EECS 240
Analog Integrated Circuits

Topic 14: Output Stages

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Output Stages

- Driving large (resistive) loads
  - RC-filters (anti-aliasing)
  - Off-chip loads
  - Line driver
    - Twisted pair: Ethernet, ISDN, ADSL, HPNA
    - Coax

OTA

- Transconductance amplifier (common-source)

$$A_v = g_m R_L = \frac{2I_D}{V^*} R_L$$

- Excessive power dissipation

$$I_D \ge \frac{V^* A_v}{2R_L}$$

$$\frac{200\text{mV} \times 10{,}000}{2 \times 50\Omega} = 20\text{A}$$

$$\frac{200\text{mV} \times 10}{2 \times 50\Omega} = 20\text{mA}$$

$$\frac{200\text{mV} \times 10{,}000}{2 \times 10\text{k}\Omega} = 100\text{mA}$$

$$\frac{200\text{mV} \times 10}{2 \times 10\text{k}\Omega} = 100\mu\text{A}$$

- Only appropriate for modest loads and multi-stage amplifiers

Source Follower

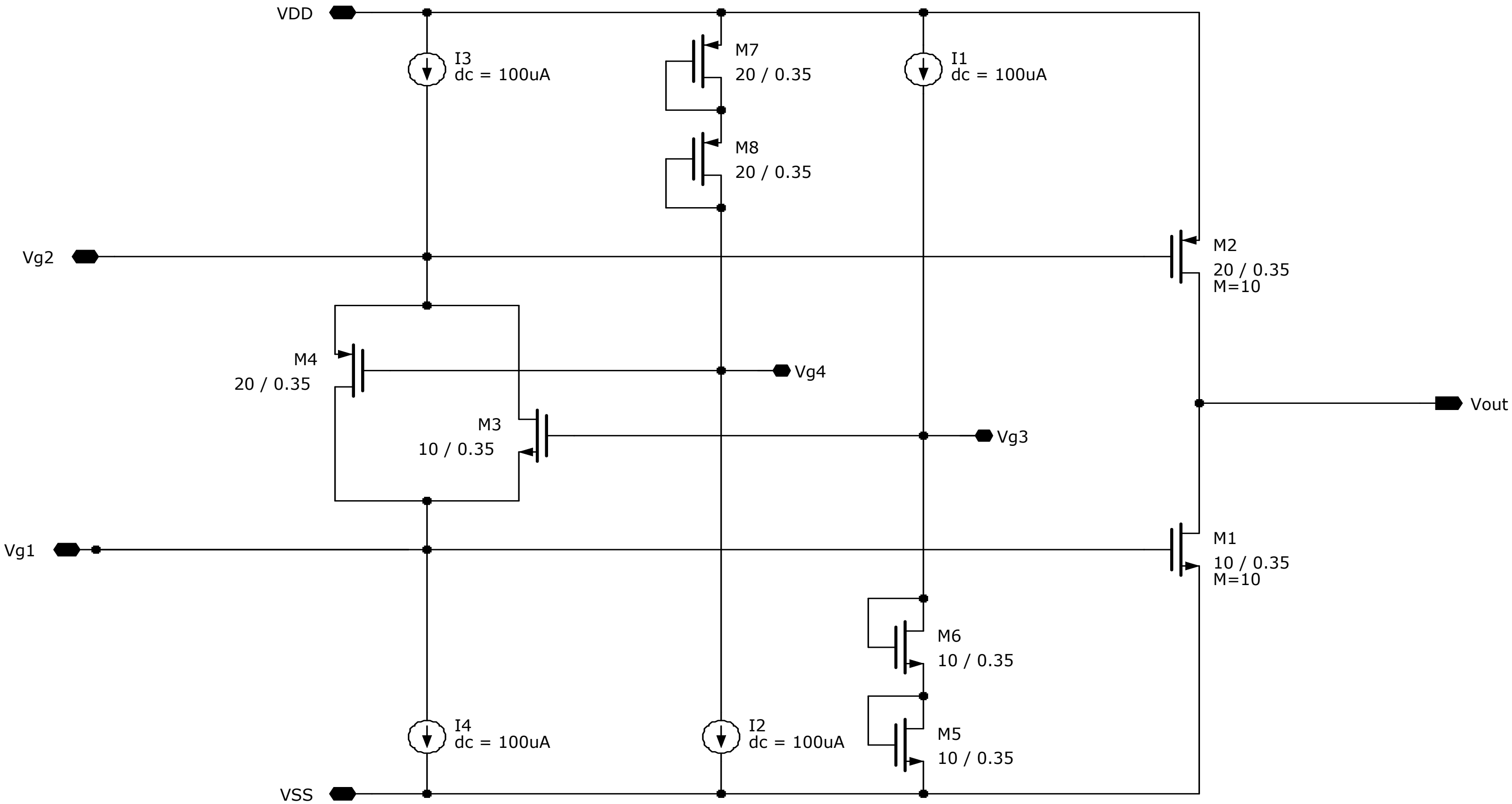
- Impractical for $V_{DD} < 5V$

- Push-pull follower
  - Class (A)B
  - Cross-over distortion
  - Quiescent current control

Class (A)B Common-Source

- Essentially inverter
- Very nonlinear
  - Need feedback
  - Local (error amplifiers)
  - Global
- Biasing
  - Dynamic
  - Floating voltage source

Floating Voltage Source



References

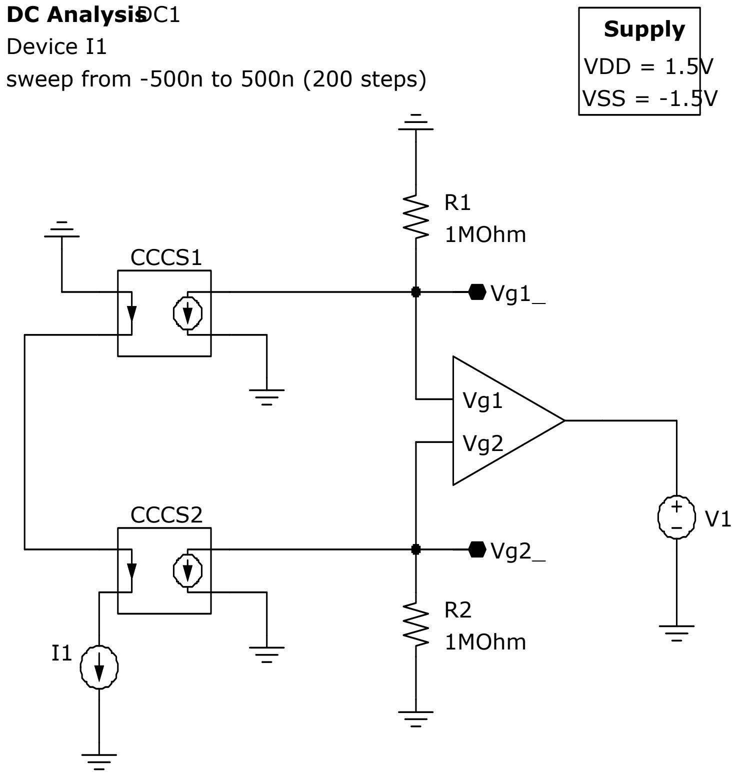
- D. M. Monticelli, "A quad CMOS single-supply op amp with rail-to-rail output swing," *IEEE Journal of Solid-State Circuits,* vol. 21, pp. 1026 - 1034, December 1986.
  Original idea.

- R. Hogervorst, J. P. Tero, R. G. H. Eschauzier, and J. H. Huijsing, "A compact power-efficient 3 V CMOS rail-to-rail input/output operational amplifier for VLSI cell libraries," *IEEE Journal of Solid-State Circuits,* vol. 29, pp. 1505 - 1513, December 1994.
  A CMOS realization.

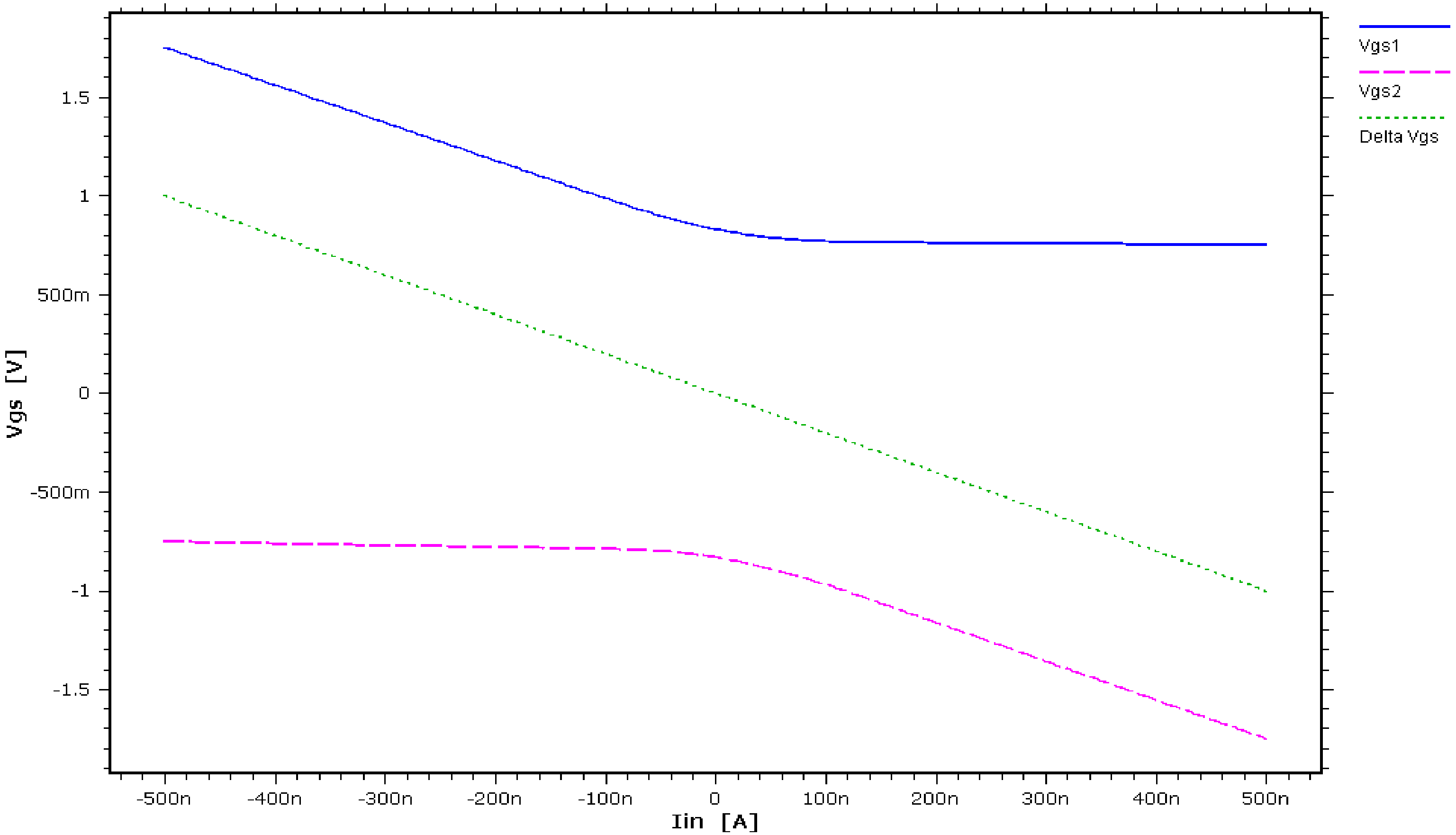
- K. de Langen and J. H. Huijsing, "Compact low-voltage power-efficient operational amplifier cells for VLSI," *IEEE Journal of Solid-State Circuits,* vol. 33, pp. 1482 - 1496, October 1998.
  Alternative implementation of floating voltage source for low V_{DD} *operation.*

- J. N. Babanezhad, "A low-output-impedance fully differential op amp with large output swing and continuous-time common-mode feedback," IEEE Journal of Solid-State Circuits, vol. 26, pp. 1825 - 1833, December 1991.
  Combination of CS & CD class AB output stages.

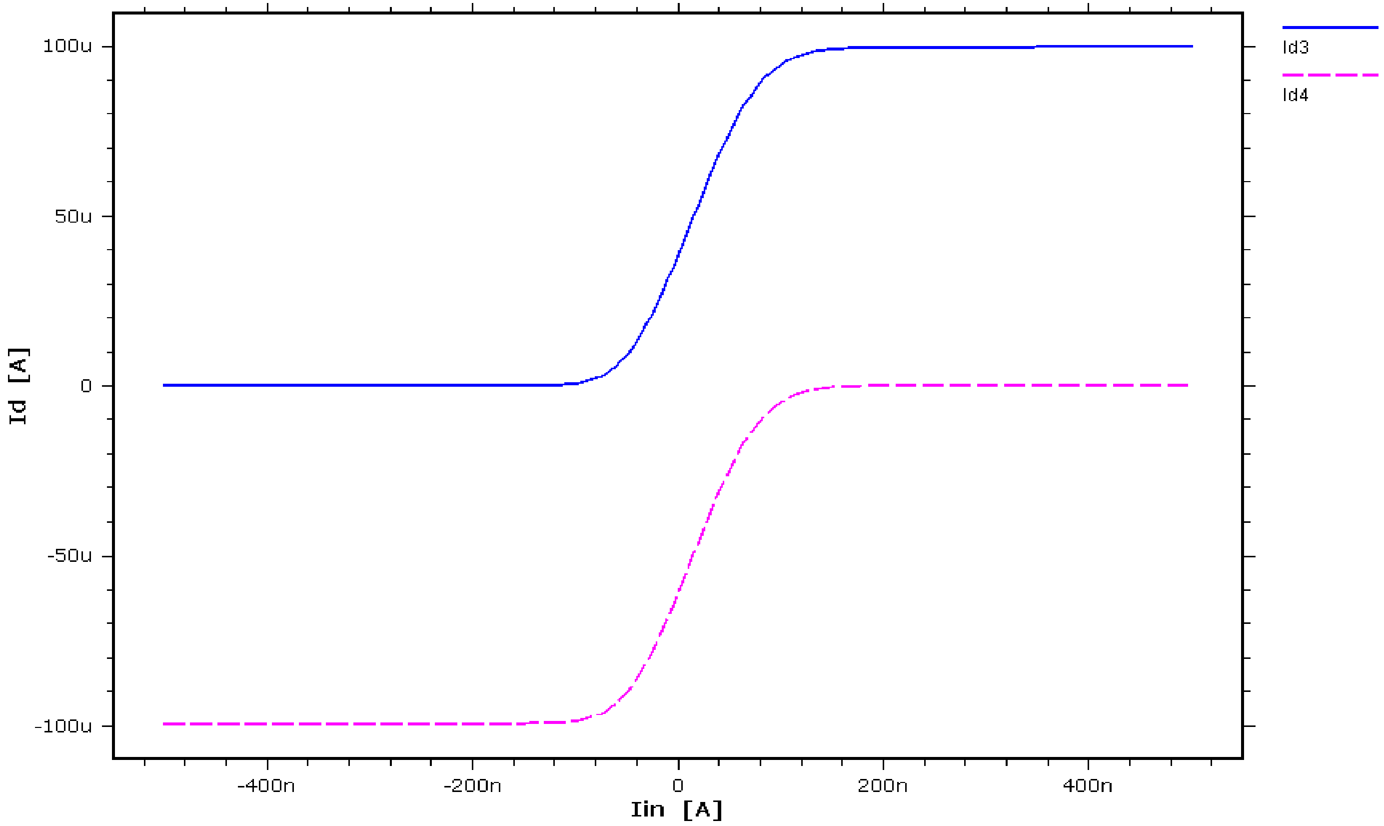
Test Setup


DC Analysis DC1
Device I1
sweep from -500n to 500n (200 steps)
Supply
VDD = 1.5V
VSS = -1.5V
R1
1MOhm
CCCS1
Vg1_
Vg1
Vg2
V1
CCCS2
Vg2_
R2
1MOhm
I1

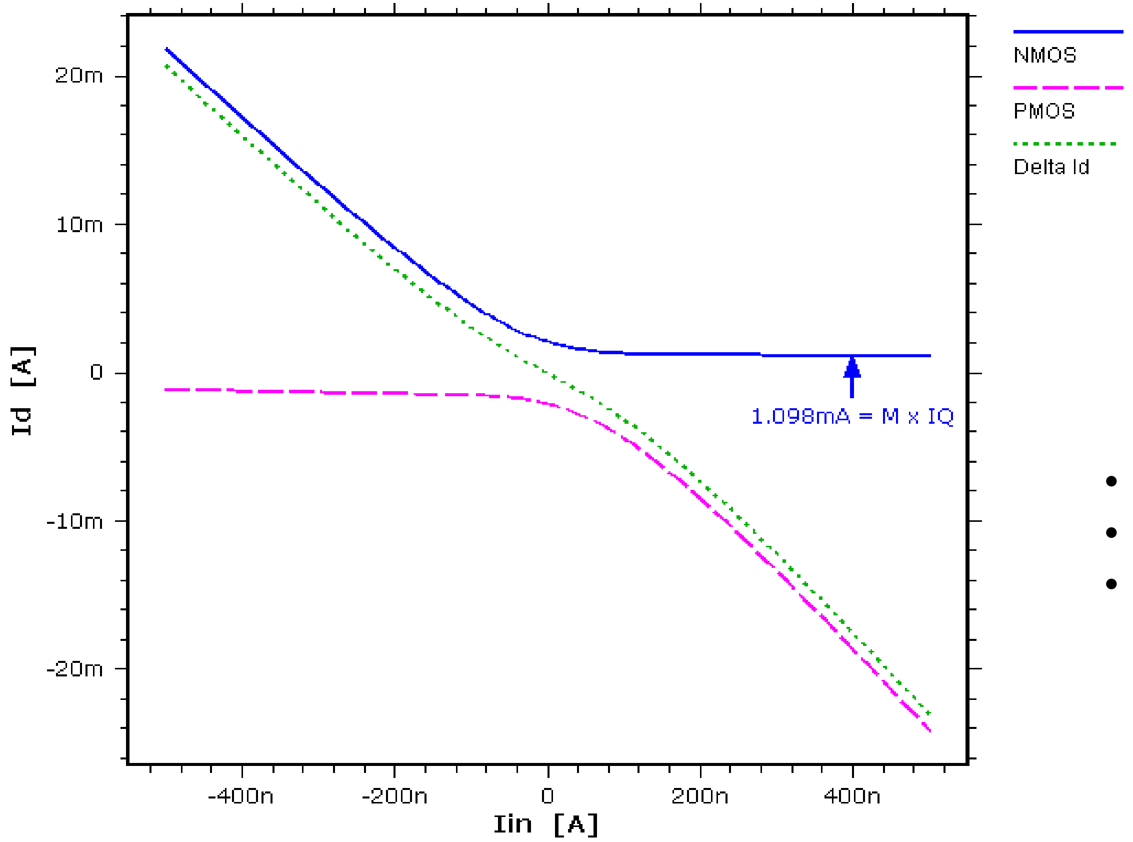
V_{gs1}, V_{gs2}


Vgs1
Vgs2
Delta Vgs
Vgs [V]
1.5
1
500m
0
-500m
-1
-1.5
-500n
-400n
-300n
-200n
-100n
0
100n
200n
300n
400n
500n
Iin [A]

I_{D3}, I_{D4}

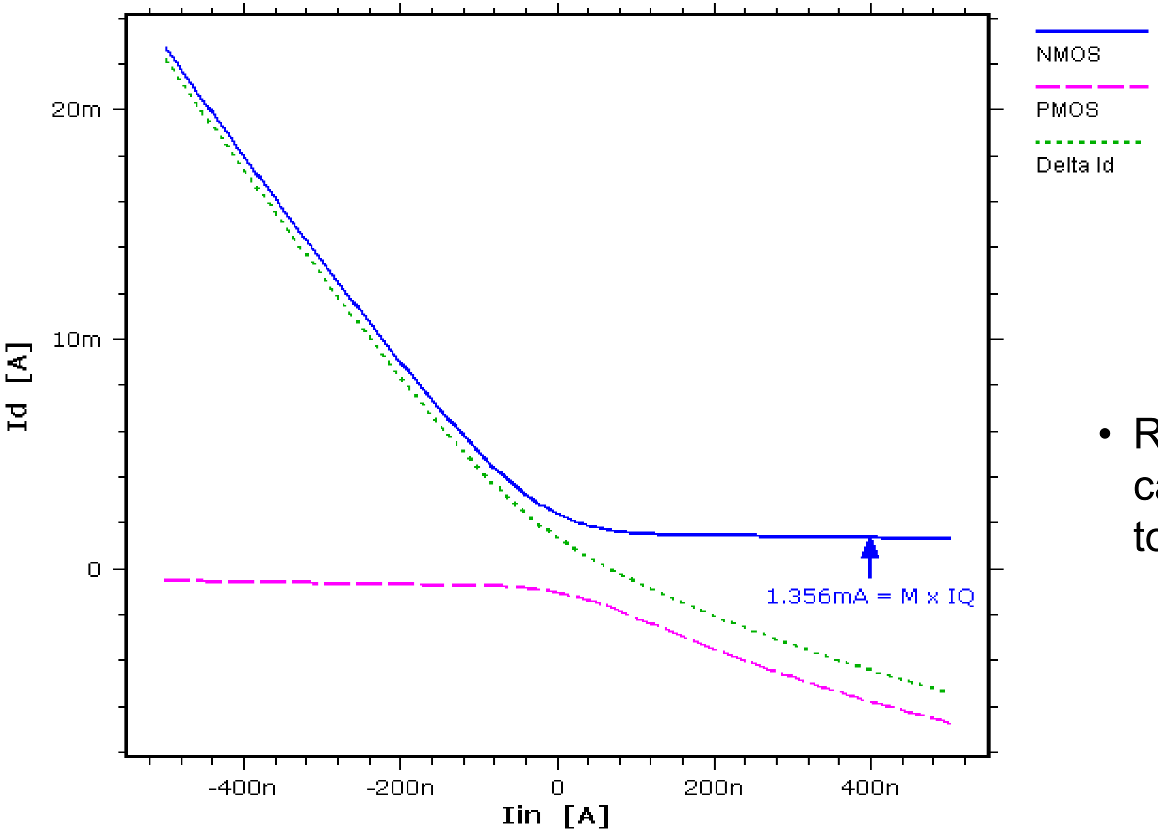


I_{D1}, I_{D2} (V_{out} = 0V)



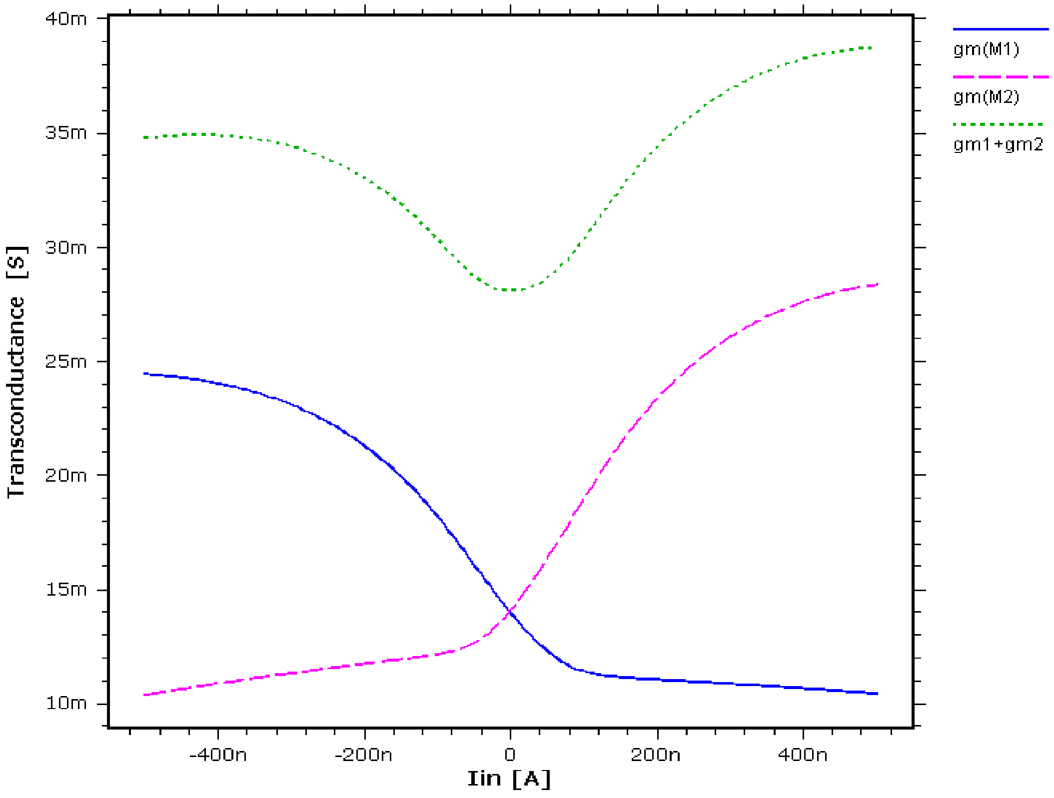
- Large current capability
- Defined quiescent current
- M1, M2 never turn off

I_{D1}, I_{D2} (V_{out} = 1.3V)



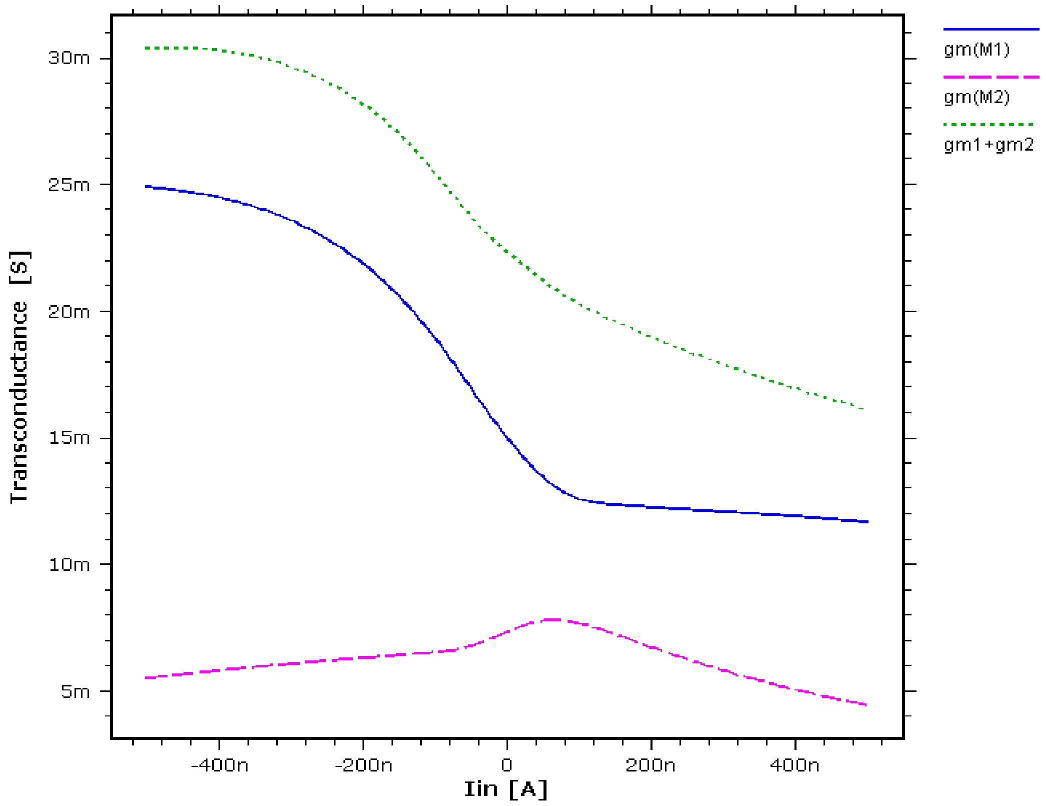
- Reduced current drive capability for outputs close to rail

g_{m1}, g_{m2} $(V_{out} = 0V)$



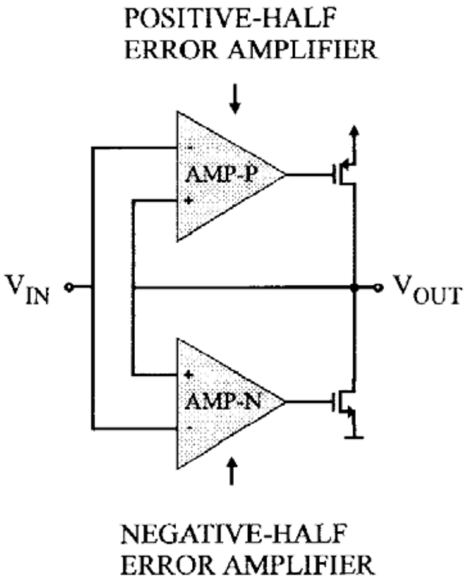
- Significant variation
- Weak inversion?
- Circuit not linear!
- Stability?

g_{m1}, g_{m2} ($V_{out} = 1.3V$)

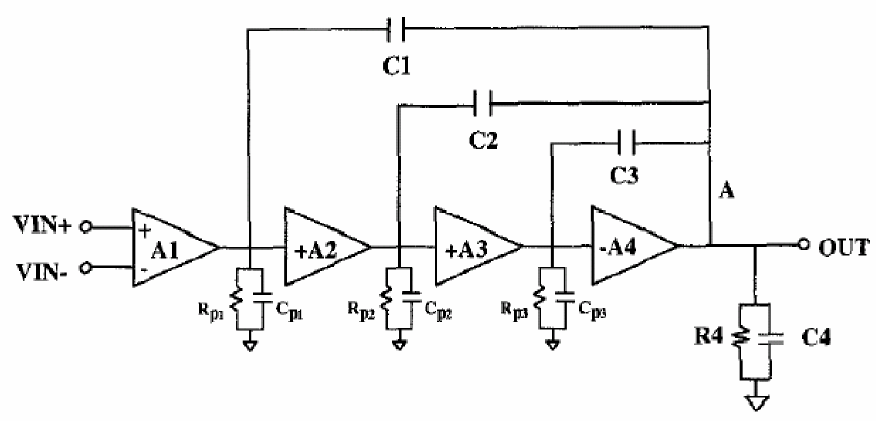


Feedback

Local



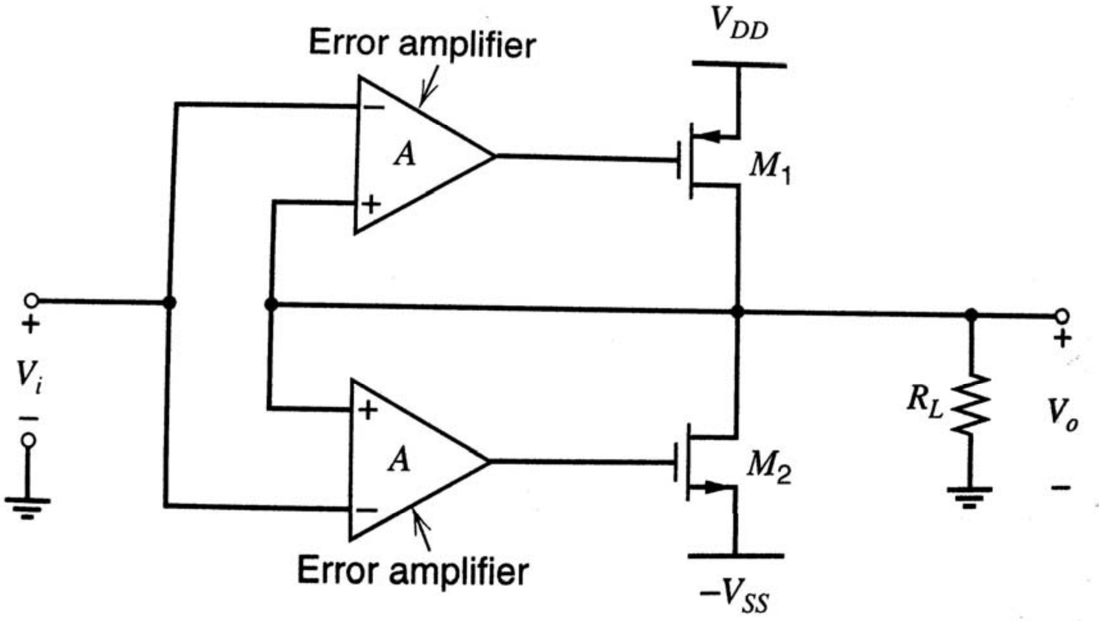
Global



K. E. Brehmer and J. B. Wieser, "Large swing CMOS power amplifier," *IEEE Journal of Solid-State Circuits,* vol. 18, pp. 624 - 629, December 1983.

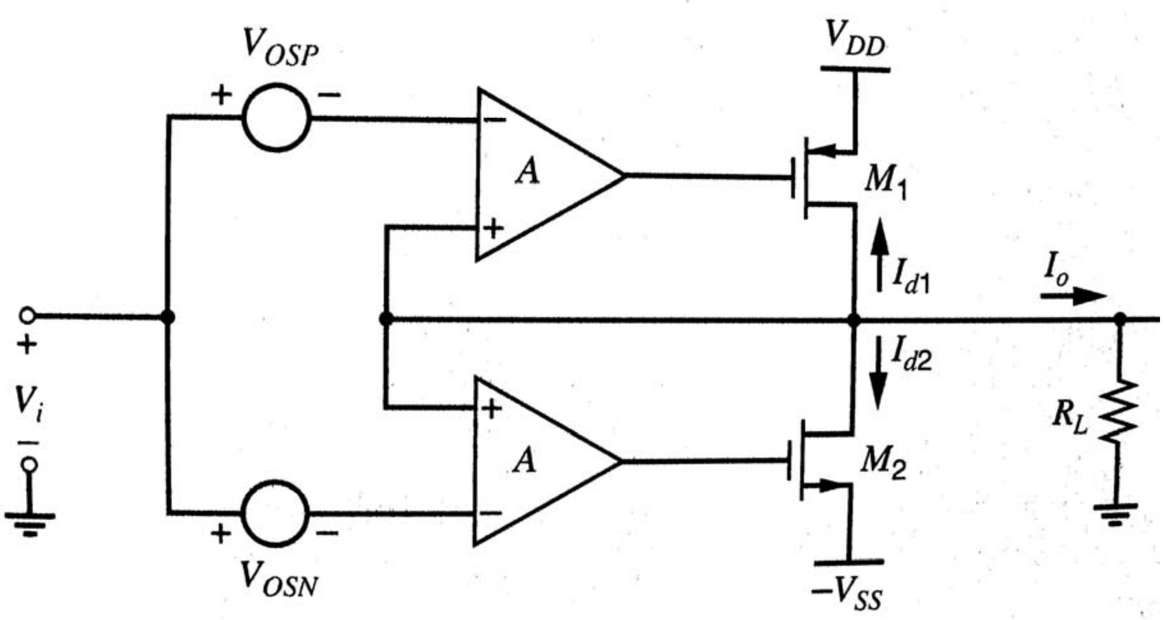
J. H. Huijsing and D. Linebarger, "Low-voltage operational amplifier with rail-to-rail input and output ranges," *IEEE Journal of Solid-State Circuits,* vol. 20, pp. 1144 - 1150, December 1985.

Using Helper Amps



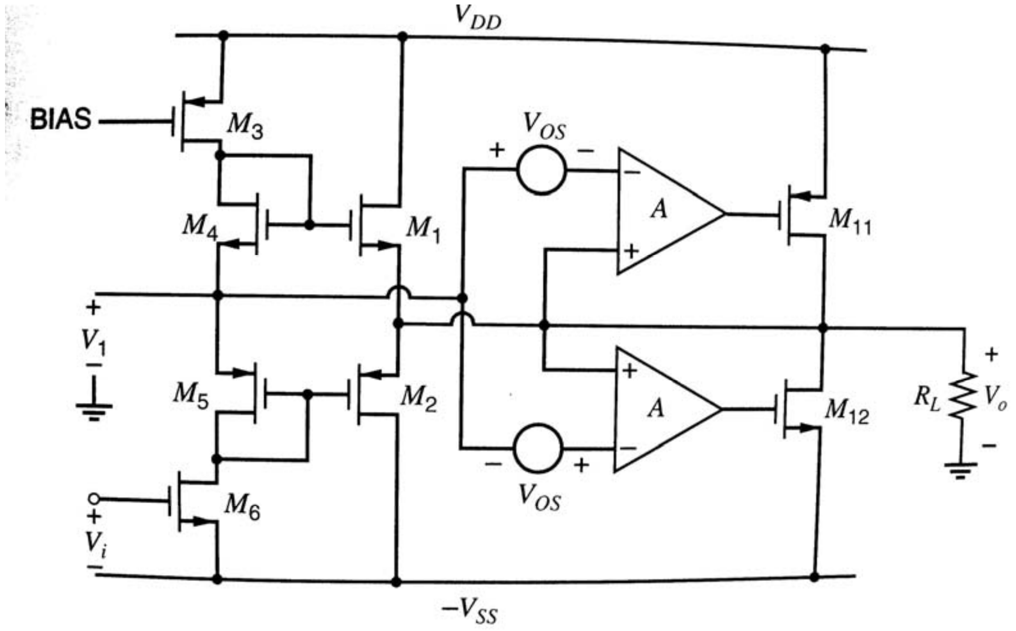
- Lower output resistance, reject distortion
- Introduce offset

Offset Error



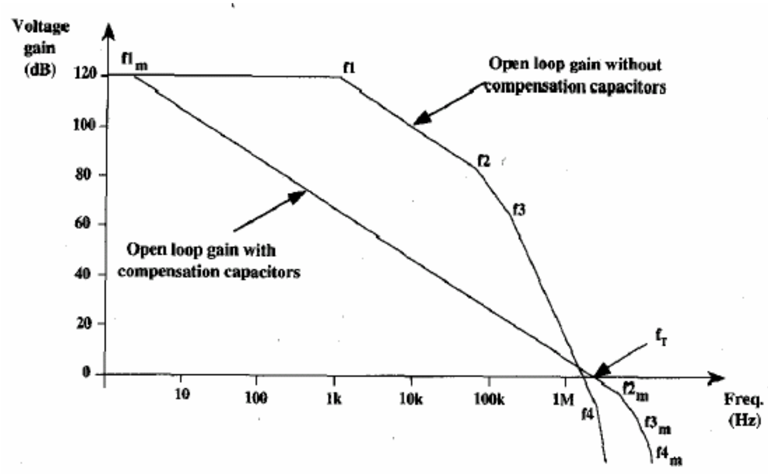
- Amplifier offset limits gain A

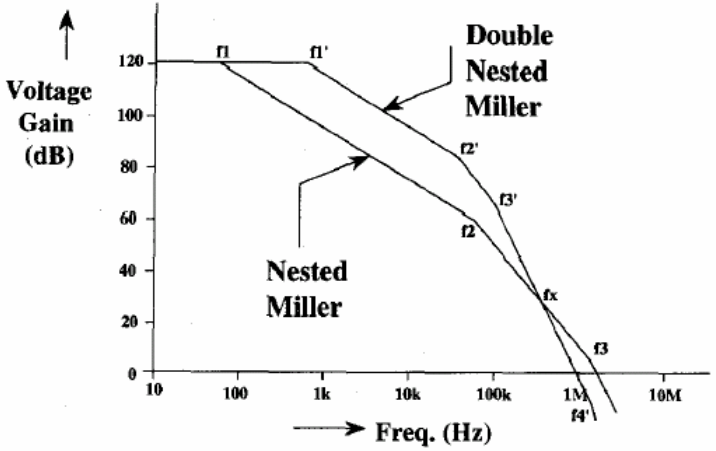
Hybrid Architecture



- Use followers and CS output stage together in parallel. M11/M12 only active for high swing.
- Since M11/M12 class B, can increase gain A

Nested Miller Feedback

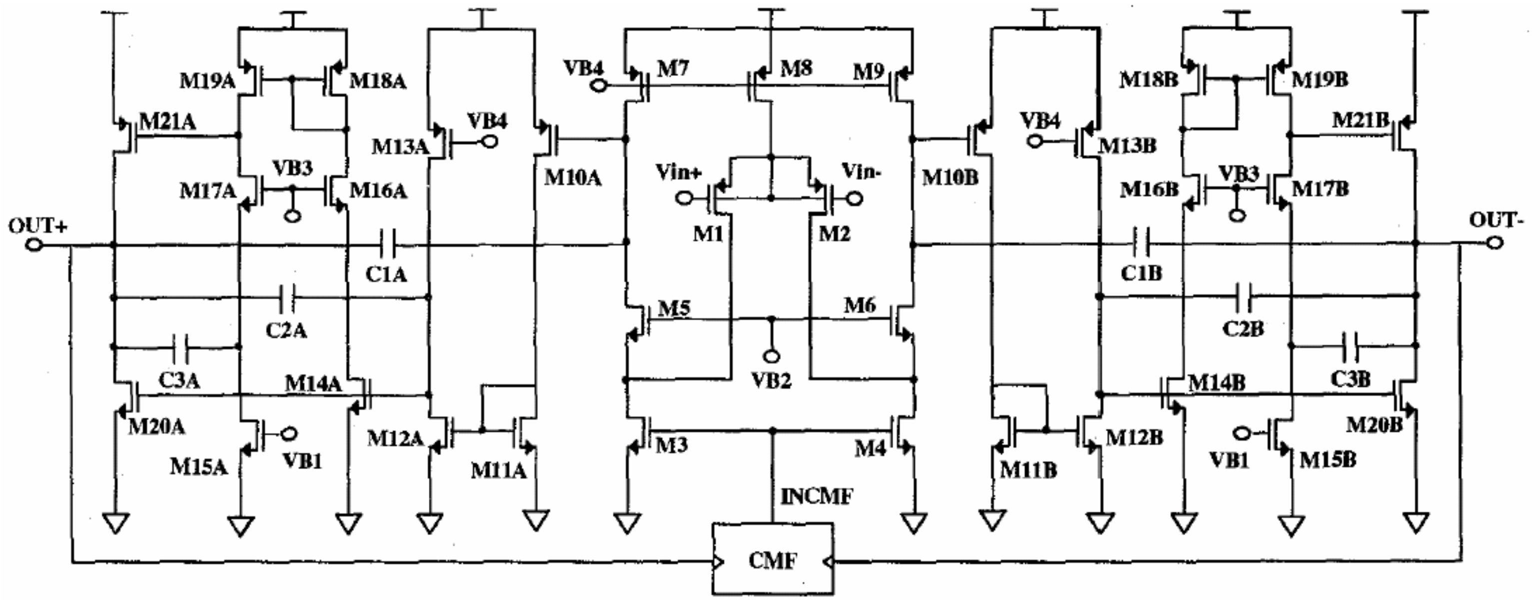




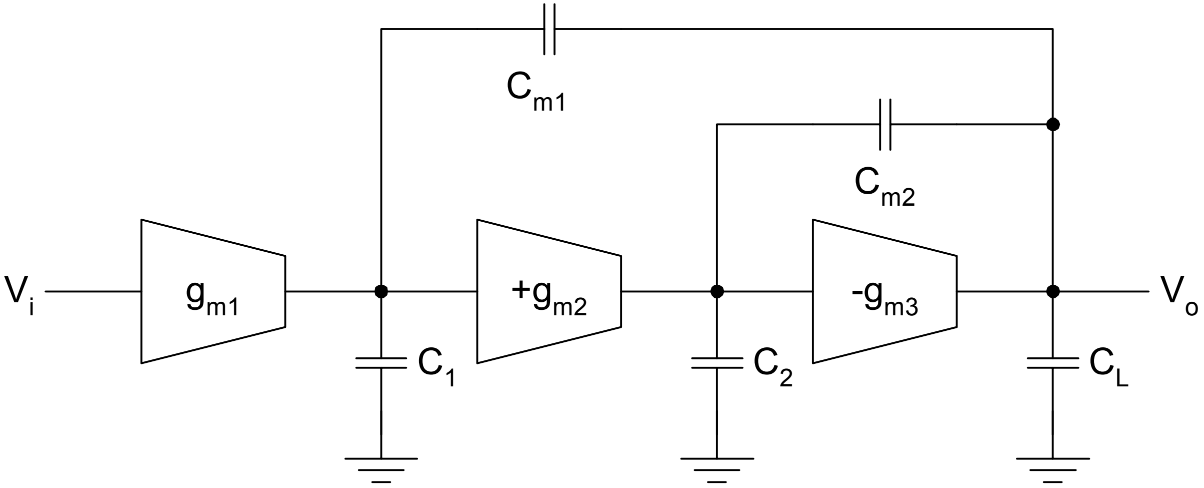
- Nonlinearities are attenuated by loop-gain with all loops (compensation) opened → multistage amps have an advantage in the mid-band over single-stage with same dc gain
- Some implementations combine local with nested Miller feedback

Ref: S. Pernici, G. Nicollini, and R. Castello, "A CMOS low-distortion fully differential power amplifier with double nested Miller compensation," *IEEE Journal of Solid-State Circuits,* vol. 28, pp. 758 - 763, July 1993.

Implementation Example



Nested Miller Amplifier



$$v_1 \cdot (s \cdot C_{m1}) - g_{m1} \cdot v_i - v_o \cdot s \cdot C_{m1} = 0$$

$$v_2 \cdot (s \cdot C_{m2}) - g_{m2} \cdot v_1 - v_o \cdot s \cdot C_{m2} = 0$$

$$v_o \cdot (s \cdot C_L + s \cdot C_{m1} + s \cdot C_{m2}) + g_{m3} \cdot v_2 - s \cdot C_{m1} \cdot v_1 - s \cdot C_{m2} \cdot v_2 = 0$$

Assumptions :

$C_1 << C_{m1}, \quad C_2 << C_{m2}$

$g_{m1}R_1 >> 1, \quad g_{m2}R_2 >> 1, \quad g_{m3}R_L >> 1$

Nested Miller OTA Analysis

$$a(s) = \frac{v_o}{v_i} = -\frac{g_{m1}}{s \cdot C_{m1}} \frac{1 - s \cdot \frac{C_{m2}}{g_{m3}} - s^2 \cdot \frac{C_{m1} \cdot C_{m2}}{g_{m2} \cdot g_{m3}}}{1 + s \cdot C_{m2} \cdot \left(\frac{1}{g_{m2}} - \frac{1}{g_{m3}} \right) + s^2 \cdot \frac{C_L \cdot C_{m2}}{g_{m2} \cdot g_{m3}}}$$

Dominant pole approximation:

$$D(s) = \left(1 - \frac{s}{p_2}\right)\left(1 - \frac{s}{p_2}\right)$$

$$\cong 1 - \frac{s}{p_2} + \frac{s^2}{p_2 p_3} = 1 + a_1 s + a_2 s^2$$

for $|p_3| >> |p_2|$ (p_2 is dominant pole)

$$p_2 \cong -\frac{1}{a_1}, \qquad p_3 \cong -\frac{a_1}{a_2}$$

$$p_1 = 0$$

$$p_2 = -\frac{1}{C_{m2}} \cdot \frac{g_{m2} \cdot g_{m3}}{g_{m3} - g_{m2}} = -\frac{g_{m2}}{C_{m2}}$$

$$p_3 = -C_{m2} \cdot \frac{g_{m3} - g_{m2}}{g_{m2} \cdot g_{m3}} \cdot \frac{g_{m2} \cdot g_{m3}}{C_L \cdot C_{m2}} = -\frac{g_{m3} - g_{m2}}{C_L} = -\frac{g_{m3}}{C_L}$$

$$\omega_u = \frac{g_{m1}}{C_{m1}}$$

Assumptions : $|p_3| >> |p_2|$ and $|p_2| >> \omega_u$

Note: for larger parasitics, p2, p3 can be complex. Faster?

Feedforward Zeros

$$1 - s\cdot\frac{C_{m2}}{g_{m3}} - s^{2}\cdot\frac{C_{m1}\cdot C_{m2}}{g_{m2}\cdot g_{m3}} = 0$$

$$z_1 = -\frac{1}{2}\cdot\frac{g_{m2}}{C_{m1}}\cdot\left(1 + \sqrt{1 + 4\cdot\frac{C_{m1}\cdot g_{m3}}{C_{m2}\cdot g_{m2}}}\right) < 0$$

LHP

$$z_2 = -\frac{1}{2}\cdot\frac{g_{m2}}{C_{m1}}\cdot\left(1 - \sqrt{1 + 4\cdot\frac{C_{m1}\cdot g_{m3}}{C_{m2}\cdot g_{m2}}}\right) > 0$$

RHP, potential problem

Design Example

given:

$C_L := 100\text{pF}$ $\quad f_u := 10\text{MHz}$ $\quad \omega_u := 2\cdot\pi\cdot f_u$

$|p_3| = K_3\cdot\omega_u$ $\quad K_3 := 10$

$|p_2| = K_2\cdot\omega_u$ $\quad K_2 := 3$

Small R_L could set additional constraint.

design:

$g_{m3} := K_3\cdot C_L\cdot\omega_u$ $\qquad g_{m3} = 62.832\,\text{mS}$

$\omega_{T3} := 2\cdot\pi\cdot 1\text{GHz}$ $\quad C_2 := \dfrac{g_{m3}}{\omega_{T3}}$ $\quad C_2 = 10\,\text{pF}$

$C_{m2} := 3\cdot C_2$ $\quad C_{m2} = 30\,\text{pF}$

$g_{m2} := K_2\cdot C_{m2}\cdot\omega_u$ $\qquad g_{m2} = 5.655\,\text{mS}$

$\omega_{T2} := 2\cdot\pi\cdot 1.5\text{GHz}$ $\quad C_1 := \dfrac{g_{m2}}{\omega_{T2}}$ $\quad C_1 = 0.6\,\text{pF}$

$C_{m1} := 3\cdot C_1$ $\quad C_{m1} = 1.8\,\text{pF}$

$g_{m1} := C_{m1}\cdot\omega_u$ $\qquad g_{m1} = 0.113\,\text{mS}$

$$z_1 := -\frac{1}{2}\cdot\frac{g_{m2}}{C_{m1}}\cdot\left(1 + \sqrt{1 + 4\cdot\frac{C_{m1}\cdot g_{m3}}{C_{m2}\cdot g_{m2}}}\right) \qquad \frac{z_1}{2\cdot\pi} = -728.714\,\text{MHz} \qquad \frac{z_1}{\omega_u} = -72.871$$

$$z_2 := -\frac{1}{2}\cdot\frac{g_{m2}}{C_{m1}}\cdot\left(1 - \sqrt{1 + 4\cdot\frac{C_{m1}\cdot g_{m3}}{C_{m2}\cdot g_{m2}}}\right) \qquad \frac{z_2}{2\cdot\pi} = 228.714\,\text{MHz} \qquad \frac{z_2}{\omega_u} = 22.871$$

More Conservative Choices

given:

$$C_L := 100\text{pF} \qquad f_u := 10\text{MHz} \qquad \omega_u := 2\cdot\pi\cdot f_u$$

$$|p_3| = K_3\cdot\omega_u \qquad K_3 := 12$$

$$|p_2| = K_2\cdot\omega_u \qquad K_2 := 4$$

design:

$$g_{m3} := K_3\cdot C_L\cdot\omega_u \qquad g_{m3} = 75.398\,\text{mS}$$

$$\omega_{T3} := 2\cdot\pi\cdot 1\text{GHz} \qquad C_2 := \frac{g_{m3}}{\omega_{T3}} \qquad C_2 = 12\,\text{pF}$$

$$C_{m2} := 6\cdot C_2 \qquad C_{m2} = 72\,\text{pF}$$

$$g_{m2} := K_2\cdot C_{m2}\cdot\omega_u \qquad g_{m2} = 18.096\,\text{mS}$$

$$\omega_{T2} := 2\cdot\pi\cdot 1.5\text{GHz} \qquad C_1 := \frac{g_{m2}}{\omega_{T2}} \qquad C_1 = 1.92\,\text{pF}$$

$$C_{m1} := 8\cdot C_1 \qquad C_{m1} = 15.36\,\text{pF}$$

$$g_{m1} := C_{m1}\cdot\omega_u \qquad g_{m1} = 0.113\,\text{mS}$$

$$z_1 := -\frac{1}{2}\cdot\frac{g_{m2}}{C_{m1}}\cdot\left(1 + \sqrt{1 + 4\cdot\frac{C_{m1}\cdot g_{m3}}{C_{m2}\cdot g_{m2}}}\right) \qquad \frac{z_1}{2\cdot\pi} = -293.848\,\text{MHz} \qquad \frac{z_1}{\omega_u} = -29.385$$

$$z_2 := -\frac{1}{2}\cdot\frac{g_{m2}}{C_{m1}}\cdot\left(1 - \sqrt{1 + 4\cdot\frac{C_{m1}\cdot g_{m3}}{C_{m2}\cdot g_{m2}}}\right) \qquad \frac{z_2}{2\cdot\pi} = 106.348\,\text{MHz} \qquad \frac{z_2}{\omega_u} = 10.635$$