds12}}{g_{m12} C_c} \gg GBW_{main} \]
Regulated Current Source: Stability issues

For stability:

\[
\frac{g_{oa}g_{ds12}}{g_{m12}C_c} \gg GBW_{main} \quad \Rightarrow \quad \frac{g_{ma12}g_{ds12}}{g_{m12}C_{caux}} \gg GBW_{main}
\]
Regulated Current Source: Stability issues

\[ \frac{g_{ma12}g_{ds12}}{g_{m12}C_{aux}} \gg GBW_{main} \]

\[ GBW_{aux} = \frac{g_{ma12}}{C_{aux}} \]

\[ GBW_{aux} \geq 4 \times GBW_{main} \]

- Stability condition
Regulated Current Source: Gain

\[ A_I = \frac{v_{out1} \cdot v_{in_{aux}}}{v_{in_{aux}} \cdot v_{in}} = \frac{A_0 \cdot g_{m2} \cdot g_{m34}}{(g_{ds2} + g_{ds4})^2} \]

\[ A_{II} = \frac{g_{m6}}{g_{ds6} + g_{ds7}} \]

\[ A_{total} = \frac{A_0 \cdot g_{m2} \cdot g_{m34} \cdot g_{m6}}{(g_{ds2} + g_{ds4})^2 \cdot (g_{ds6} + g_{ds7})} \]
Gain Enhancement: Options

- Modify first stage
  - Cascode: Reduced voltage headroom
  - Folded-cascode: Higher power consumption
  - Cross-coupled current mirror: Susceptible to instability
  - Regulated current source:
    - High gain
    - High dynamic
    - Can be systematically stabilized
The Op-Amp: Design Methodology

\[ GBW_{total} = \frac{g_{m34}}{C_c} \]

\[ \frac{g_{m6}}{g_{m34}} \geq 3 \frac{C_L}{C_c} \]

\[ GBW_{aux} \geq 4 GBW_{total} \]

\[ A_{total} = \frac{A_0 g_{m2} g_{m34}}{(g_{ds2} + g_{ds4})^2} \cdot \frac{g_{m6}}{g_{ds6} + g_{ds7}} \]
The Op-Amp: Design Methodology

- **Constraints**
  - Gain
  - Power
  - GBW
  - Load capacitance
  - Variable power/speed

- **Decisions/Discretion**
  - Current allocation between stages
  - Gain allocation between stages

- **Tools**
  - Design equations
  - $g_m/I_D$ method
The Op-Amp: Layout

Area = 0.16 mm$^2$
Layout Considerations

- Large device sizes
- Minimum distance b/w devices
- Symmetrical layout
- Same orientation
- Same environment
- Multi-finger transistors
- Common-centroid layout
Layout: PIP vs. MOSCAP
Simulation Results: Frequency Response


A Mangla

Master Project
Simulation Results: Transient Response

Slew Rate = 4.90 V/us
Settling time = 150 ns
Simulation Results: Transient Response

Feedback gain = 4
Simulation Results: CMRR

Simulation Results: PSRR

Simulation Results: Noise

![Graph showing Noise (nV/sqrt[Hz])](image)

- 1: 6
- 2: 15.2
- 3: 17.47
- 4: 27

References:
[2] This work
Simulation Results: Power Consumption


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Master Project
Simulation Results: Low Speed Mode

Power Consumption = 69 uW
# Performance Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Speed</th>
<th>Low Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage (V)</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Quiescent Current (μA)</td>
<td>210</td>
<td>23</td>
</tr>
<tr>
<td>DC Gain (dB)</td>
<td>143</td>
<td>155.4</td>
</tr>
<tr>
<td>GBW (MHz) (10 pF load)</td>
<td>7.98</td>
<td>0.86</td>
</tr>
<tr>
<td>Slew Rate (V/μs)</td>
<td>4.90</td>
<td>0.49</td>
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<tr>
<td>Settling time (ns)</td>
<td>150</td>
<td>2.7e3</td>
</tr>
<tr>
<td>Noise at 100 KHz (nV/√Hz)</td>
<td>15.2</td>
<td>51.7</td>
</tr>
<tr>
<td>CMRR (dB)</td>
<td>112.3</td>
<td>121.8</td>
</tr>
<tr>
<td>PSSR+ (dB)</td>
<td>116.2</td>
<td>126.1</td>
</tr>
<tr>
<td>PSRR- (dB)</td>
<td>121.7</td>
<td>130.6</td>
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<tr>
<td>Phase Margin (deg)</td>
<td>41</td>
<td>67</td>
</tr>
<tr>
<td>Output Swing (V)</td>
<td>2.78</td>
<td>2.78</td>
</tr>
<tr>
<td>Offset (mV) (100 run MC simulation)</td>
<td>1.95</td>
<td>4.37</td>
</tr>
</tbody>
</table>
Achievements

- Analysis of cross-coupled current mirror load
  - Gain
  - Stability
- Analysis of regulated current source load
  - Gain
  - Stability
- Unified design methodology for two-stage op-amp with regulated current source
- Complete op-amp design