Design of an Amplifier for Sensor Interfaces

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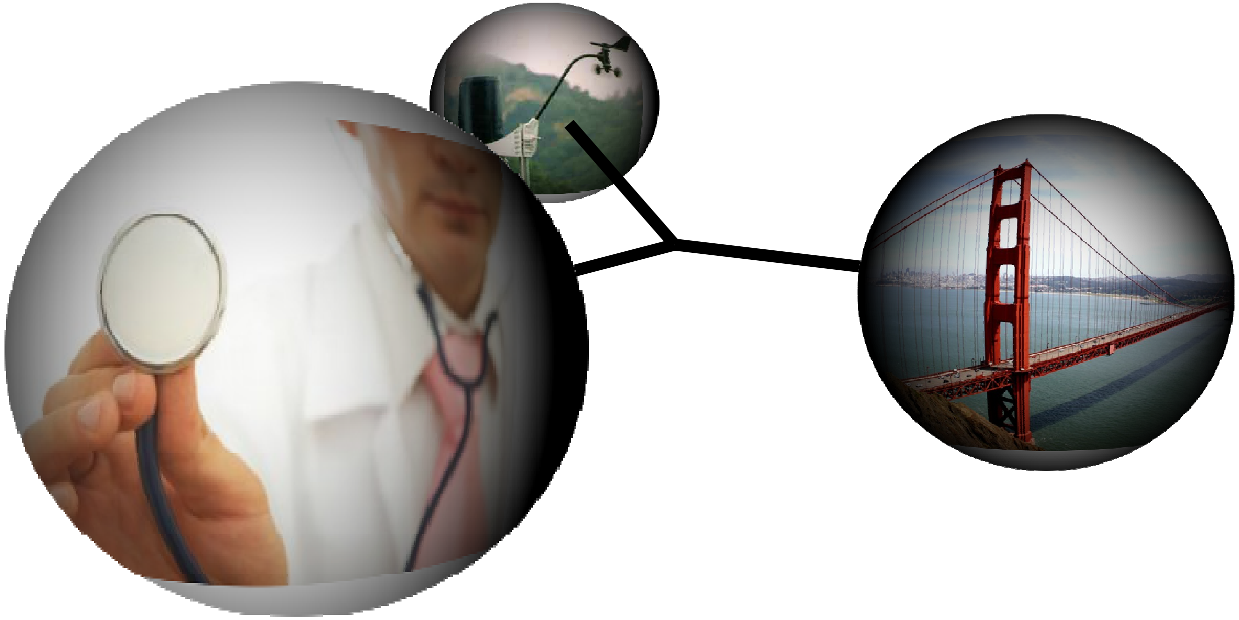
Outline

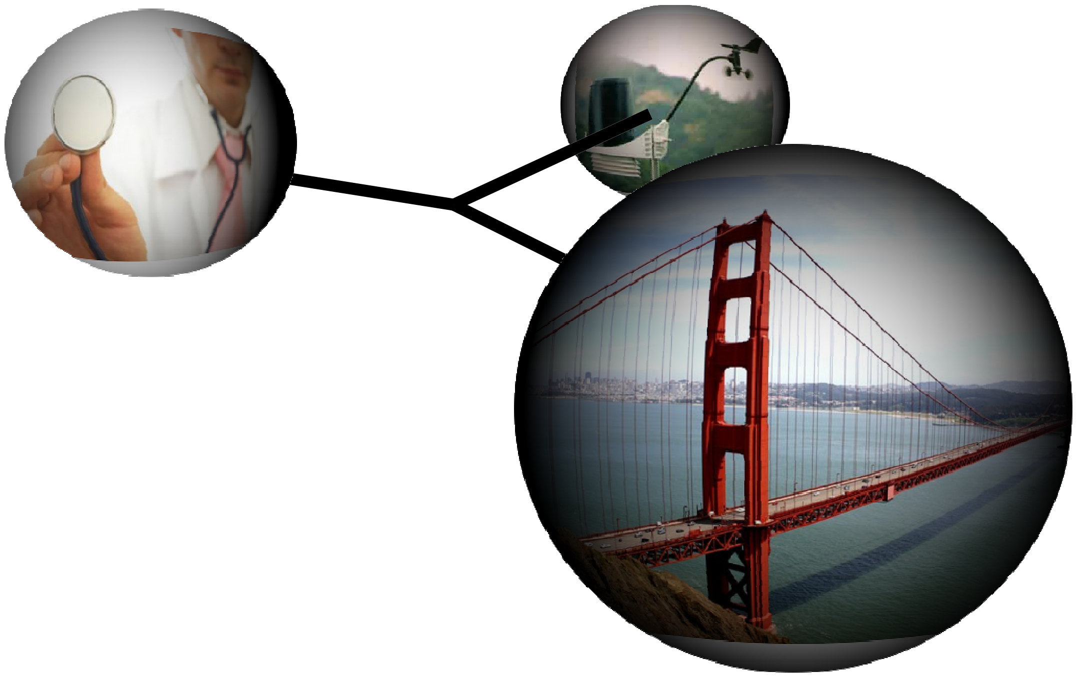
- Introduction
- Need for high gain
- Gain enhancement methods
  - Cross-coupled current mirror
  - Regulated current source
- Design methodology for high-gain op-amp
- Simulation Results
- Summary

Sensors



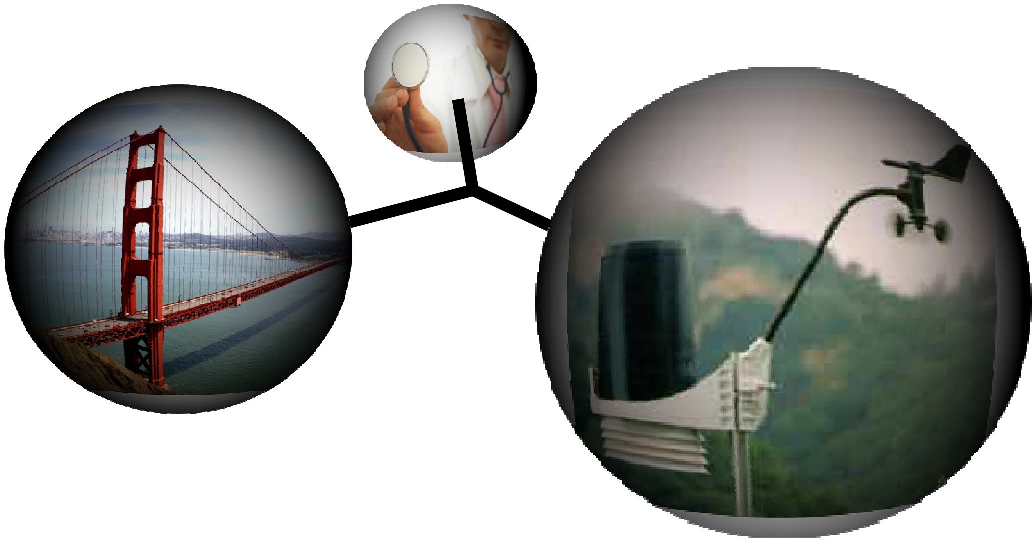
Healthcare Monitoring

Sensors



Structural Monitoring

Sensors



Weather & Agricultural Monitoring

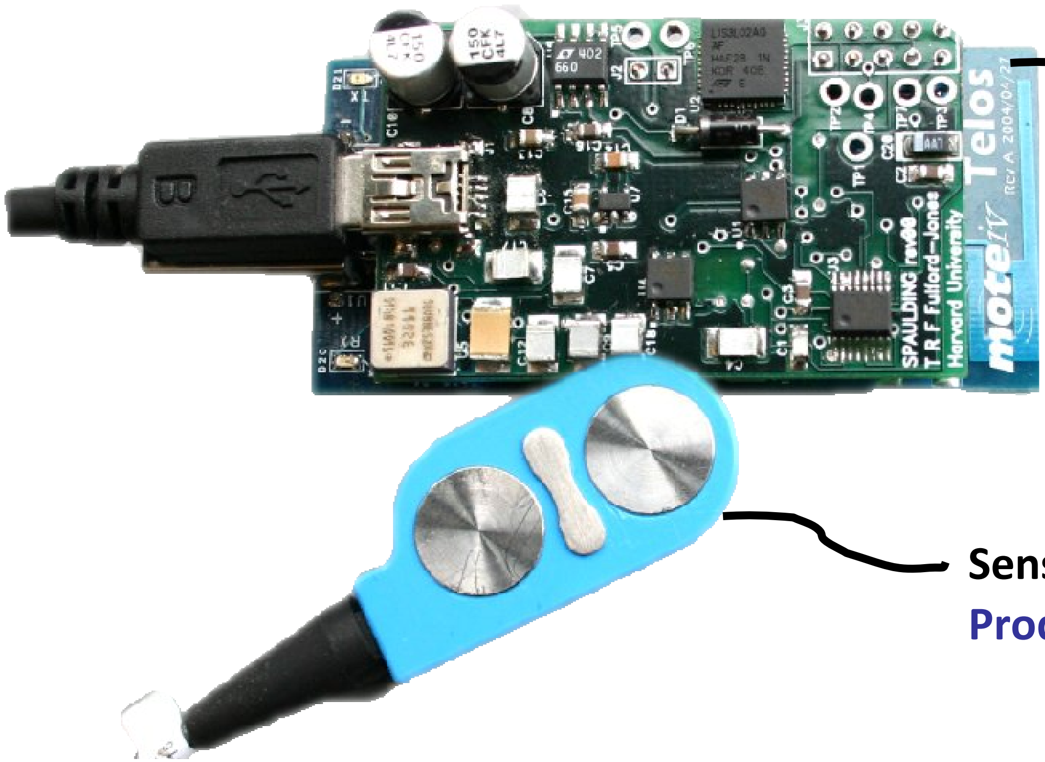
…even in the iPhone

Accelerometer

Capacitive touch sensor

CCD sensors

The Role of Amplifiers



Circuitry for
Signal Conditioning/
Processing/Transmission

Signal amplification required

Sensor
Produces low-level signal ⚠

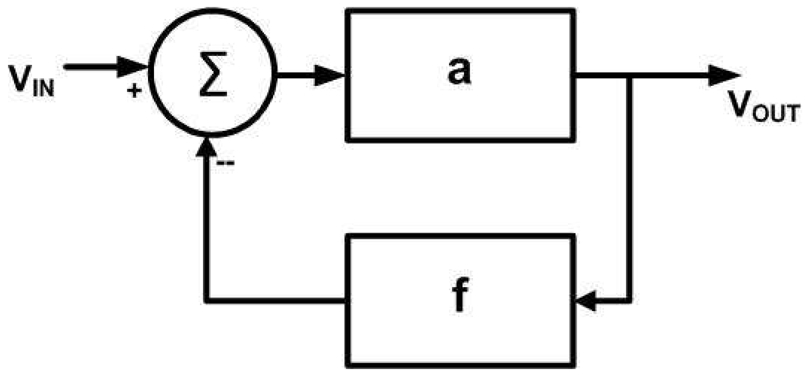
Target Design Specifications

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

The Need for High Gain

$$A = \frac{a}{1 + af}$$

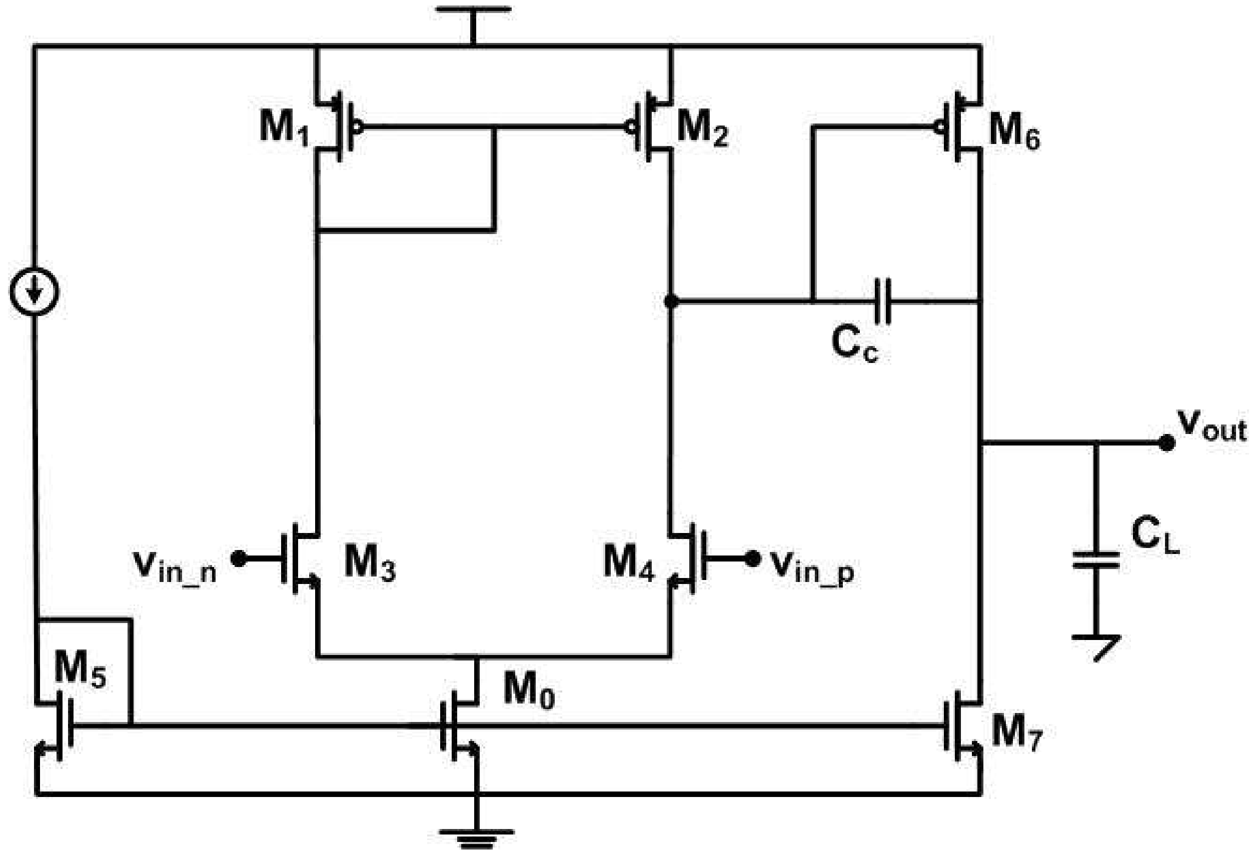
$$A \approx \frac{1}{f}$$ for af >> 1



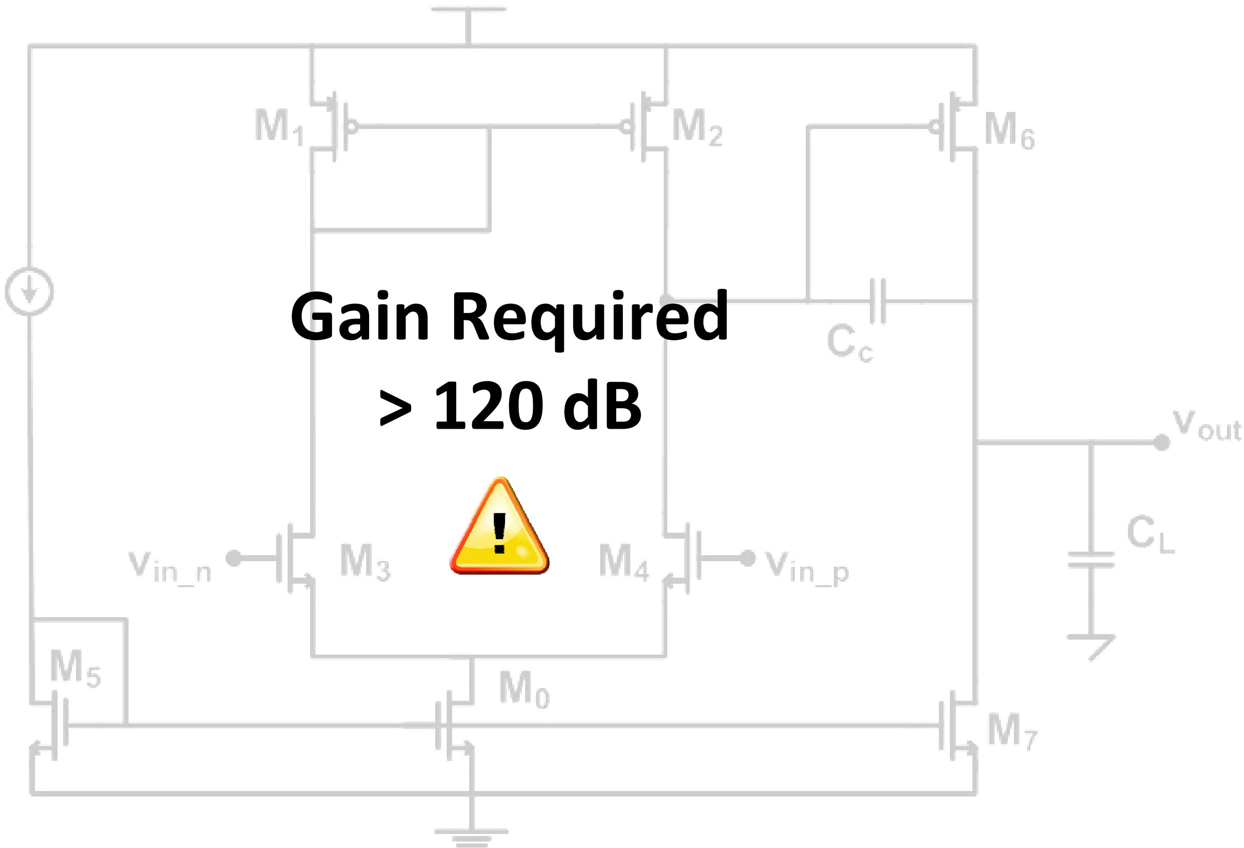
$$\frac{dA}{A} = \frac{da}{a}\left(\frac{1}{1 + af}\right)$$

-> 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
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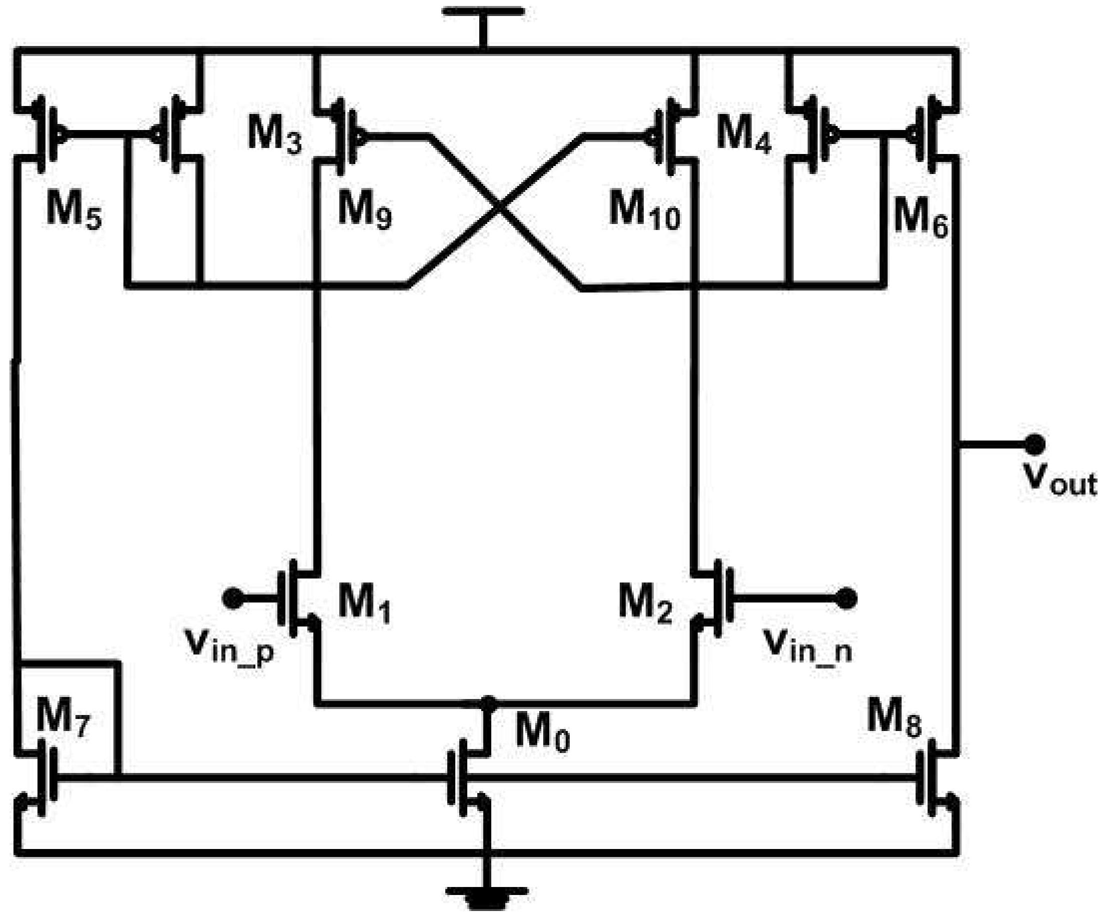
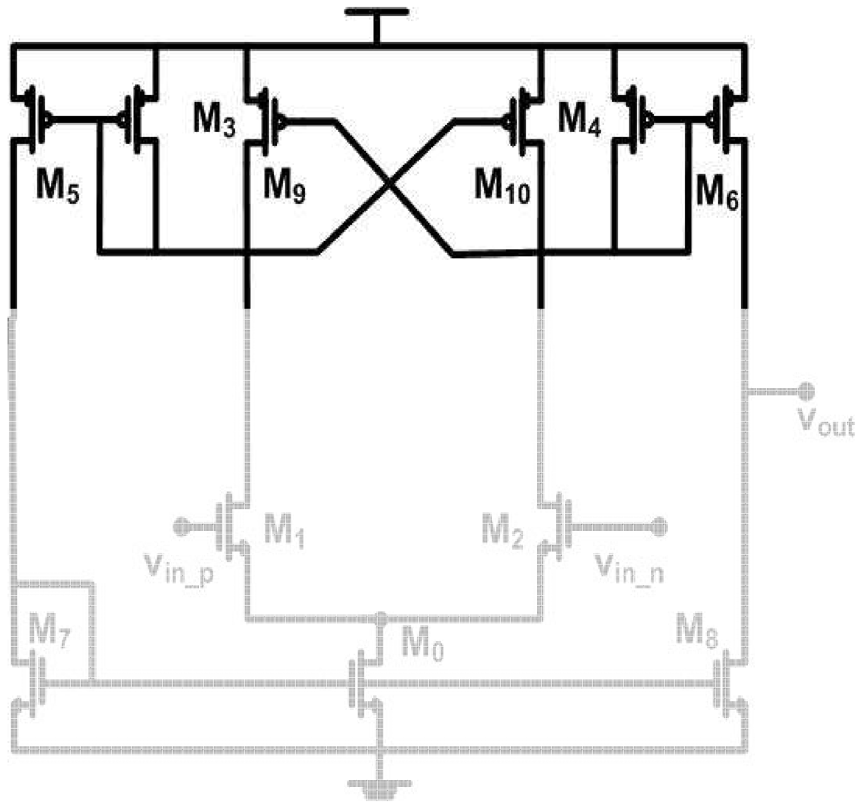
Gain Enhancement: Cross Coupled Load



Cross Coupled Current Mirror Load



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

$$\eta = \frac{\Delta I_3}{\Delta I_{10}} = \frac{G_{m9}}{G_{m3}}$$ **Loop Gain**

$$G_m = \frac{G_{m1}}{1-\eta}$$ **Effective Transconductance**

Cross Coupled Load: Stability Issues

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

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

- If η -> 1, amplifier can become unstable
- If η -> 0, no gain improvement
- Critical value of η needs to be chosen

Cross Coupled Load: Stability Issues

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

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

$$\sigma_{\eta}{}^{2} = \frac{1}{4}\eta^{2}(\sigma_{ID3}{}^{2} + \sigma_{ID9}{}^{2}) + \sigma_{Ispec3}{}^{2} + \sigma_{Ispec9}{}^{2}$$

- 1/ 3σ : max. possible gain enhancement
- Susceptible to instability due to mismatch
- 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

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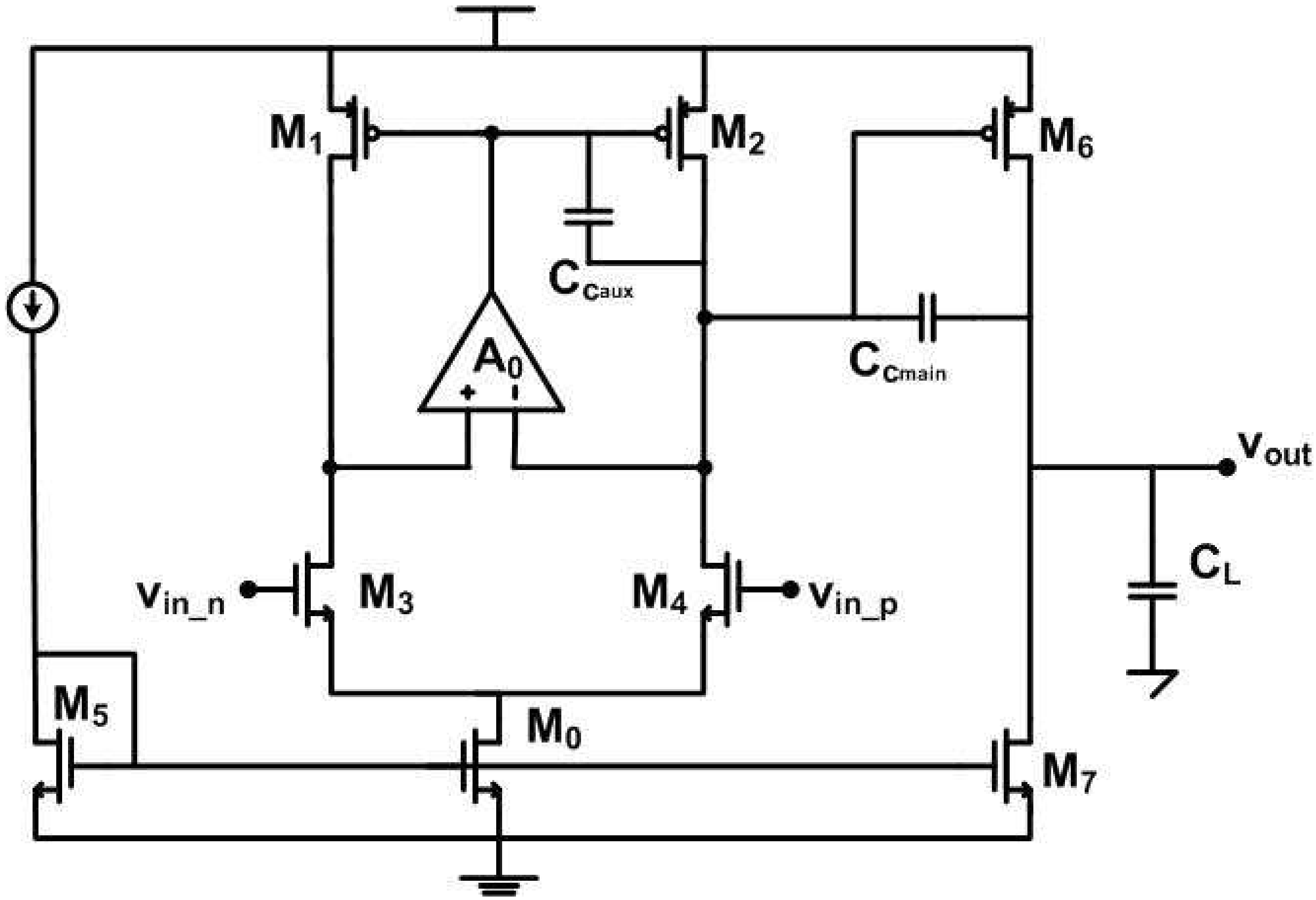
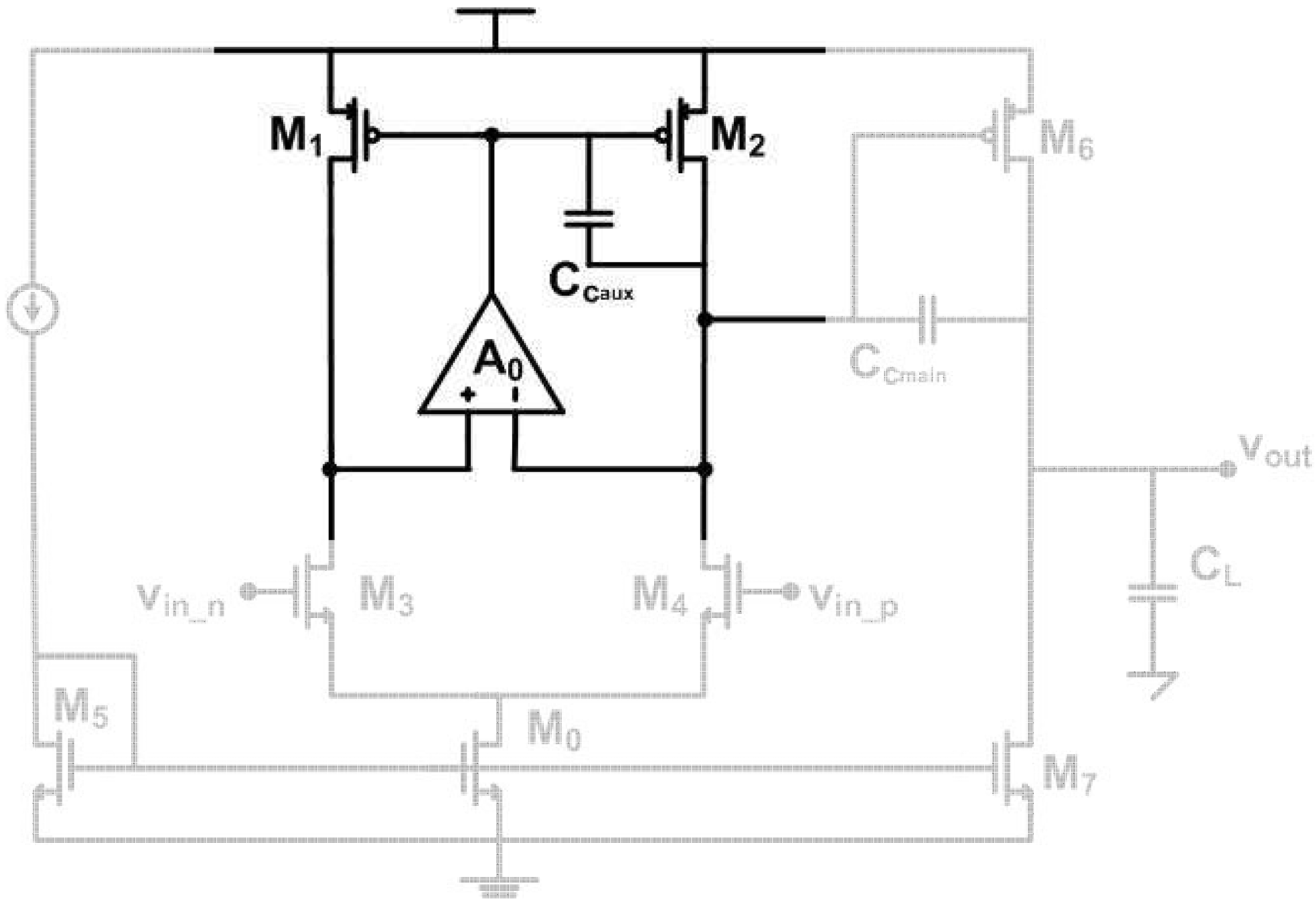
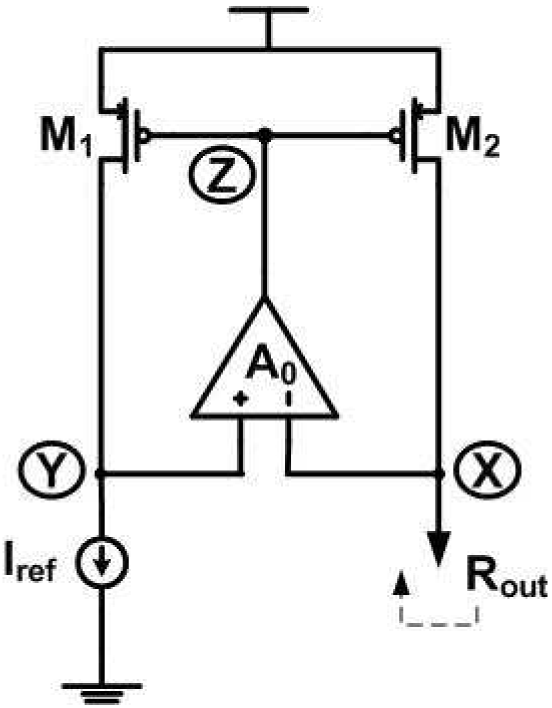
Gain Enhancement: Regulated Current Source

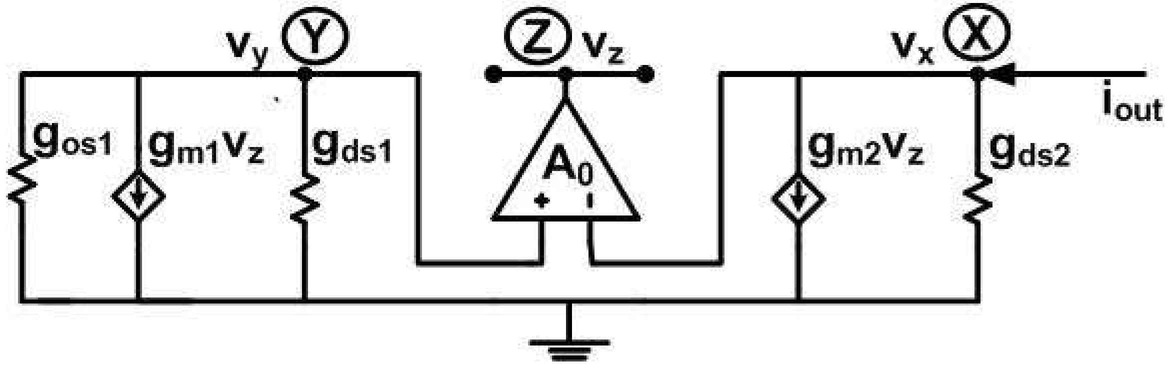


Gain Enhancement: Regulated Current Source



Regulated Current Source

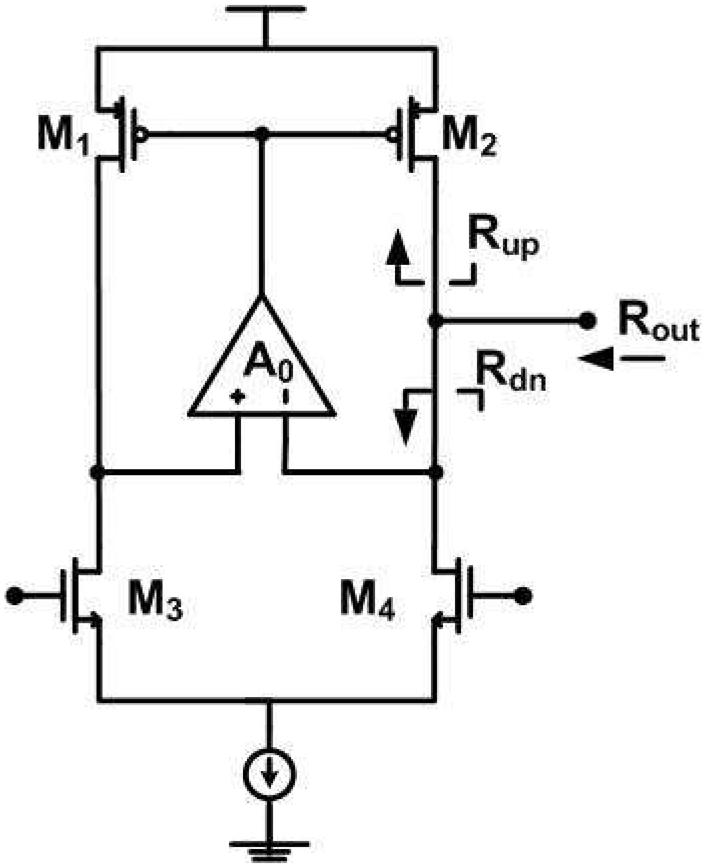




V_x tracks V_y

$$R_{out} \approx -1/g_{os}$$

Regulated Current Source

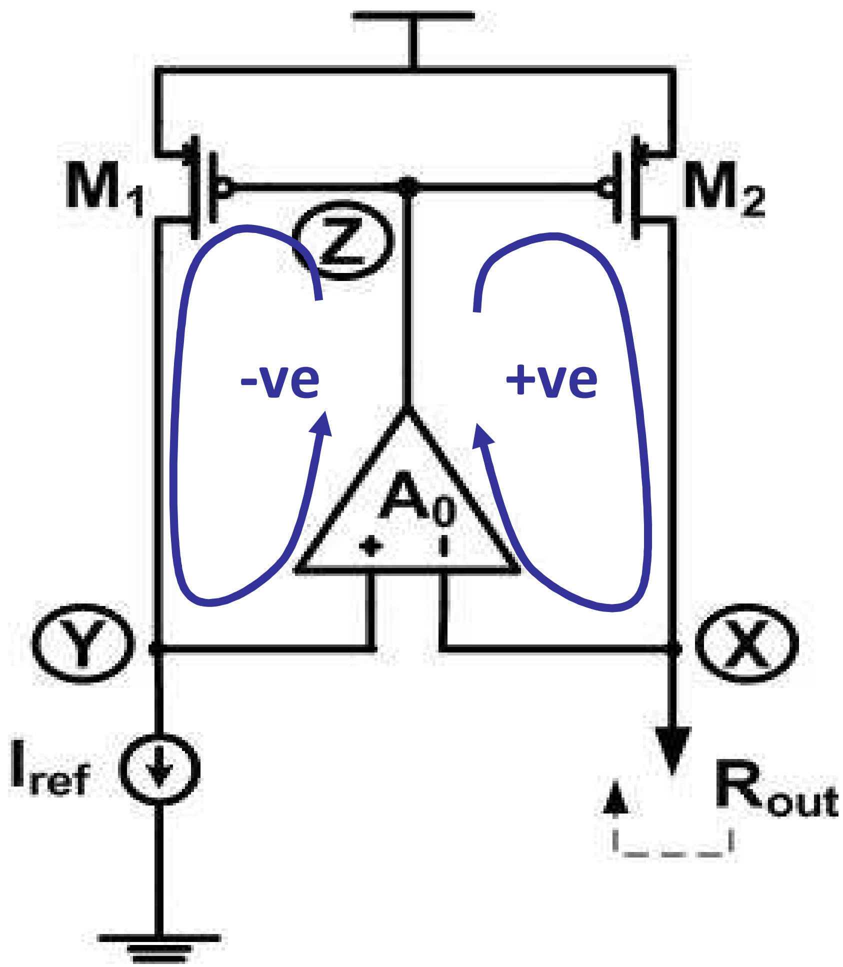


$$R_{up} \approx -\frac{1}{g_{ds_{M_3}}}$$

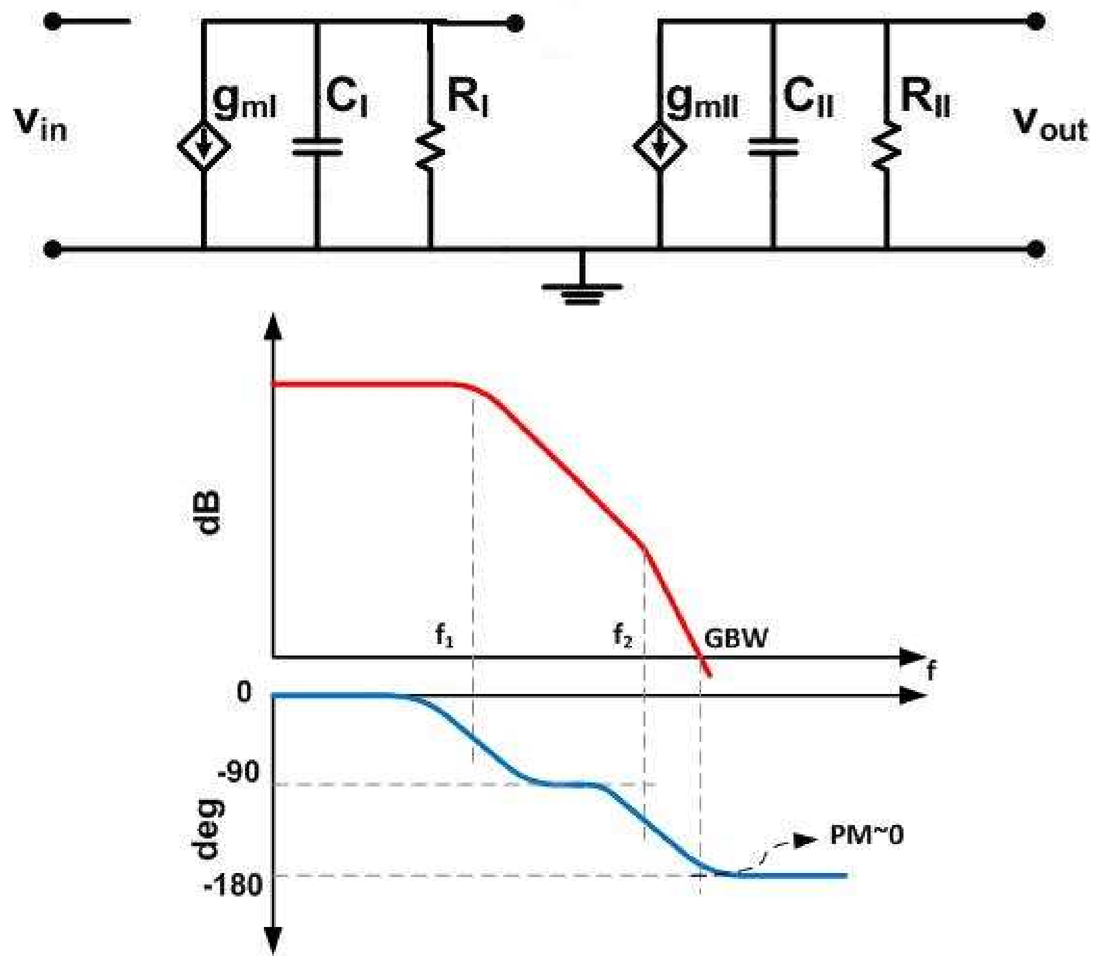
$$R_{dn} = \frac{1}{g_{ds_{M_4}}}$$

$$R_{out} \rightarrow \infty$$

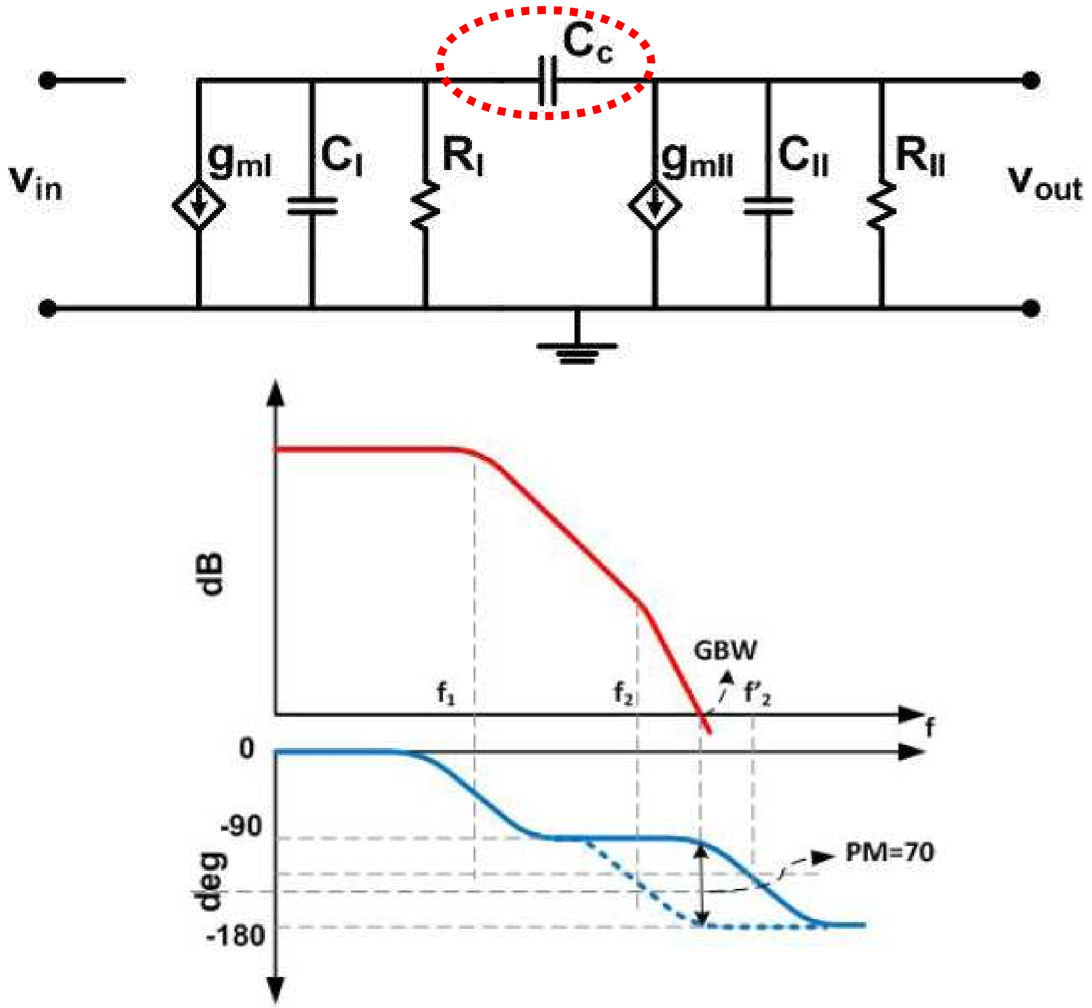
Regulated Current Source: Stability issues



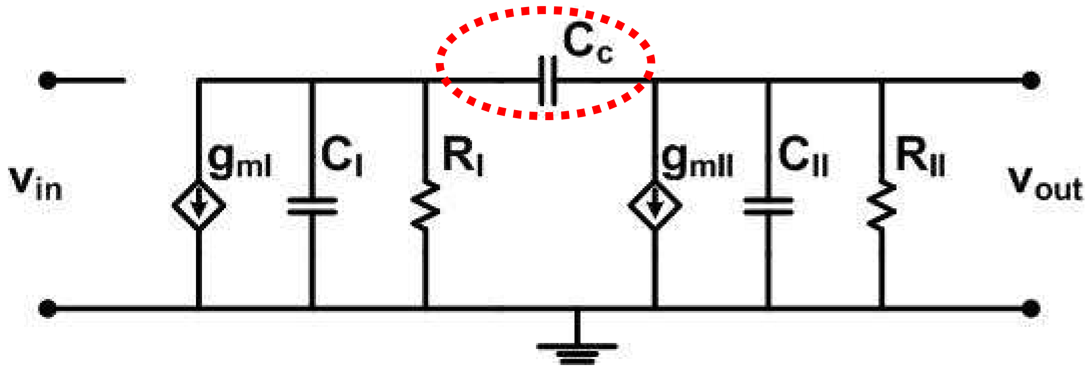
Instability: A Detour

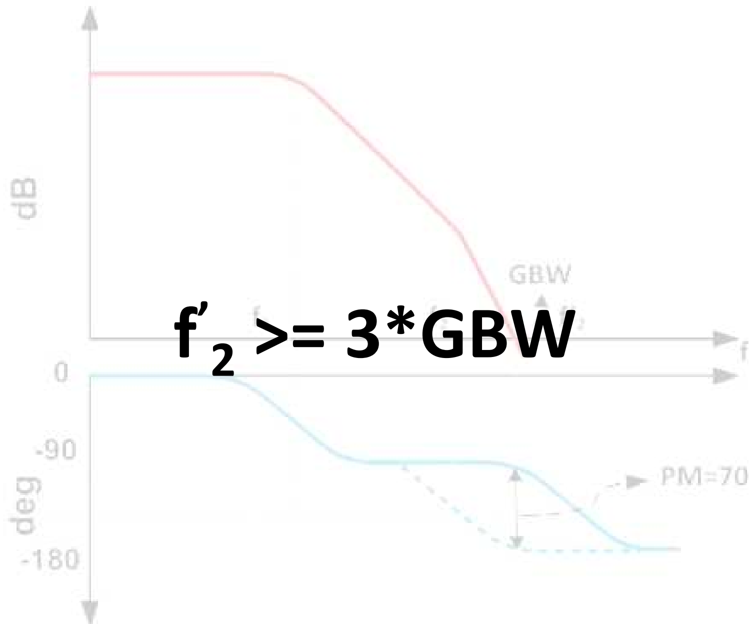


Compensation



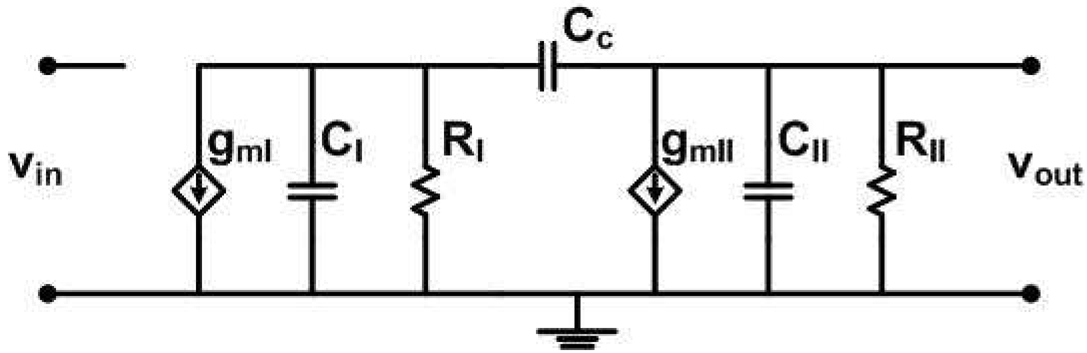
Compensation

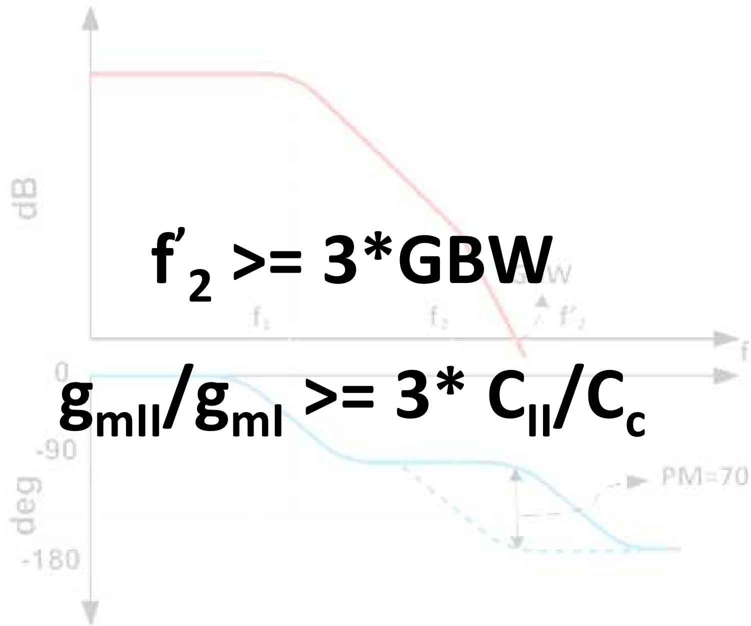




$f'_2 >= 3*GBW$

Compensation

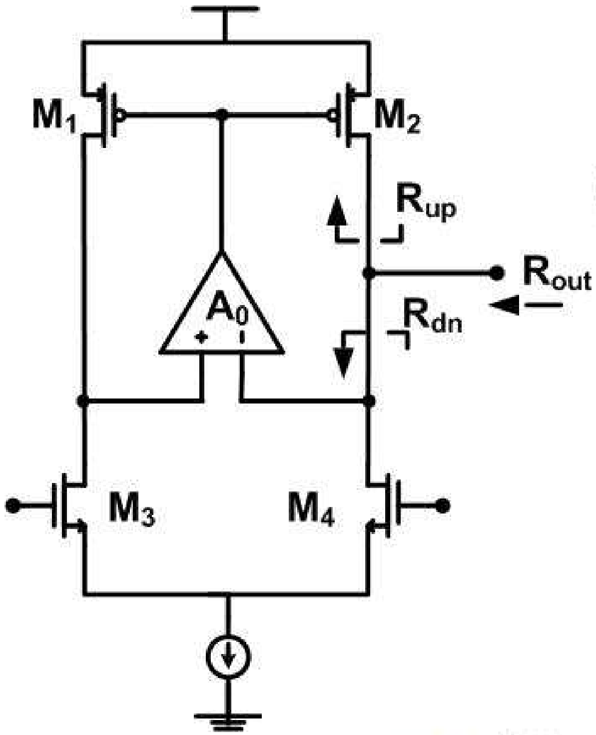


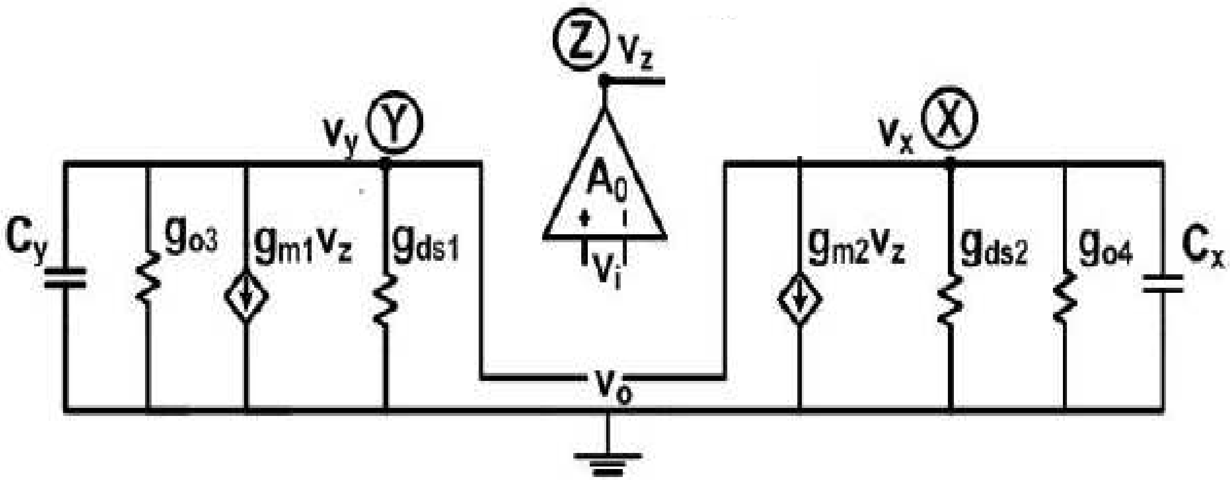


$$f'_2 >= 3*GBW$$

$$g_{mII}/g_{mI} >= 3* C_{II}/C_c$$

Regulated Current Source: Stability issues



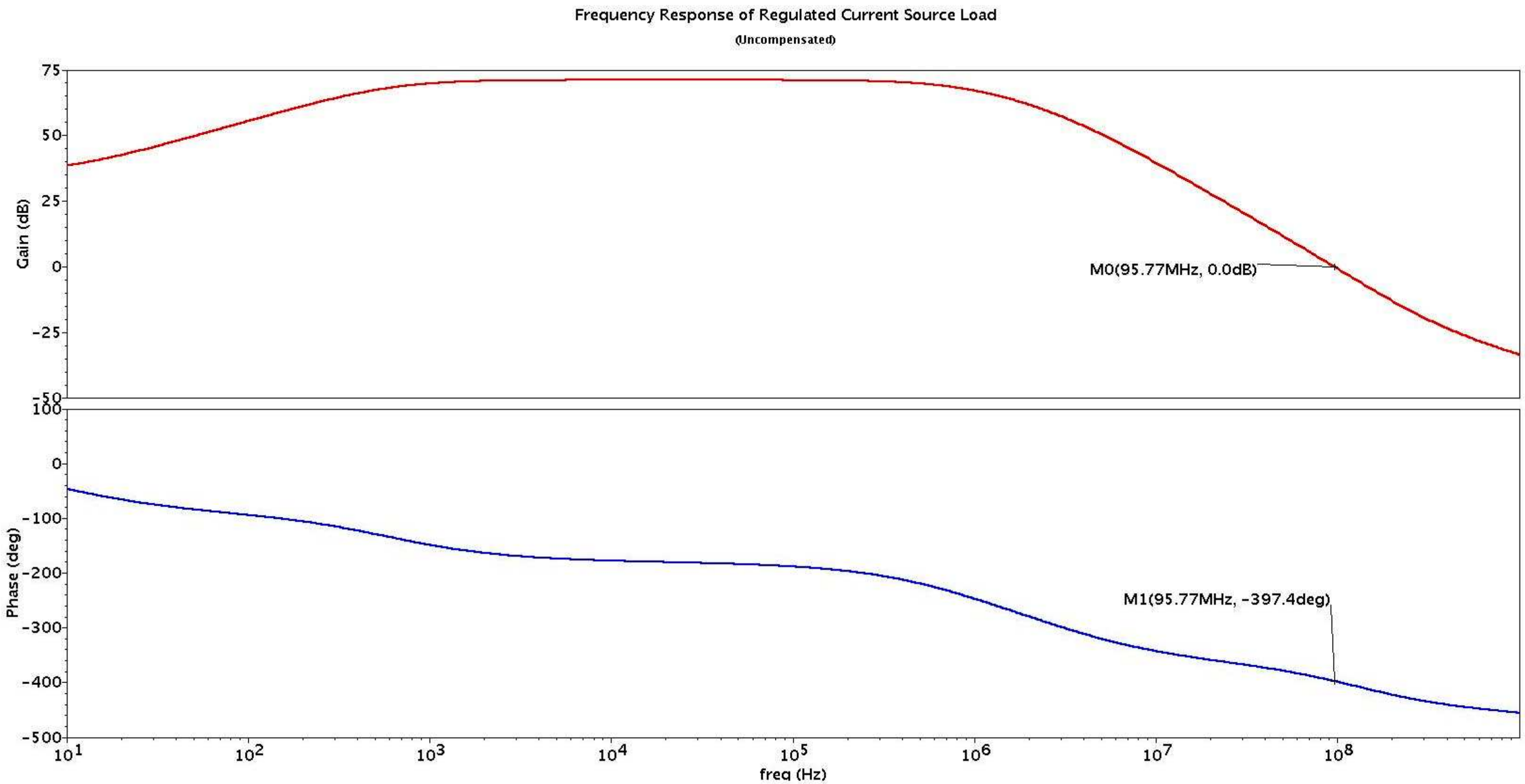


$$A(s) = \frac{A_0}{1 + sC_z/g_{oa}}$$

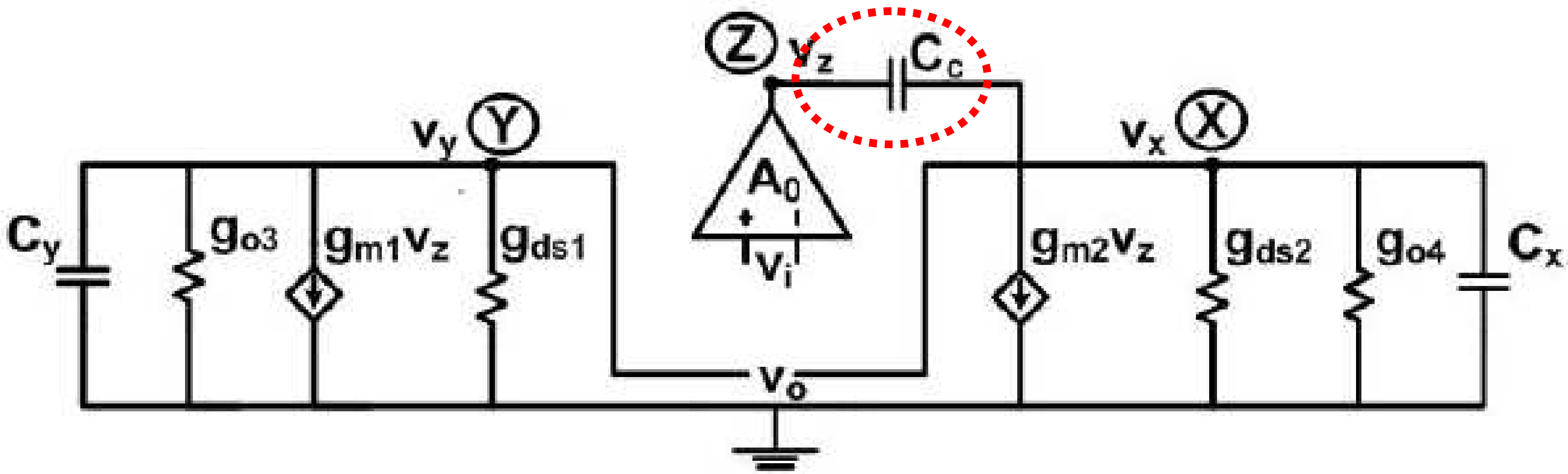
$$H_{OL}(s) = \frac{A_0\, g_{m12}(g_{o4} - g_{o3})}{g_{ds12}(g_{ds12} + g_{o4})} \cdot \frac{1 + s(C_x - C_y)/(g_{o4} - g_{o3})}{(1 + s/p_x)(1 + s/p_y)(1 + s/p_z)}$$

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



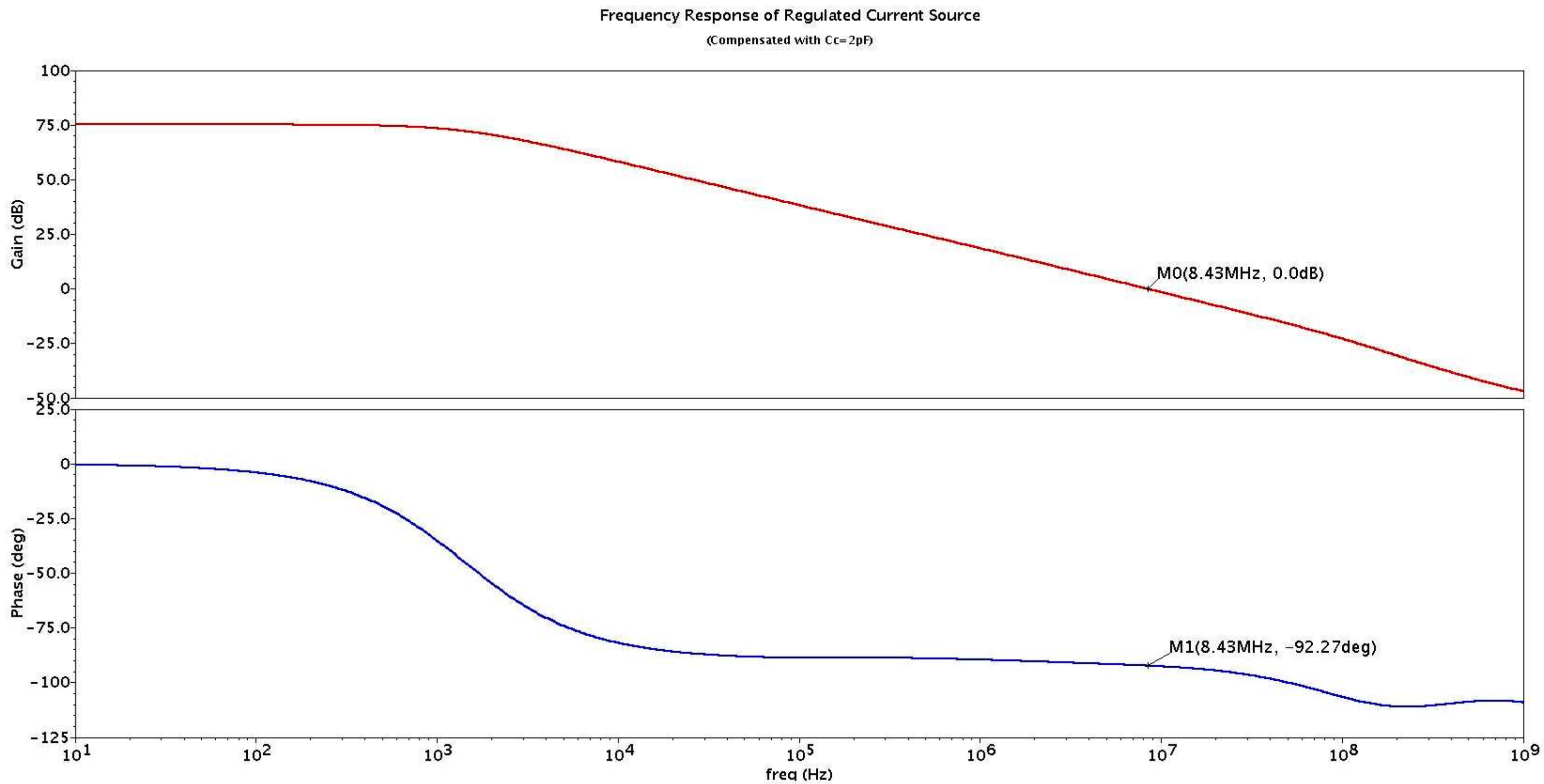
Regulated Current Source: Stability issues



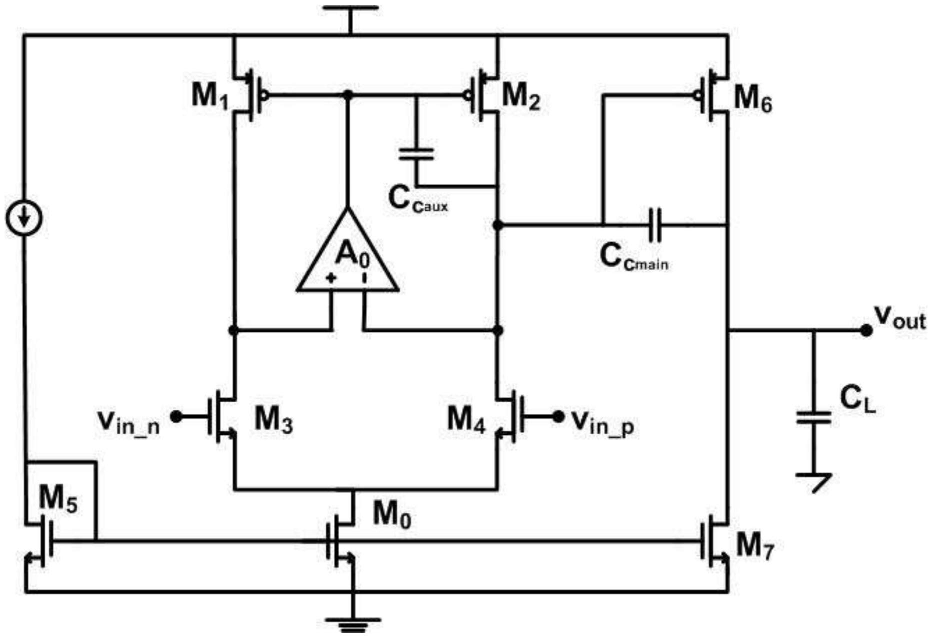
$$H_{OL}(s) = \frac{A_0\, g_{m12}(g_{o4} - g_{o3})}{(g_{ds12} + g_{o3})(g_{ds12} + g_{o4})} \cdot \frac{(1 - s/z_1)(1 + s/z_2)}{(1 + s/p_x')(1 + s/p_y)(1 + s/p_z')}$$

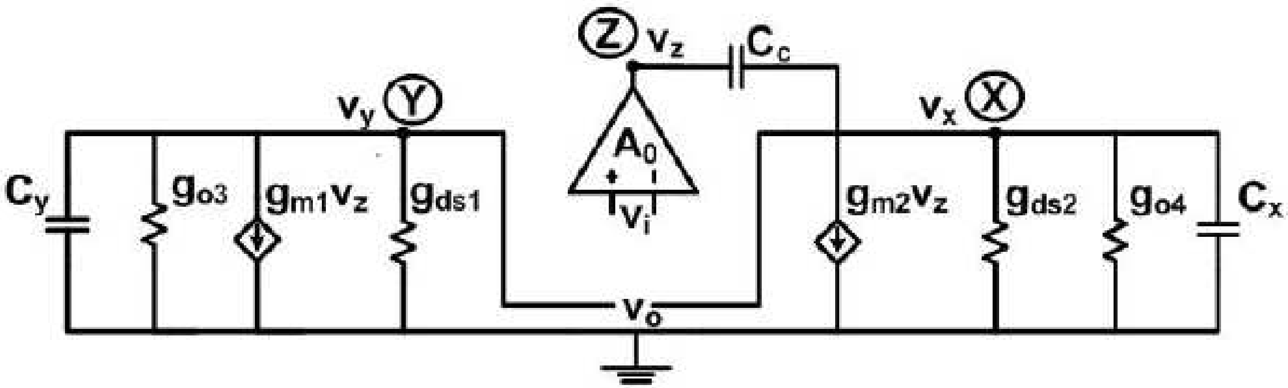
where $p_x' = g_{m12}/(C_x + C_y)$,
$p_z' = g_{oa} g_{ds12}/g_{m12} C_c$,
$z_1 = (g_{o4} - go3).g_{m12}/C_c\,(g_{m12} + g_{o4})$ and
$z_2 = g_{m12}/C_x$.

Regulated Current Source: Stability issues



Regulated Current Source: Stability issues



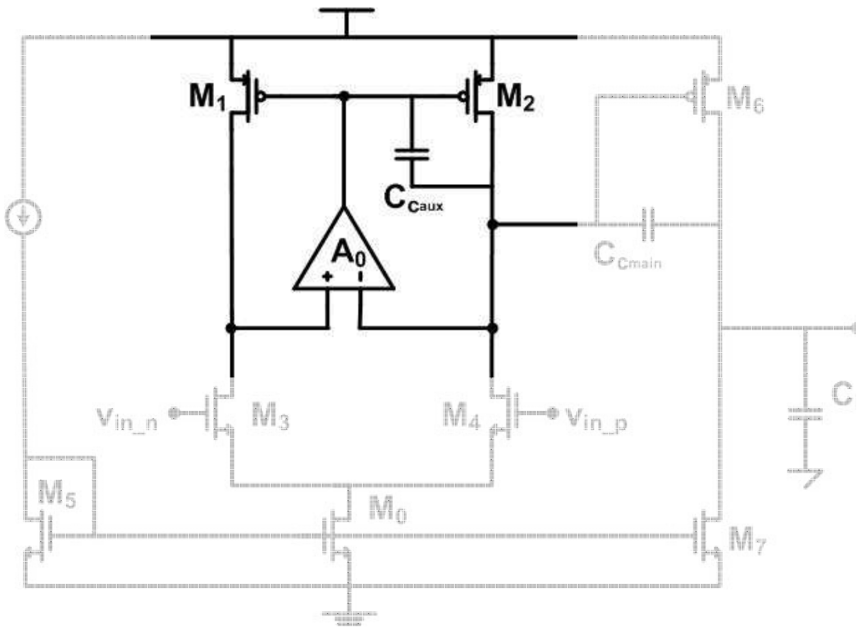


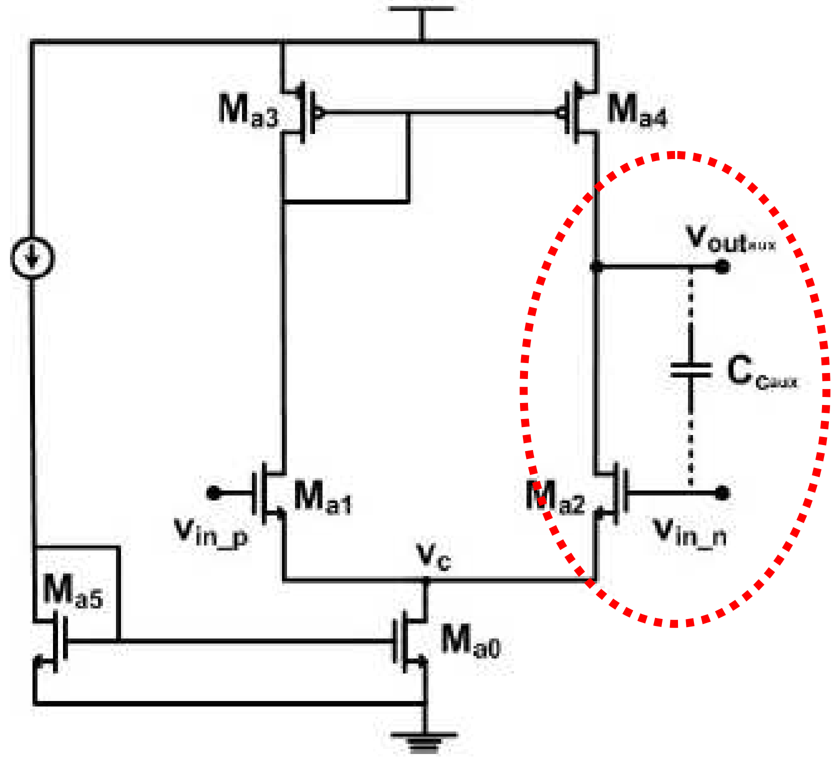
For stability:

$$p_z' >> GBW_{main}$$

$$\frac{g_{oa} g_{ds12}}{g_{m12} C_c} >> GBW_{main}$$

Regulated Current Source: Stability issues





For stability:

$$\frac{g_{oa} g_{ds12}}{g_{m12} C_c} >> GBW_{main} \quad \rightarrow \quad \frac{g_{ma12} g_{ds12}}{g_{m12} C_{caux}} >> GBW_{main}$$

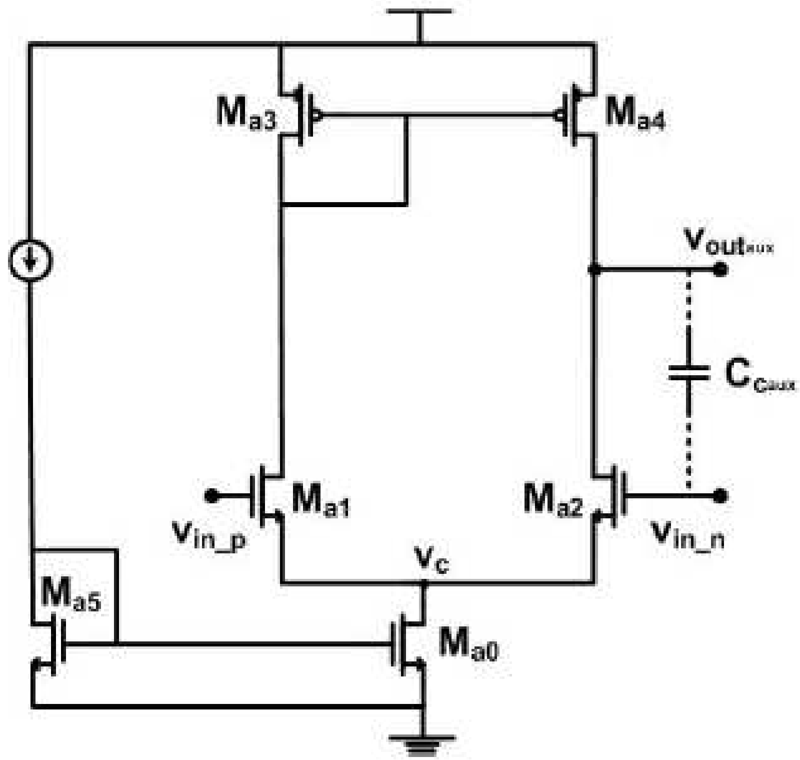
Regulated Current Source: Stability issues

$$\frac{g_{ma12}g_{ds12}}{g_{m12}C_{c_{aux}}} >> GBW_{main}$$

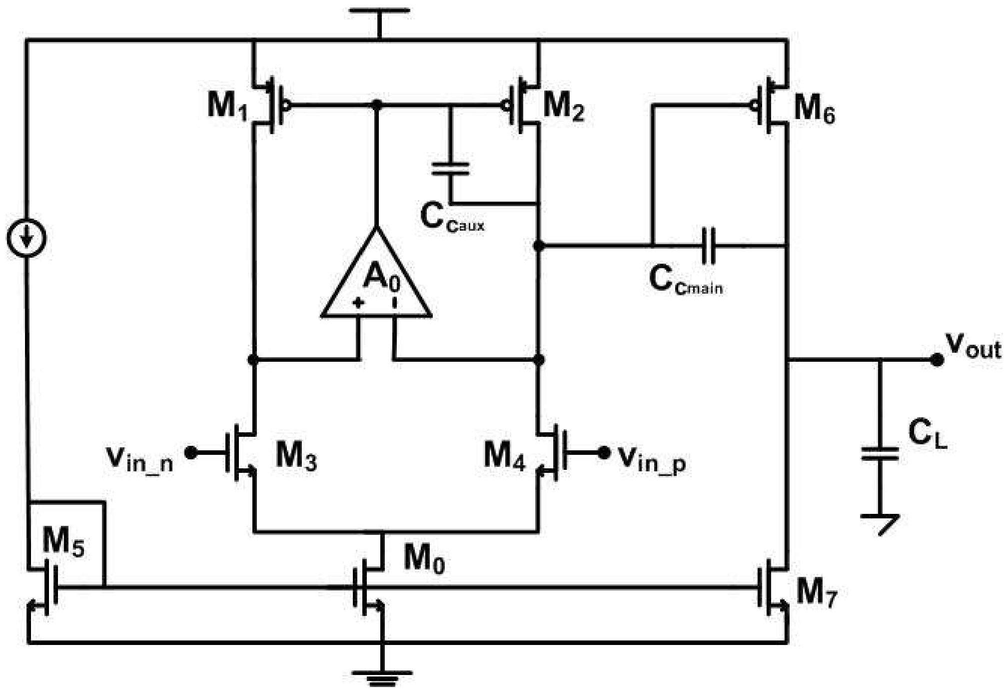
$$GBW_{aux} = \frac{g_{ma12}}{C_{c_{aux}}}$$

$$GBW_{aux} \geq 4\,GBW_{main}$$

- Stability condition



Regulated Current Source: Gain



$$A_I = \frac{v_{out_1}}{v_{in_{aux}}} \cdot \frac{v_{in_{aux}}}{v_{in}} = \frac{A_0 \, g_{m2} \, g_{m34}}{(g_{ds2} + g_{ds4})^2}$$

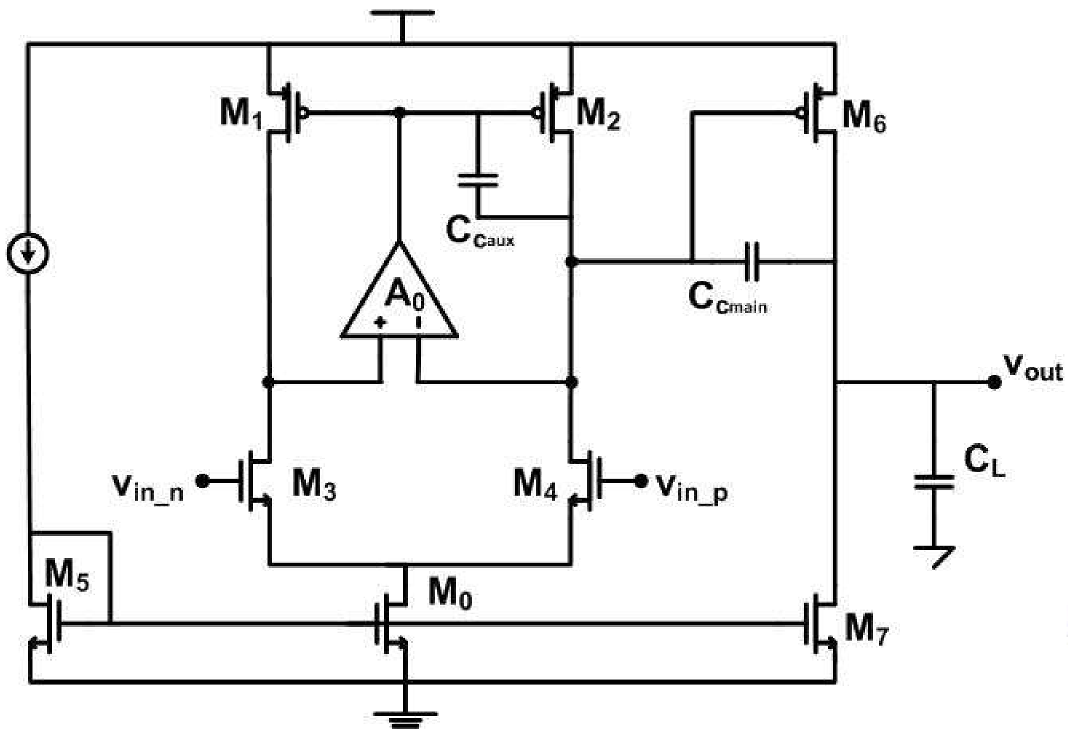
$$A_{II} = \frac{g_{m6}}{g_{ds6} + g_{ds7}}$$

$$A_{total} = \frac{A_0 \, g_{m2} \, g_{m34}}{(g_{ds2} + g_{ds4})^2} \cdot \frac{g_{m6}}{g_{ds6} + g_{ds7}}$$

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



$$GBW_{total} = \frac{g_{m34}}{C_c}$$

$$\frac{g_{m6}}{g_{m34}} \geq 3\,\frac{C_L}{C_c}$$

$$GBW_{aux} \geq 4\,GBW_{total}$$

$$A_{total} = \frac{A_0\, g_{m2}\, g_{m34}}{(g_{ds2} + g_{ds4})^2} \cdot \frac{g_{m6}}{g_{ds6} + g_{ds7}}$$

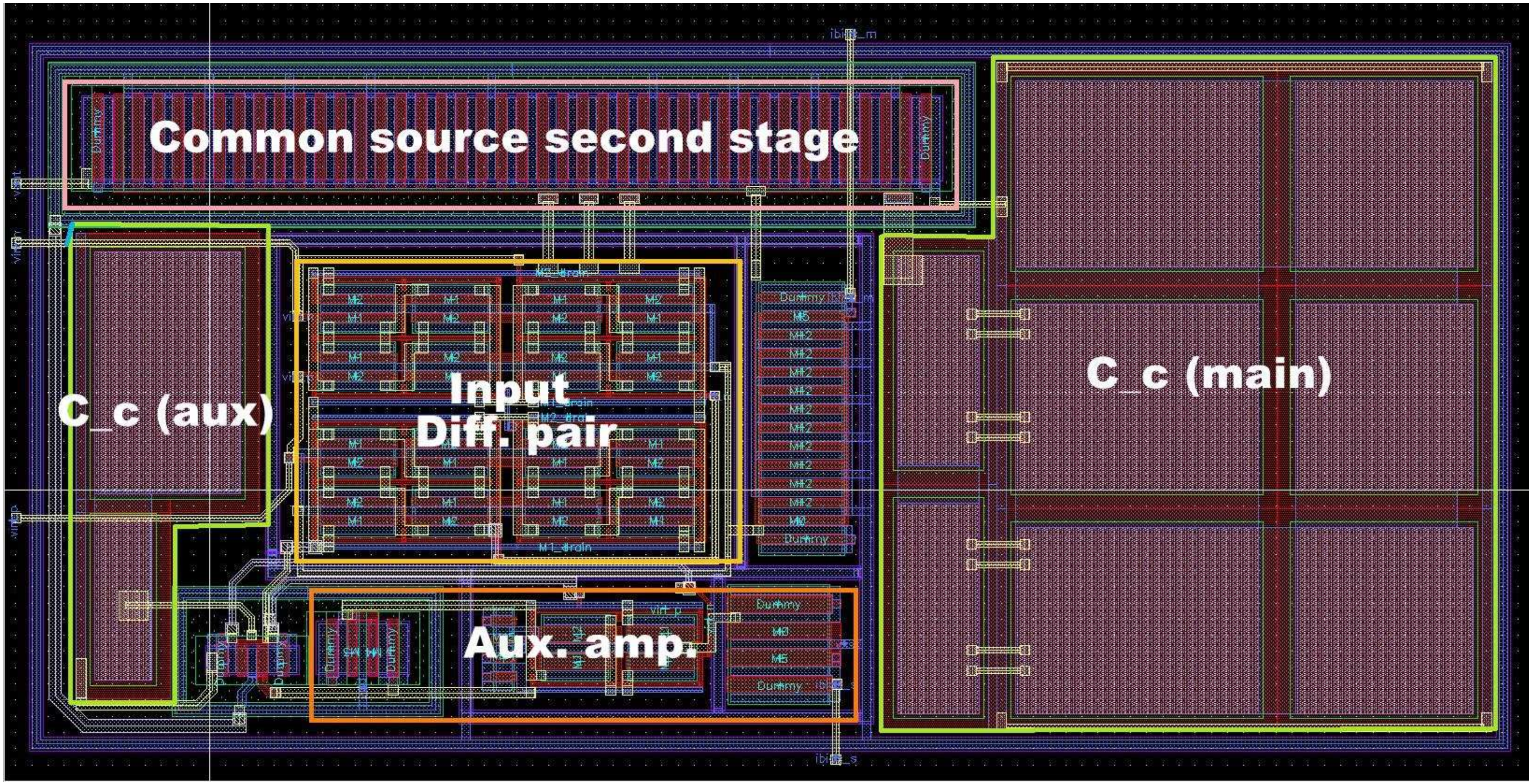
The Op-Amp: Design Methodology

- 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

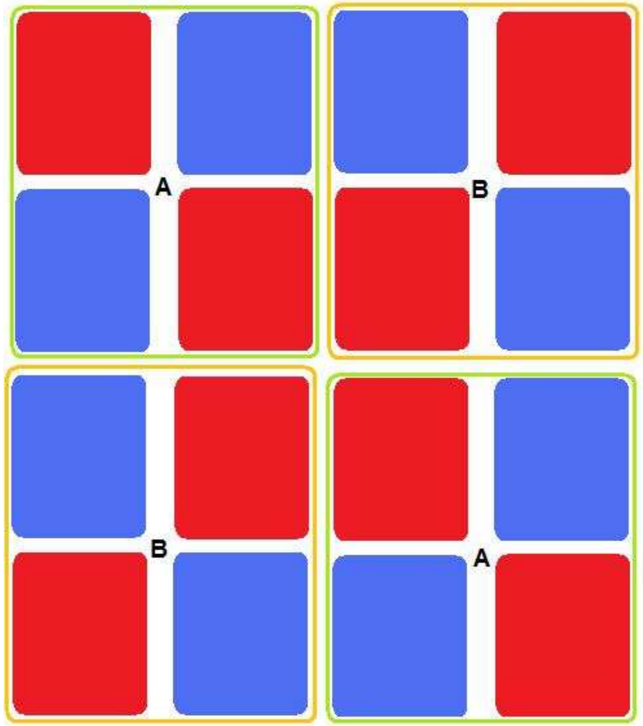
The Op-Amp: Layout



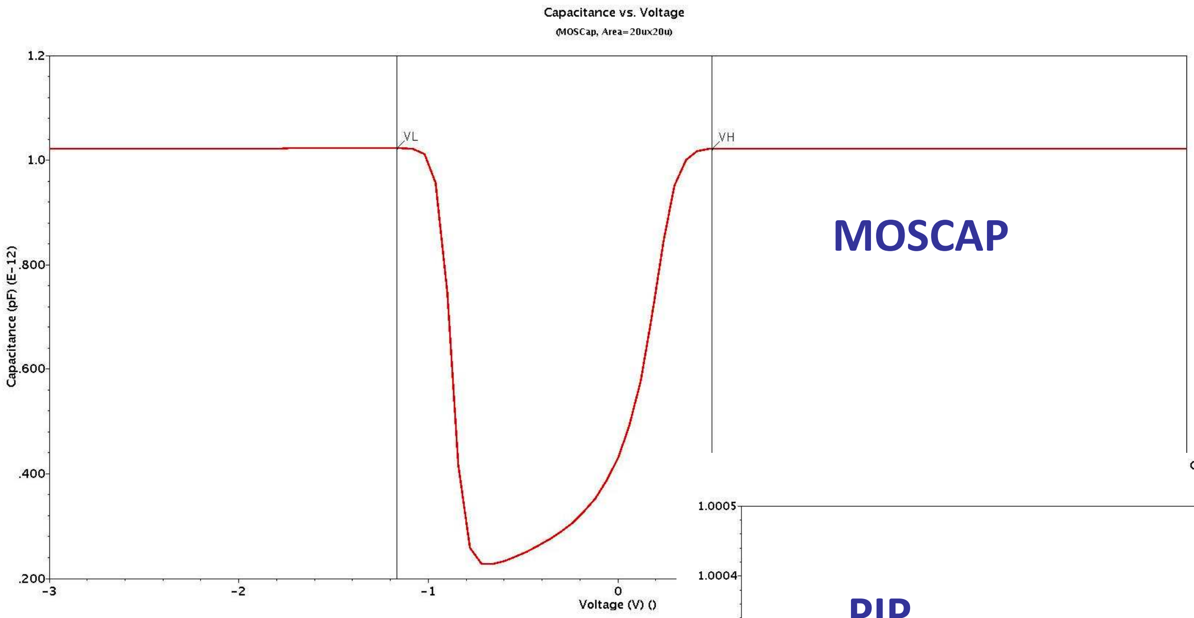
Area= 0.16 mm^2

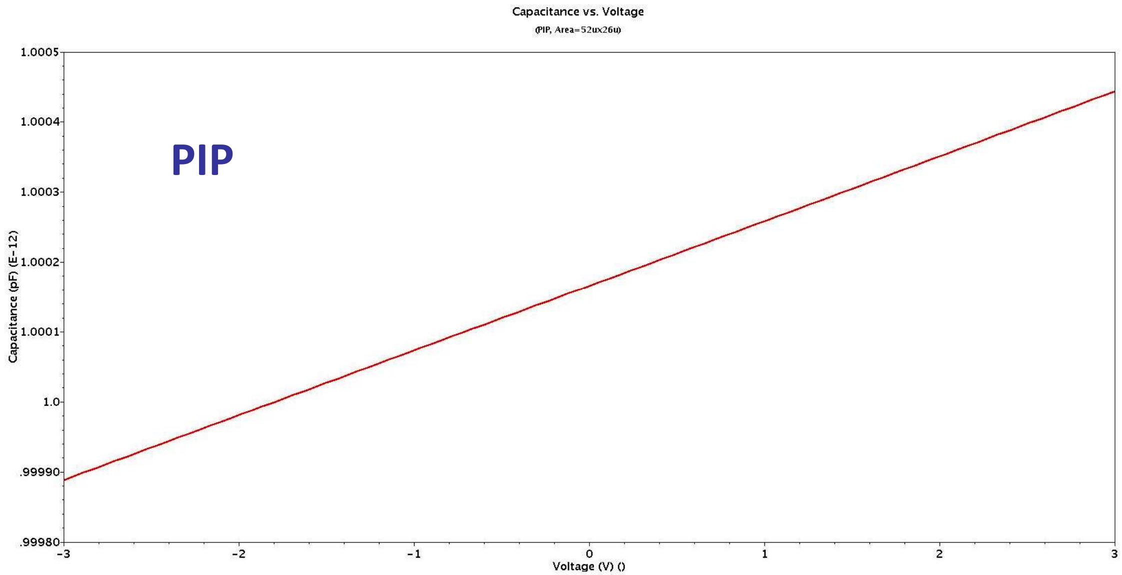
Layout Considerations

- Large device sizes
- Minimum distance b/w devices
- Symmetrical layout
- Same orientation
- Same environment
- Multi-finger transistors
- Common-centroid layout

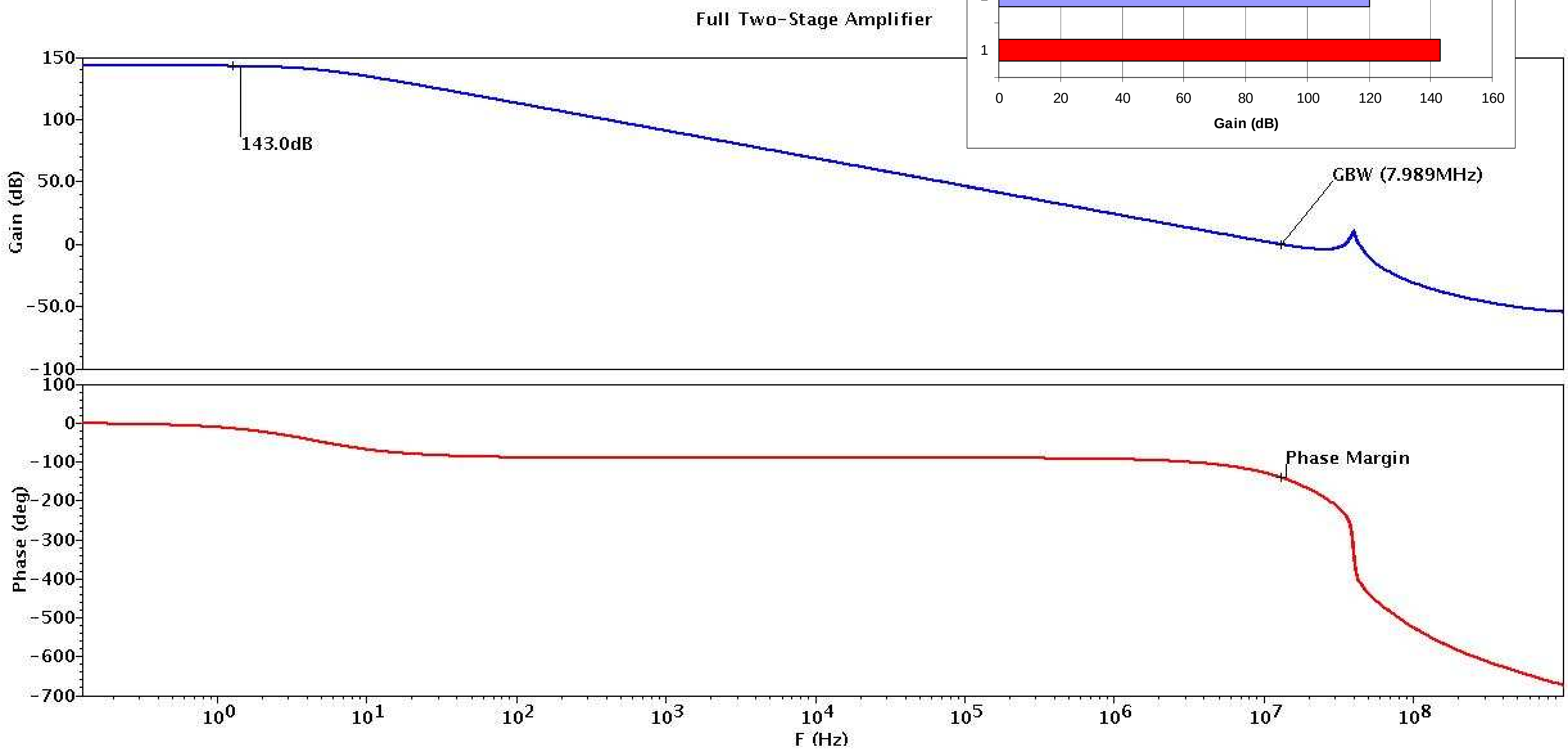


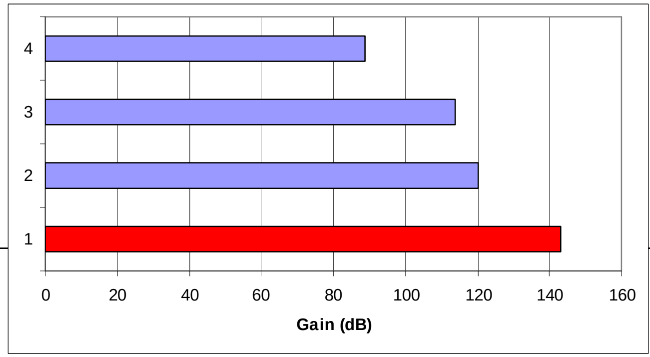
Layout: PIP vs. MOSCAP





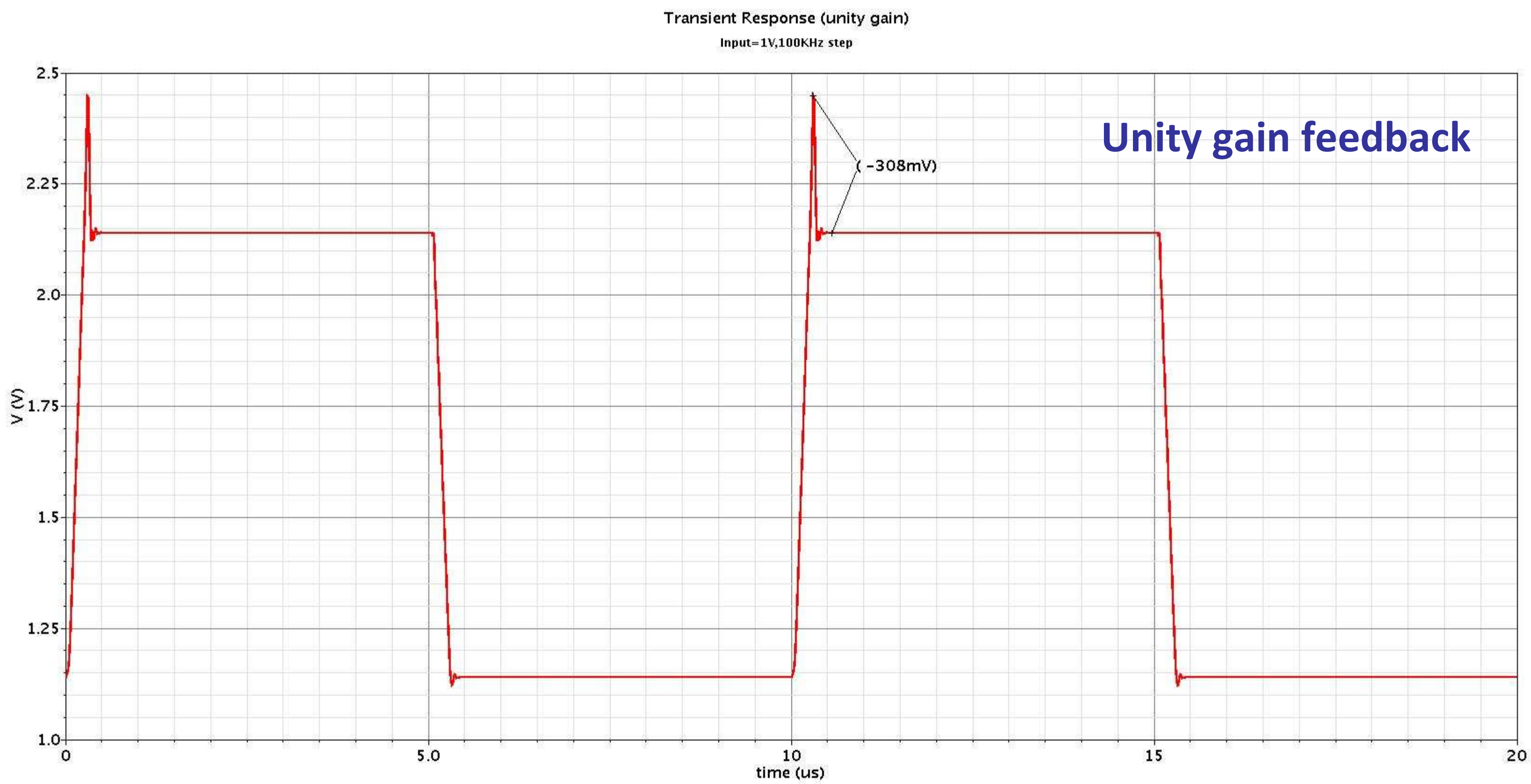
Simulation Results: Frequency Response





[1] This work [2] Ivanov, IEEE Trans. Ckts & Sys. 2007 [3] Zhang, IEEE APCCAS 2008 [4] Yang, IEEE Conf. on Sensors 2006

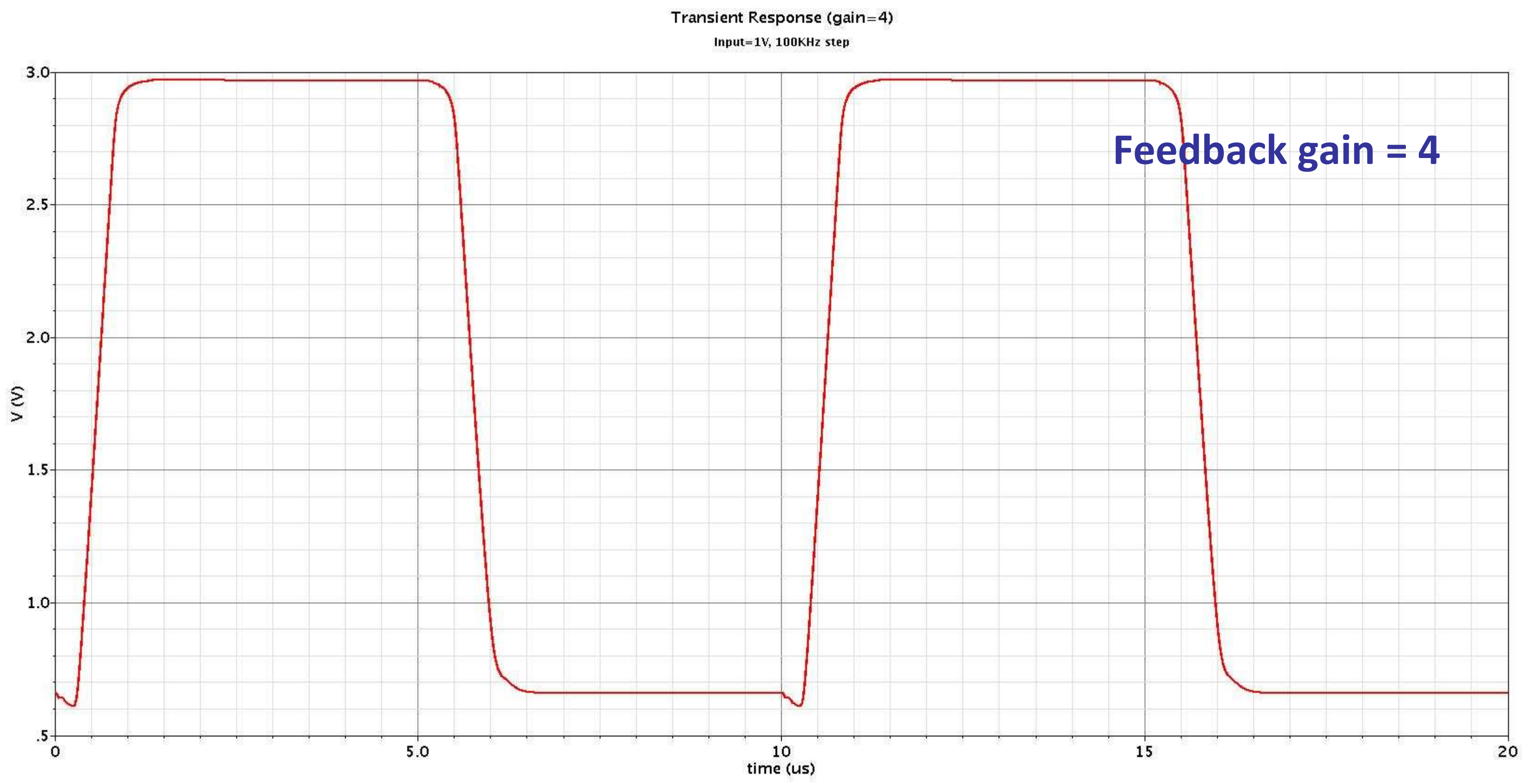
Simulation Results: Transient Response



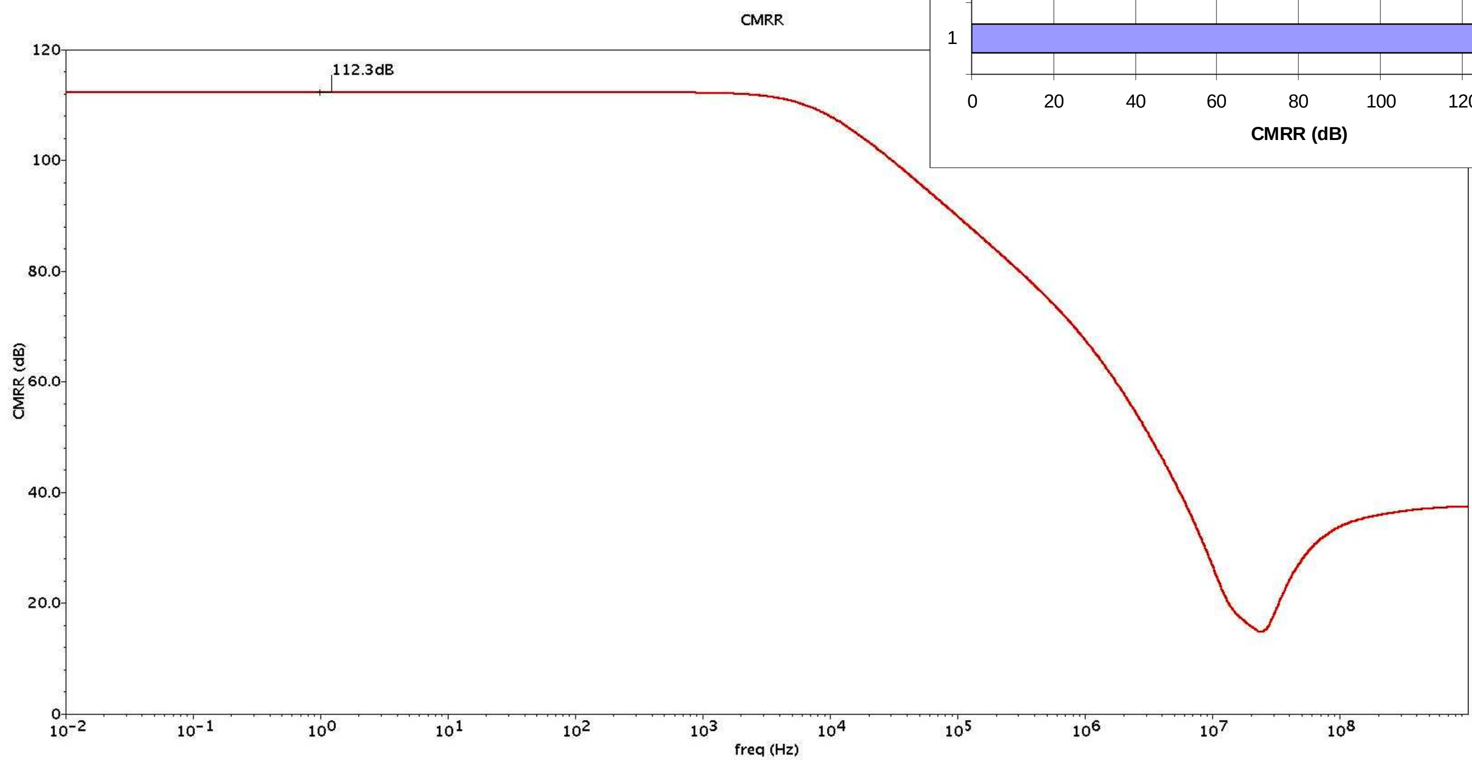
Slew Rate = 4.90 V/us

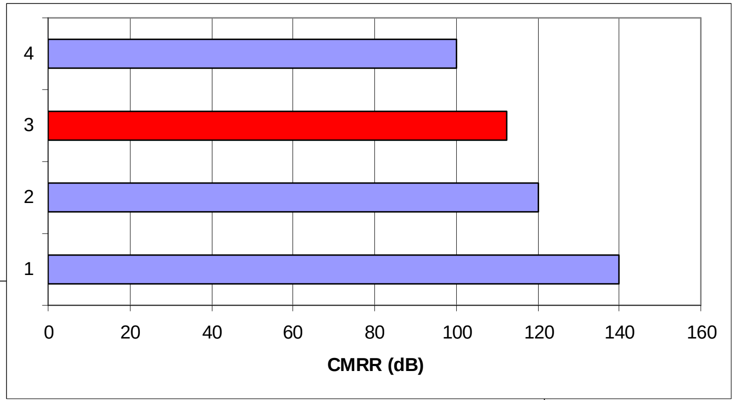
Settling time = 150 ns

Simulation Results: Transient Response



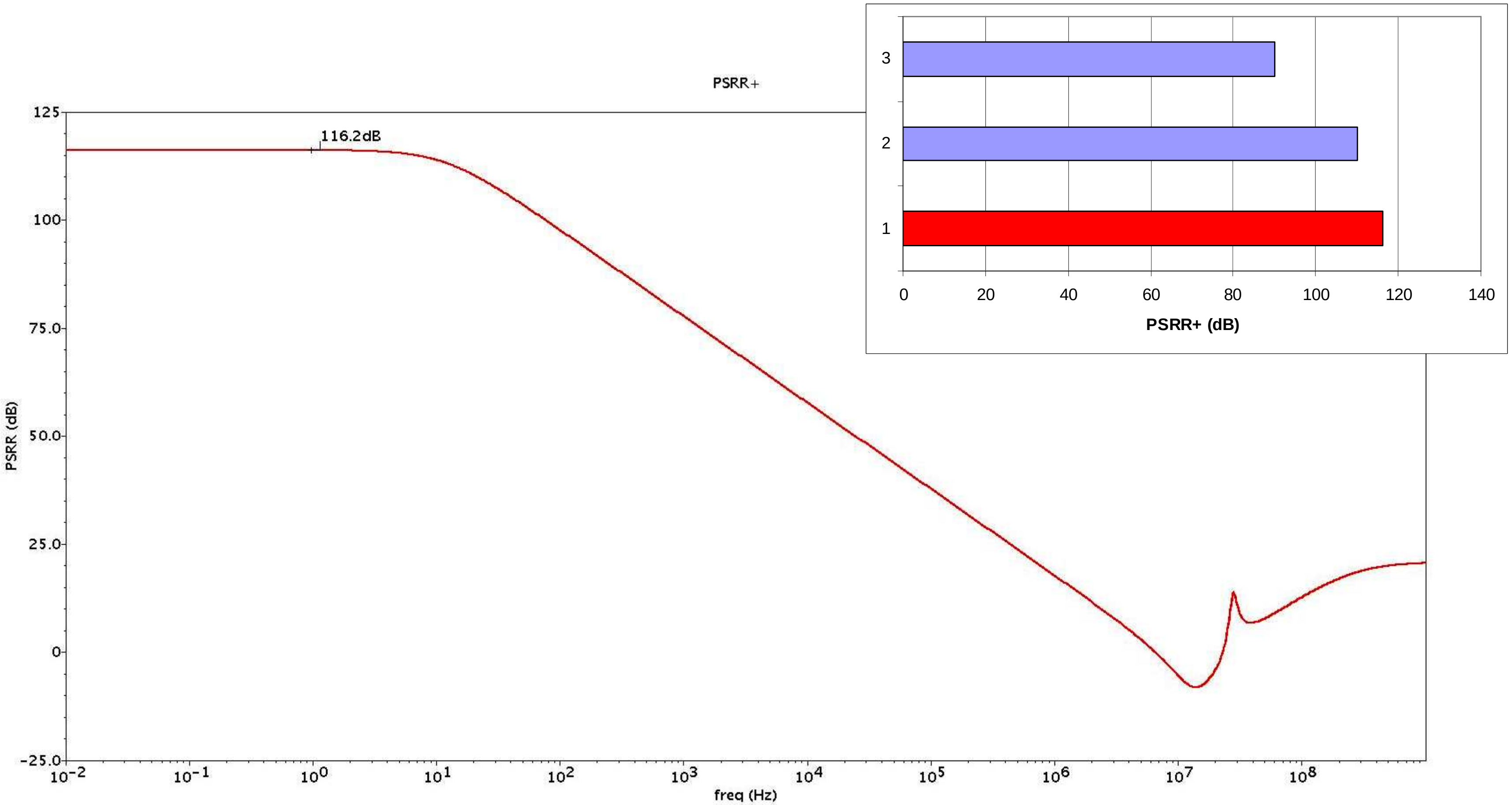
Simulation Results: CMRR





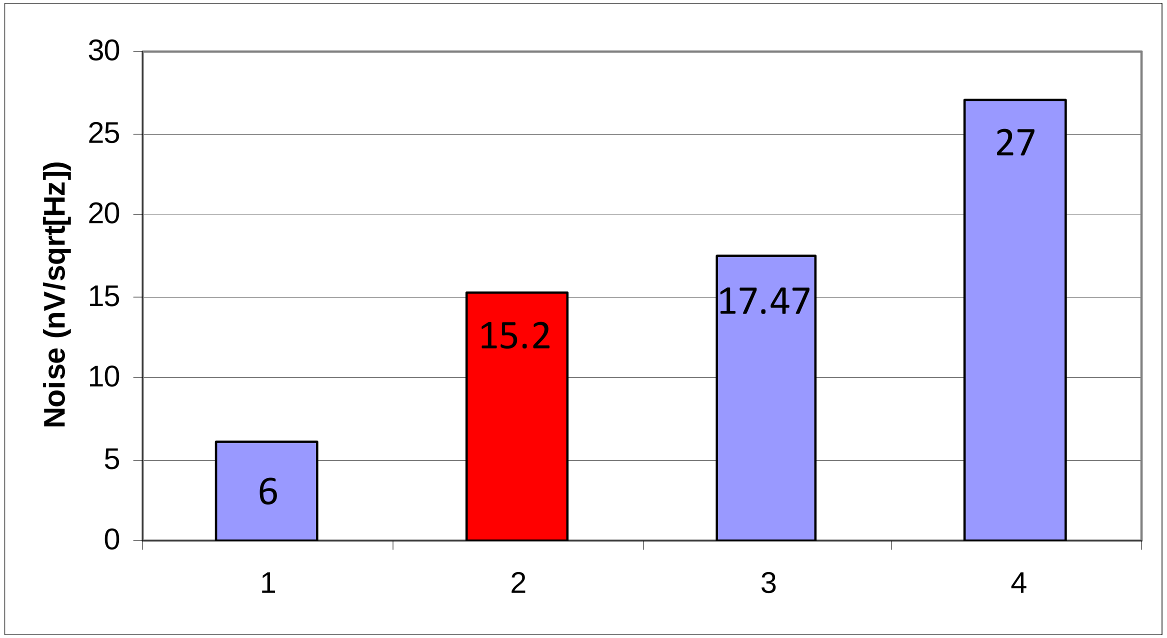
[1] Pertijs, ISSCC 2009 [2] Zhang, IEEE APCCAS 2008 [3] This work [4] Ivanov, IEEE Trans. Ckts & Sys. 2007

Simulation Results: PSRR



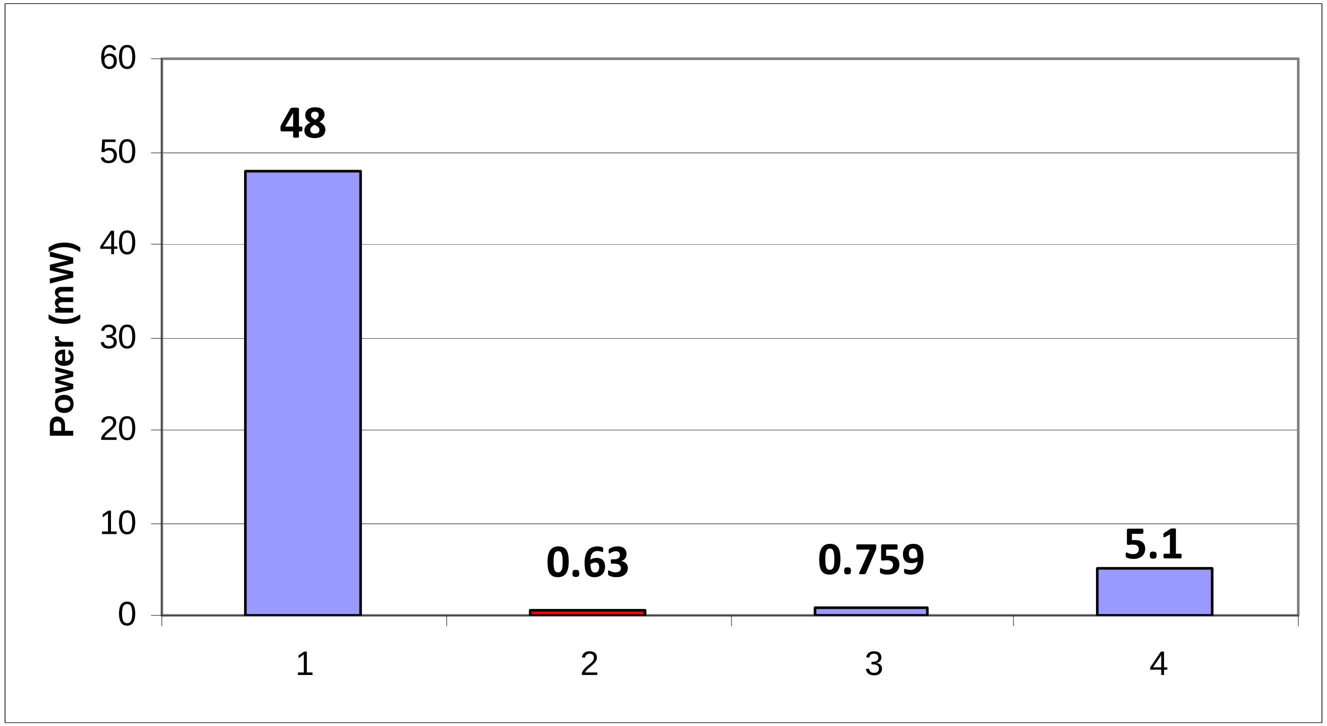
[1] This work [2] Zhang, IEEE APCCAS 2008 [3] Ivanov, IEEE Trans. Ckts & Sys. 2007

Simulation Results: Noise



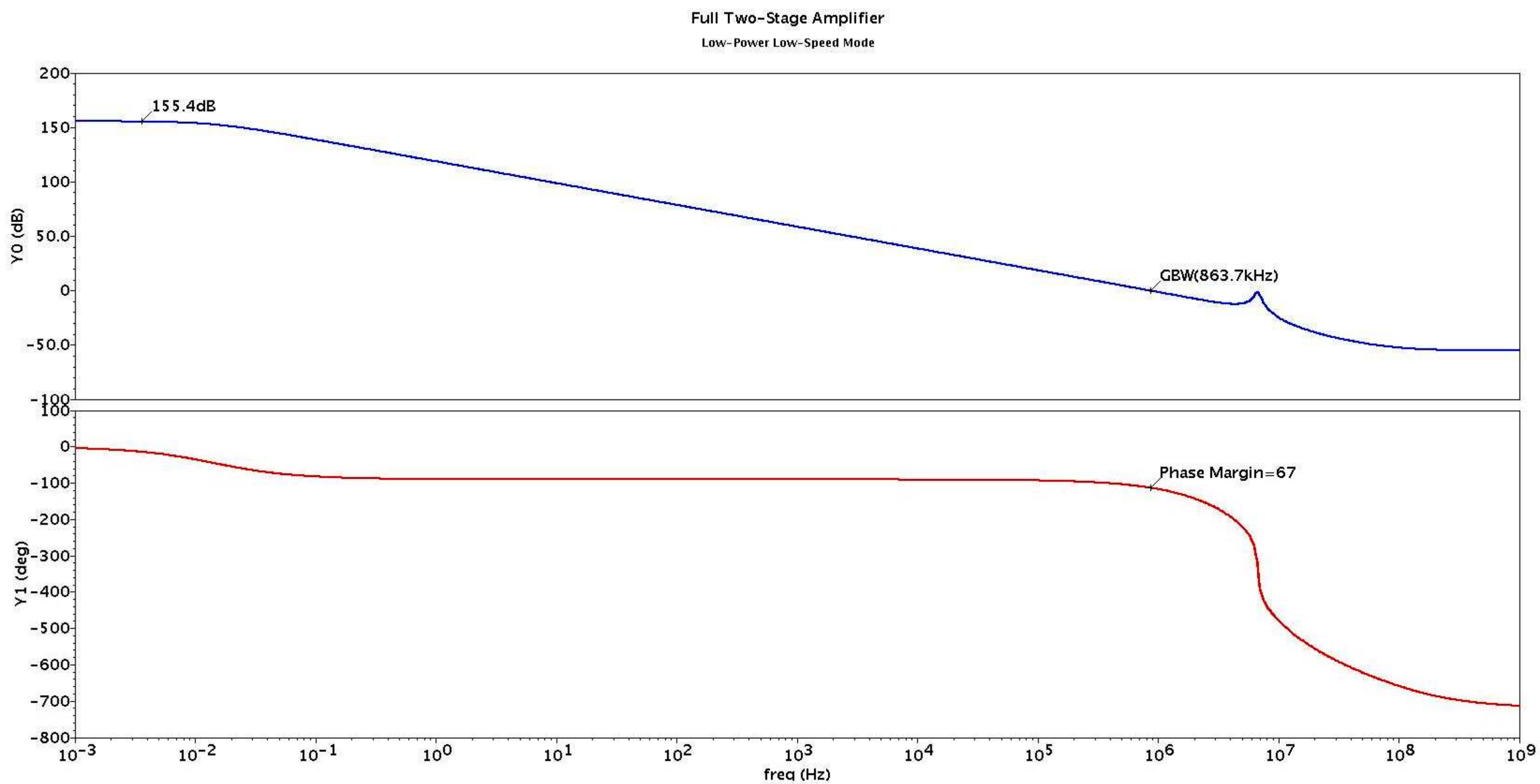
[1] Ivanov, IEEE Trans. Ckts & Sys. 2007 [2] This work [3] Zhang, IEEE APCCAS 2008 [4] Pertijs, ISSCC 2009

Simulation Results: Power Consumption



[1] Ivanov, IEEE Trans. Ckts & Sys. 2007 [2] This work [3] Zhang, IEEE APCCAS 2008 [4] Pertijs, ISSCC 2009

Simulation Results: Low Speed Mode



Power Consumption = 69 uW

Performance Summary

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

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