Polytech'Montpellier – MEA4
M2 EEA – Systèmes Microélectroniques

Analog IC Design

Miller Operational Transconductance Amplifier &
Miller Operational Amplifier

Pascal Nouet – 2015/2016 - nouet@lirmm.fr

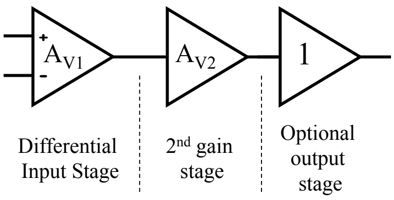
http://www.lirmm.fr/~nouet/homepage/lecture_ressources.html

Introduction

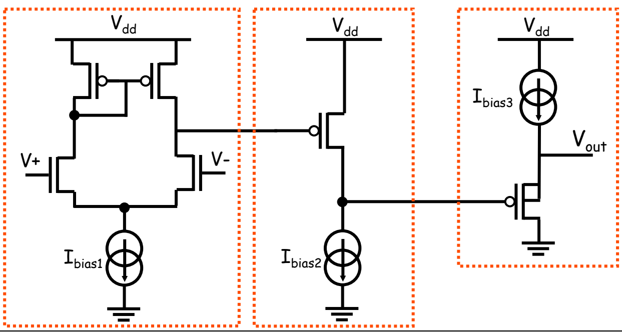
$$V_+ = V_{mc} + \frac{v_{in}}{2}$$

$$V_- = V_{mc} - \frac{v_{in}}{2}$$

$$v_{in} = V_+ - V_-$$



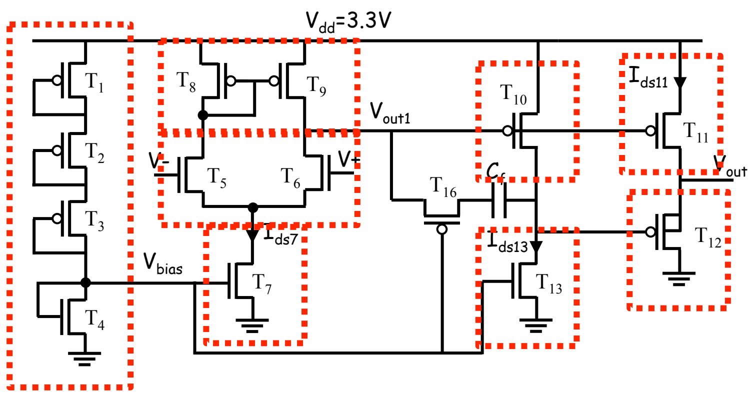
$$V_{out} = A_v \cdot v_{in}$$



Outline

- Introduction
- AOP assembly
- Dynamic behavior
- AOP stability
- AOP compensation
- Homework & Labs

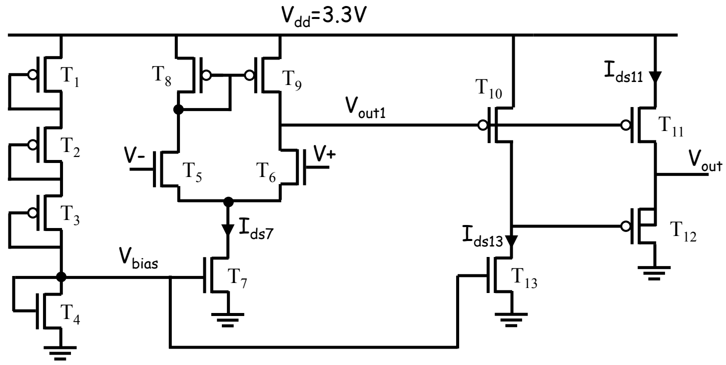
AOP assembly



Voltage reference **Differential pair** **Common source**

Current sources **Active load** **Common drain**

AOP assembly: connecting first stage to the second



$$I_{d13} = I_{d7}$$

$$V_{eff7} = V_{eff13}$$

$$I_{ds10} = 2I_{d8,9}$$

$$V_{eff10} = V_{eff8,9}$$

$$\left.\frac{W}{L}\right|_{10} = 2\left.\frac{W}{L}\right|_{8,9}$$

$\mathbf{g_{m10}}$ (and so 2nd stage gain) depends on the first stage design ($V_{eff8,9}$)

$$A_{v1} = \frac{v_{out1}}{v_{ind}} = -\frac{g_{m6}}{g_{ds6} + g_{ds9}}$$

$$A_{v2} = \frac{v_{out}}{v_{out1}} = -\frac{g_{m10}}{g_{ds10} + g_{ds13}}$$

Total dc gain

$$A_{v1} = \frac{v_{out1}}{v_{ind}} = -\frac{g_{m6}}{g_{ds6} + g_{ds9}}$$

$$g_{m6} = \frac{2\frac{I_{ds7}}{2}}{V_{eff6}} = \frac{I_{ds7}}{V_{eff6}}$$

$$g_{ds6} = \lambda_n \frac{I_{ds7}}{2}$$

$$g_{ds9} = \lambda_p \frac{I_{ds7}}{2}$$

$$A_{v2} = \frac{v_{out}}{v_{out1}} = -\frac{g_{m10}}{g_{ds10} + g_{ds13}}$$

$$g_{m10} = \frac{2I_{ds13}}{V_{eff110}}$$

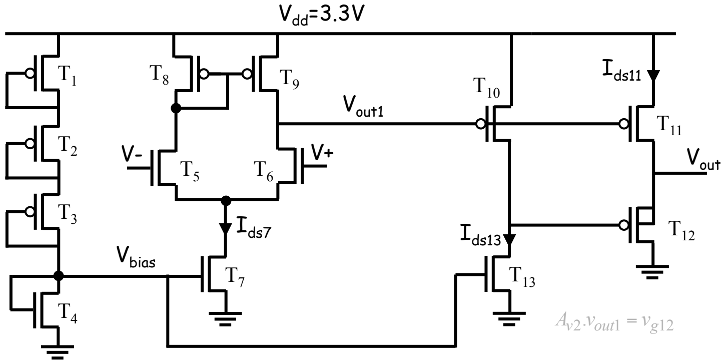
$$g_{ds10} = \lambda_p I_{ds13}$$

$$g_{ds13} = \lambda_n I_{ds13}$$

$$A_v = A_{v1} \times A_{v2}$$

$$A_v = \frac{4}{(\lambda_n + \lambda_p)^2 V_{eff6} V_{eff10}}$$

AOP assembly: connecting 2nd stage to the output stage



- V_{gs11} is fixed by connecting T_{11} gate to the reference voltage stage or to V_{out1} which variations are much smaller than those of V_{g12}

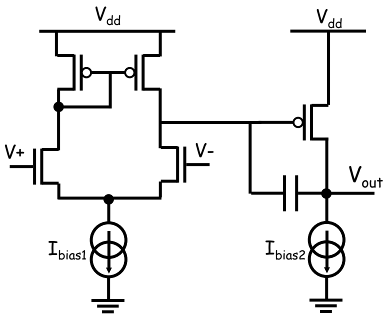
Outline

- Introduction
- AOP assembly
- Dynamic behavior
- AOP stability
- AOP compensation
- Homework & Labs

Dynamic behavior

- Miller OTA is a two-stage amplifier with high output impedance
  - DC gain

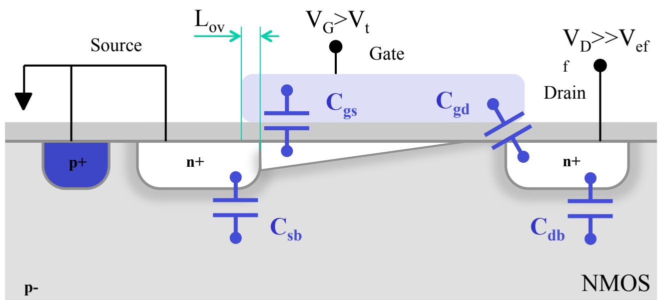
$$A_{v1} \cong -\frac{g_{m1}}{g_{out1}} \qquad A_{v2} \cong -\frac{g_{m2}}{g_{out2}}$$



- Open-Loop Dynamic Performances
  - Slew-Rate (V/s) : ***SR***
  - Unity-gain frequency (MHz) : f_u
  - Cut-off frequency / bandwidth (kHz) : f_c
  - Gain-Bandwidth product (MHz) : ***GBW***

    for a first order behaviour, GBW=f_u

MOSFET intrinsic capacitances



Gate Capacitances

$$C_{gs} \approx \left(\frac{2}{3}WLC_{ox}\right) + \left(WL_{ov}C_{ox}\right)$$

$$C_{gd} \approx \left(WL_{ov}C_{ox}\right) \qquad L_{ov} \approx \frac{L}{10}$$

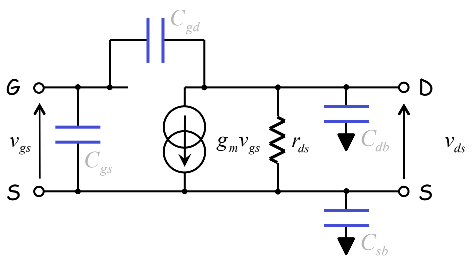
Junction Capacitance (reverse bias)

$$C_{sb} \approx \left(A_S + A_{ch}\right)C_{js} \qquad C_{jx} \approx \frac{C_{j0}}{\sqrt{1+\frac{V_{xb}}{\psi_0}}}$$

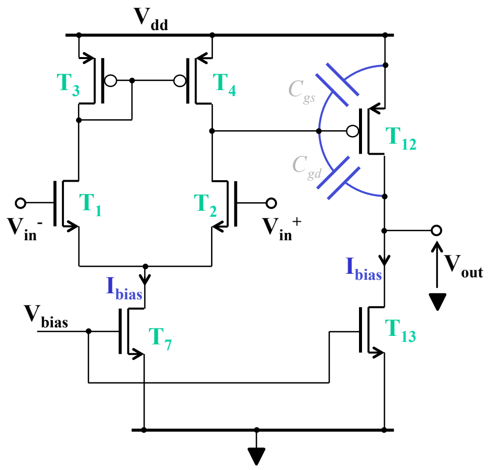
$$C_{db} \approx A_d C_{jd}$$

MOSFET dynamic small-signal model

MOS Transistor "Small Signal" model for dynamic analysis



First Pole Analysis



$$A_{v1} = \frac{v_A}{v_{in}} = -\frac{g_{m1}}{g_{ds2} + g_{ds4} + g_{in12}}$$

$$g_{in12} = ?$$

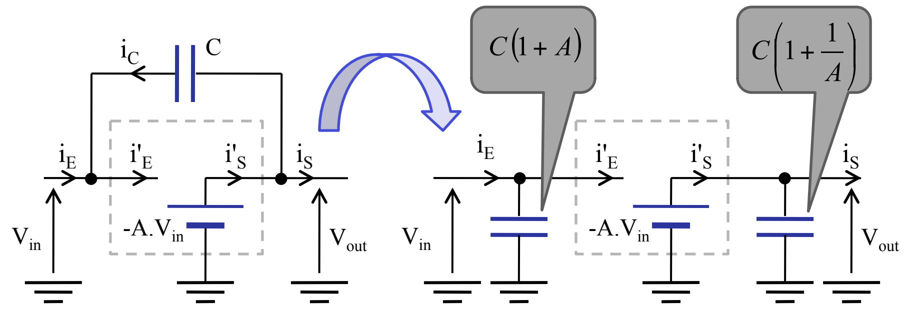
$$C_{d4}, C_{d2}$$

$$C_{gd12} = 10\% \cdot C_{g12}$$

$$C_{gs12} = \frac{2}{3} \cdot C_{g12}$$

$$C_{g12} = C_{oxp} \cdot W_{12} \cdot L_{12}$$

Miller Transformation



Input Current

$i_E = -i_C + i_E^{'}$ $\quad i_C = Cp(V_{out} - V_{in})$

$i_E = -CpV_{out} + CpV_{in} + i_E^{'}$

$$i_E = CpV_{in}(1 + A) + i_E^{'}$$

Output Current

$i_S^{'} = i_C + i_S = Cp(V_{out} - V_{in}) + i_S$

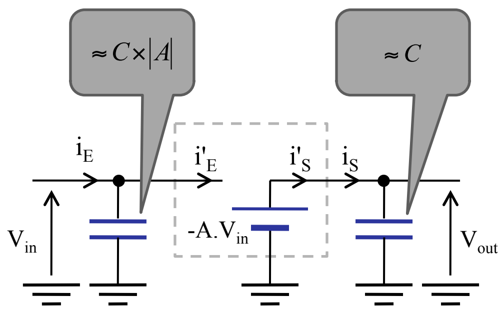
$$i_S^{'} = Cp\,V_{out}\left(1 + \frac{1}{A}\right) + i_S$$

Miller Transformation

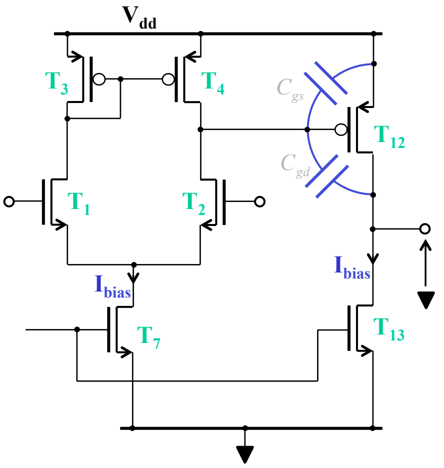
With A > 0 et |A| >> 1:

$$C(1 + A) \approx C \times |A|$$

$$C\left(1 + \frac{1}{A}\right) \approx C$$



Pole due to First Stage Output

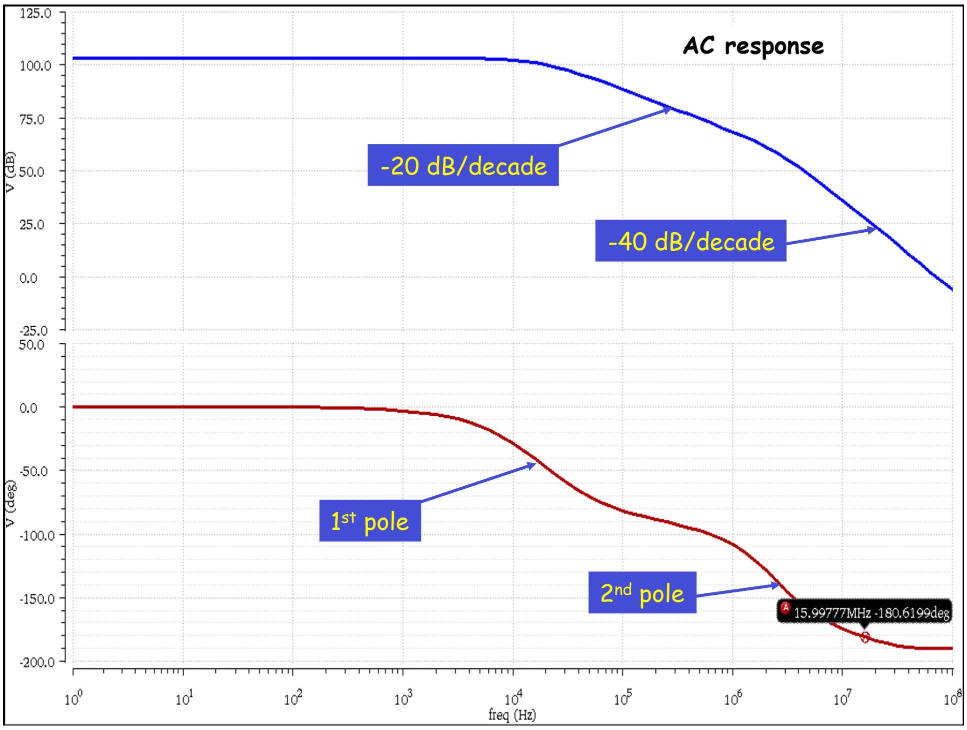


$$A_{v1} = \frac{v_A}{v_{in}} = -\frac{g_{m1}}{g_{ds2} + g_{ds4} + g_{in12}}$$

$$g_{in12} = C_{gs}p + |A_{v2}|C_{gd}p$$

$$g_{in12} = \underbrace{\left(C_{gs} + |A_{v2}|C_{gd}\right)}_{C_{in12}}p$$

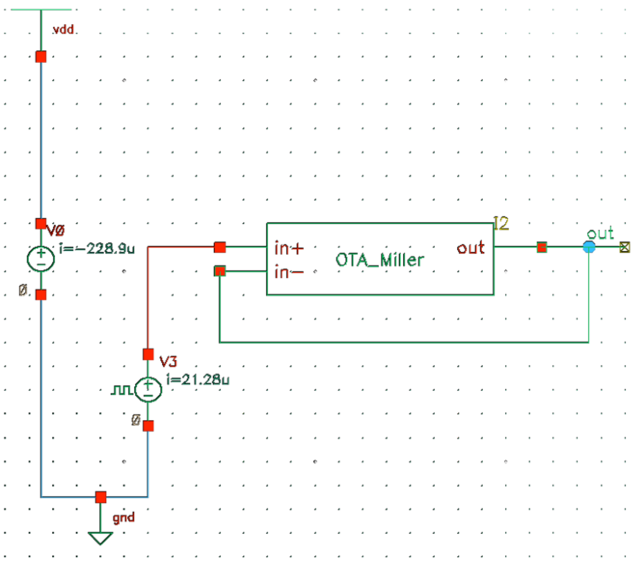
$$A_{v1} = -\frac{g_{m1}}{g_{ds2} + g_{ds4}} \times \frac{1}{\left(1 + \frac{C_{in12}}{(g_{ds2} + g_{ds4})}p\right)}$$



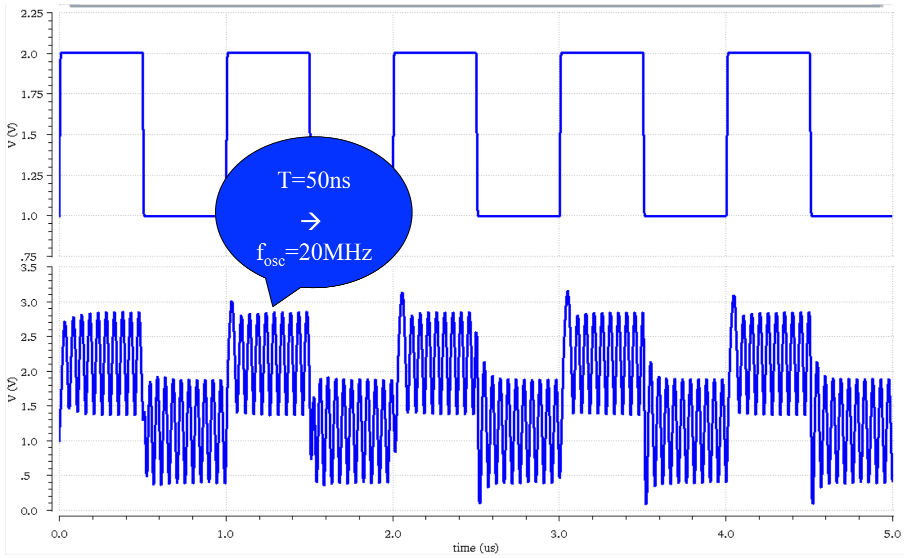
Outline

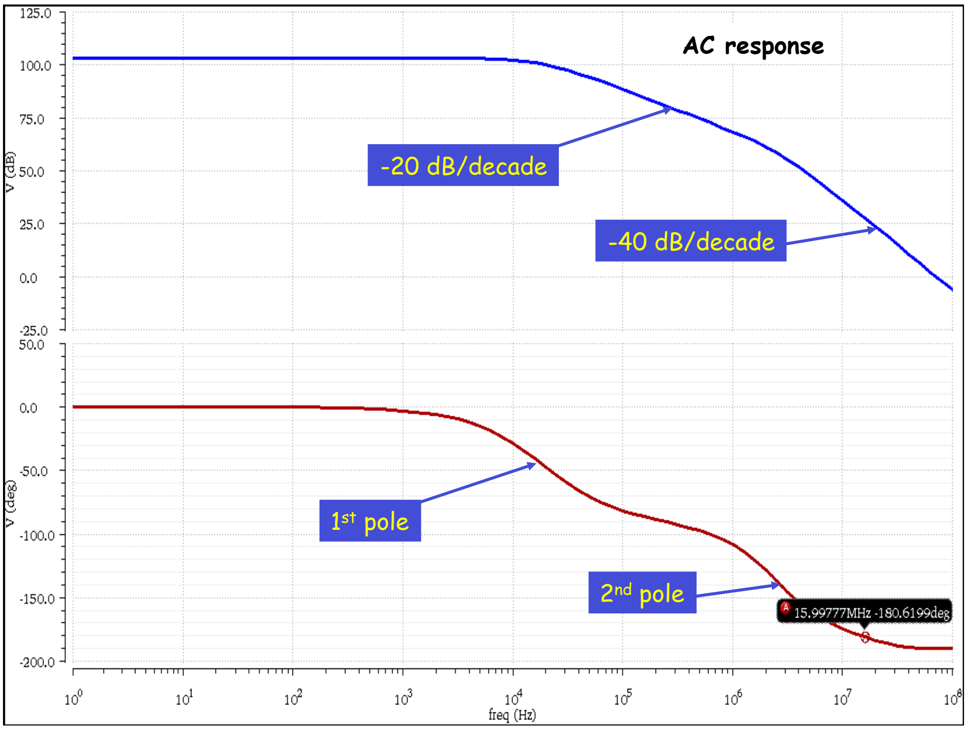
- Introduction
- AOP assembly
- Dynamic behavior
- AOP stability
- AOP compensation
- Homework & Labs

Voltage follower



Voltage follower





Summary

- Simplified Model
  - One stage → One pole
  - First stage pole is dominant (Miller Effect)
  - A two stage Amplifier should be stable…
- Simulation
  - AC simulations : f_c, f_u and ***GBW***
  - Other poles (current source, …)
  - Often, a two stage amplifier is not naturally stable

Outline

- Introduction
- AOP assembly
- Dynamic behavior
- AOP stability
- AOP compensation
- Homework & Labs

Dominant pole adjustment

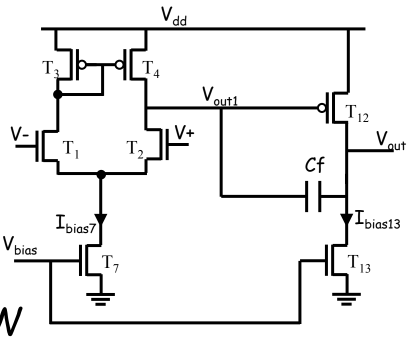
- Idea: 1st pole shifts down to low frequencies by adding C_f in parallel with C_{gd12}

$$C_f >> C_{gd12} \Rightarrow C_{total} \approx |A_{v2}| \cdot C_f \Rightarrow \tau \approx \frac{C_{total}}{g_{ds2} + g_{ds4}}$$

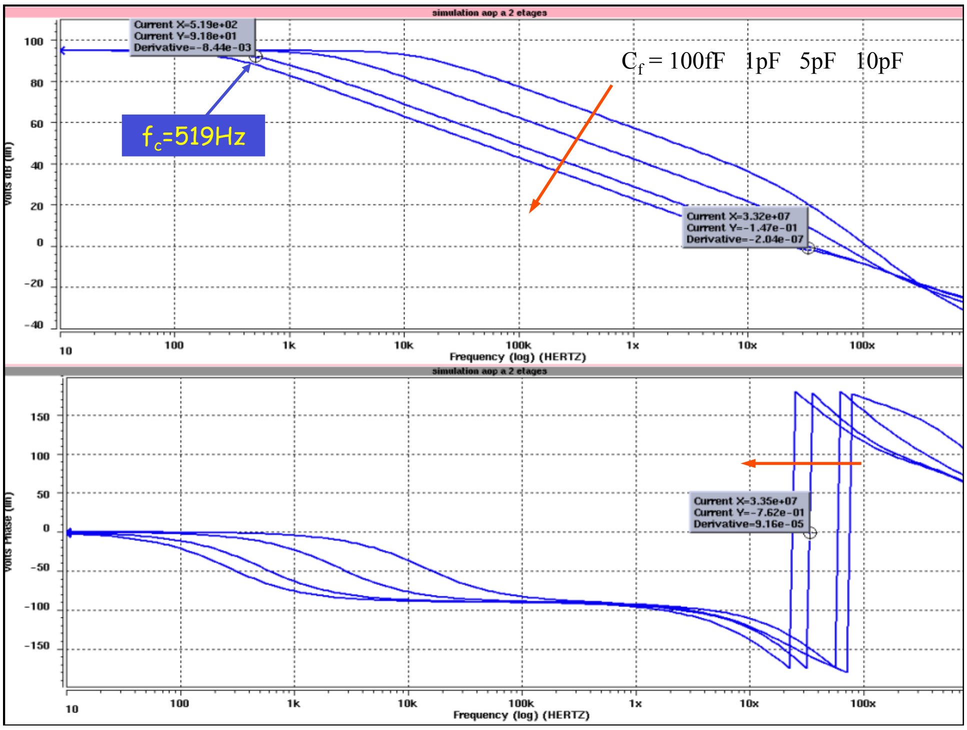
$$\Rightarrow f_{c1} = \frac{1}{2\pi\tau} = \frac{g_{ds2} + g_{ds4}}{|A_{v2}|.2\pi.C_f}$$

example: $f_{c1} = 500Hz$

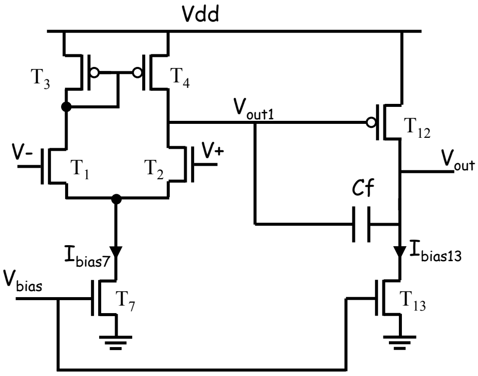
$$\Rightarrow C_f = \frac{3{,}6.10^{-6}}{227.2\pi.500} = 5pF$$



- Amplifier behaves like a first order circuit → GBW



Close-up view of the Miller effect



$r_1 \Rightarrow g_{ds2} // g_{ds4}$

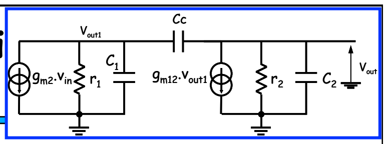
$C_1 \Rightarrow C_{d2} + C_{d4} + C_{gs12}$

$r_2 \Rightarrow g_{ds12} // g_{ds13} // g_{load}$

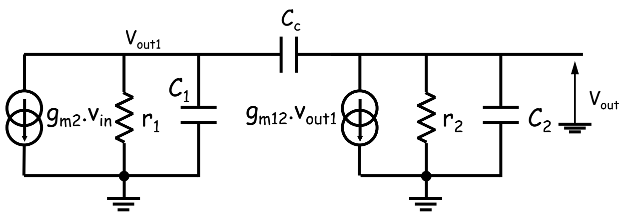
$C_2 \Rightarrow C_{d12} + C_{d13} + C_{load}$

$C_c \Rightarrow C_f + C_{gd12}$

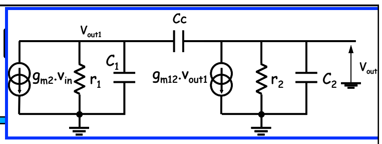
Close-up view of the Miller effect



$$-g_{m2}.v_{in} = \frac{v_{out1}}{r_1} + C_1 p.v_{out1} + C_c p.(v_{out1} - v_{out}) \Rightarrow v_{out1} = f(v_{in}, v_{out})$$



Close-up view of the Mi effect



$$\frac{v_{out}}{v_{in}} = \frac{g_{m2}r_1 \cdot g_{m12}r_2 \cdot \left(1 - \frac{C_c p}{g_{m12}}\right)}{1 + ap + bp^2}$$

$$1 + ap + bp^2 = \left(1 + \frac{p}{\omega_{p1}}\right)\left(1 + \frac{p}{\omega_{p2}}\right)$$

$$f_{p1} = \frac{1}{2\pi \cdot r_1 g_{m12} r_2 C_c}$$

$$f_{p2} = \frac{g_{m12}}{2\pi \cdot (C_1 + C_2)}$$

$$f_z = \frac{-g_{m12}}{2\pi \cdot C_c}$$

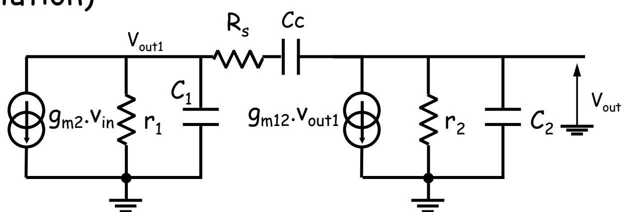
- Increasing C_c
  - f_z and f_{p1} are shifted down accordingly
- Increase of g_{m12}
  → silicon cost, power consumption
- Design Tip : higher g_{m12} increases stability

Close-up view of the Miller effect

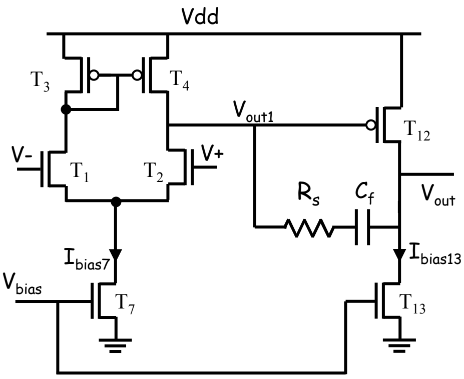
- Solution: adding a serial resistance
  - 1st and 2nd poles doesn't move a lot
  - Additional 3rd pole @ higher frequencies
  - Zero is changed:
  - →Zero can be adjusted

$$f_z = \frac{-1}{2\pi \cdot C_c (1/g_{m12} - R_s)}$$

  - → to compensate 2nd pole (not robust enough)
  - → just after the unity gain frequency (viable solution)



Zero positioning for stability: first method



- Step 1:
  - First simulation with random C_{f0} (5pF) and R_s=0
  - Choice of a phase margin
    → extract f_u
    → measure $A_v(f_u)$
- Step 2:
  - Calculation of $C_f = C_{f0}.A_v(f_u)$
  - Zero positionning @ f_u+20%
    → R_s calculation

Zero positioning for stability: 2nd method

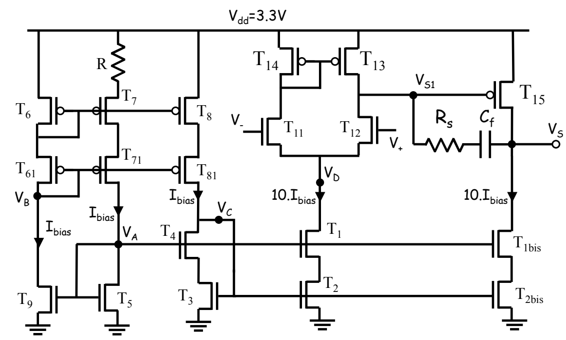
- 2nd method:
  - Choice of unity-gain frequency:
    - Example: from initial f_u=18MHz → $f_u = 10MHz$
  - Calculation of the capacitance: $C_f = \frac{g_{m2}}{2\pi f_u}$
  - Zero positionning
    - f_u + 20% : 12MHz →

$$f_z = \frac{-1}{2\pi \cdot C_c\left(1/g_{m12} - R_s\right)} = 12MHz \Rightarrow R_s = \frac{1}{2\pi f_z \cdot C_c} + \frac{1}{g_{m12}}$$

Outline

- Introduction
- AOP assembly
- Dynamic behavior
- AOP stability
- AOP compensation
- Homework & Labs

Homework & Lab



Caractérisation dynamique de l'OTA Miller

Tracez le diagramme de Bode du montage et concluez sur la stabilité de ce montage utilisé en suiveur de tension. Proposez un circuit de compensation pour cet amplificateur puis tracez à nouveau le diagramme de Bode du montage. En déduire les marges de gain et de phase de cet amplificateur utilisé en montage suiveur.

Montez l'amplificateur en suiveur de tension puis appliquez un échelon de tension entre 1V et 2V sur l'entrée et observez la sortie. Conclure et expliquez les résultats obtenus.