Advanced Analog Building Blocks
Two Stage amplifiers
Fully Differential amplifiers

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Course web
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OTA and OPAmplifiers

- **OTA**: Operational Transconductance Amplifier
  Voltage input $\rightarrow$ Current output

- **OPAmp**: Operational Amplifier
  Voltage input $\rightarrow$ Voltage output (buffered)

Key parameters:
- Gain Bandwidth Product
- DC Gain
- Stability (Phase margin)
- Biasing (symmetry and matching)
Introduction
Two Stage Amplifiers
Fully Differential amplifier

OTA and OPAmpl

General OPAmpl model

- First stage OTA: \( i_1 = (v_+ - v_-) \times g_m = v_{\text{diff}} \times g_m \)
- Virtual short circuit in \( v_1 \); \( \rightarrow \frac{v_o}{i_1} = -\frac{1}{sC_c} \)
- Thus; \( |A_v(f)| = \frac{g_m}{2\pi f C_c} \)
- \( \text{GBW} = A_v(f) f_T = 1 = \frac{g_m}{2\pi C_c} \)
Two stage amplifier;
- First stage: OTA
- Second stage: Inverter
- Miller capacitance between first and second stage
• 3-node for analysis (3 virtually grounded in ac)
• Load affects stability!

\[
\left(\frac{W}{L}\right)_8 = \left(\frac{W}{L}\right)_7 \\
\left(\frac{W}{L}\right)_5 \gg \left(\frac{W}{L}\right)_7 \\
\text{(Typically x10)}
\]
• Small-signal model (node 2 is low-resistance node).

\[ g_{o2,4} = g_{o2} + g_{o4} \]
\[ G'_L = G_L + g_{o5} + g_{o6} \]
\[ C'_L = C_L + C_4 \]

\[ A_V = \frac{v_o}{v_{in}} = \frac{v_i}{v_{in}} \frac{v_o}{v_i} = \left( \frac{g_{m1}}{g_{o2,4}} \right) \left( \frac{g_{m6}}{G'_L} \right) = A_{V1} A_{V2} \]
Miller OTA - Pole splitting effect

\[ V_i \rightarrow V_i \]

\[ R_S \quad C_{GS} \quad C_{GD} \quad g_m \quad C_{DS} \quad R_L \]

- **Miller OTA - schematic**
- **Miller OTA - analysis**
- **Design**
- **Characteristics**

Pole splitting effect:

- \( f_c = f_a \)
- \( f_n = f \)
- \( C_{gs} + C_{gs} = 3.5p \)

Frequency response: \( |A_v(C_{gs})| \)
Miller OTA - Circuit poles

- Circuit poles without $C_c$
  
  - $f_{p1} = \frac{g_{o2.4}}{2\pi C_1} \rightarrow C_1 = C_{GD2} + C_{DB2} + C_{GD4} + C_{DB4} + C_{GS6}$
  
  - $f_{p4} = \frac{G_L'}{2\pi (C_L + C_4)} \rightarrow C_4 = C_{GD5} + C_{DB5} + C_{DB6}$
  
  - $f_{p2} = \frac{g_{m3}}{2\pi C_2} \rightarrow C_2 = C_{GS3} + C_{DB3} + C_{GS4} + C_{GD4} + C_{GD1} + C_{DB1}$

- $f_{p2}$ goes to high frequency forming a pole-zero pair, so can be neglected.

- **Adding $C_c$ the dominant pole becomes more dominant;**

  $BW \approx f_d = \frac{g_{o2.4}}{2\pi A_v2 C_c}$ (applying Miller effect)

  $GBW \approx \frac{g_{m1}}{2\pi C_c}$

- Non-dominant pole, assuming $C_1 << C_c, C'_L$ and $g_{m6} >> G_L'$;

  $f_{nd} \approx \frac{g_{m6}}{2\pi C'_L}$

- $PM \approx 90^\circ - \arctg \frac{GBW}{f_{nd}} \rightarrow f_{nd} = 3GBW$ ($PM \approx 70^\circ$)
Variation of poles and zeros with $C_c$

- $C_c$ value is fundamental to achieve enough GBW and PM

- $\text{GBW} \approx \frac{g_{m1}}{2\pi C_c}$

- $\text{PM} \approx 90^\circ - \arctg \frac{\text{GBW}}{f_{nd}}$

- $f_{nd} \approx \frac{g_{m6}}{2\pi C_L'}, g_m = \frac{2I_D}{(V_{GS}-V_T)}$

- $f_{nd} = 3\text{GBW (PM} \approx 70^\circ)$
Miller OTA - Steps for design

- Take a value for $I_{D6} = I_{D5}$
- For $M_6$;
  1. Choose the overdrive voltage (ex. $V_{GS} - V_T = 0.2$).
  2. Obtain $g_{m6} = \frac{2I_{D6}}{V_{GS6} - V_T}$ and $(\frac{W}{L})_6 = \frac{g_{m6}}{K'(V_{GS5} - V_T)}$
  3. Use minimum $L_6$ to get $W_6$
- Repeat for $M_5$ (now use $V_{GS} - V_T = 0.5$ for better matching, reduced swing)
- Calculate $C_c$ for desired $A_v$.
- Use around a factor 10 between $M_5$ and first stage bias.
- Iterate on simulation to fine tune values.
Miller OTA - characteristics

- Common mode input:
  \[ V_{CM_{MAX}} = V_{DD} - V_{GS1} - V_{DS7} \]
  \[ V_{CM_{MIN}} = V_{SS} + V_{GS3} - V_{DS1} - V_{GS1} \]
- Output voltage range, with no \( R_L \) rail-to-rail with some distortion due to MOS linear operation close to rails.
- Slew rate, non linear effect. Maximum rate output voltage variation. \( SR = \frac{I_{bias_{1st\ stage}}}{C_c} \)
- Output impedance: (will limit output voltage when \( R_L \))
Fully differential amplifiers show excellent CMRR and PSRR which make them very useful for mixed-signal design.

- No current mirror as load, just current sources.
- Nodes 1 and 2 become symmetric.
- $GBW \approx \frac{g_{m1}}{2\pi C_L}$

**Problem**
Keep all transistors saturated, regulation of $V_{B1,2}$
• The common-mode output voltage is sensed and fed back to load sources (CMFB: Common-Mode FeedBack).
Introduction
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Schematic
CMFB

Fully Differential - CMFB

- More usual implementation

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Open loop gain:
\[ A_{vCM} = B_1 B_2 g_m R_L \]
\[ GBW_{CM} = \frac{B_1 B_2 g_m}{2\pi C_L} \]

- GBW can be made high with more power.
- Condition:
  \[ GBW_{CM} > GBW_{DIFF} \]
- The CMFB increases the CMRR.
Exercise 1: Miller OTA

Design a Miller OTA with the following specifications:

- $A_{vDC} = 100$
- $BW = 100MHz$
- $PM > 70^\circ$
- Try to minimize power consumption.

Use $R_L = 1M, C_L = 1pF$. 
Exercise 2: Fully differential amplifier

Design a Fully differential amplifier with CMFB with the following specifications:

- \( A_{vDC} = 100 \)
- \( BW = 100\text{MHz} \)
- \( PM > 70^\circ \)
- Try to minimize power consumption.

Use \( R_L = 1M, \ C_L = 1pF \).