M2 EEA - Systèmes Microélectroniques
Polytech'montpellier - ERII 4

Analog Integrated Circuits
Chapter IX
Miller Operational Transconductance Amplifier: Dynamic performances
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Plan

• Introduction
• Two stage amplifier Dynamic Performances
  - Cut-off frequency and poles
  - AC simulations
  - Dominant pole and slew-rate
  - Stability and compensation
• From Miller OTA to Miller OPAMP
• Other amplifiers

Introduction

• Miller OTA is a two-stage amplifier with high output impedance
  \[ A_1 = \frac{g_{m1}}{g_{m1}} \quad A_2 = \frac{g_{m2}}{g_{m2}} \]

• Dynamic performances
  - Slew-Rate (SR)
  - Cut-off frequency / bandwidth (f_c)
  - Unity-gain frequency (f_u)
  - Gain-Bandwidth product (GBW)

Pole due to the first stage output

\[ f_c = \frac{1}{2\pi C_{oa} C_{os}} \]

\[ f_u = \frac{g_{m2} C_{oa}}{C_{os}} \]

\[ \tau = \frac{g_{m2}}{10 C_{oa}} \quad \text{\rightarrow} \quad f_i = \frac{1}{2\pi \tau} \]

Other amplifiers

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Studied OTA

\[ A_1 = - \frac{g_{m1}}{g_{d2} + g_{ds}} \quad A_2 = - \frac{g_{m2}}{g_{d1} + g_{ds}} \]

DC gain: impact of an output load

- \( R_{out} = 10 \, \text{M}\Omega, 1 \, \text{M}\Omega \) et 100k\( \Omega \)

\[ A_v = A_v \times \frac{g_{d2} + g_{ds}}{g_{d1} + g_{ds}} \]

Two stage OTA: ac response analysis

- Phase diagram (without compensation)
  - 1\( \text{er} \) pole : 23900 Hz
  - 2\( \text{nde} \) pole : 19,2 MHz
  - 180° phase shift: 67,6 MHz

Two stage OTA: ac response analysis

- Theoretical analysis of 1\( \text{er} \) pole due to capacitances
  - \( c_{dtot} \) 178.5f  188.1f
  - \( c_{gs} \) 655.3f
  - \( c_{gd} \) 83.27f
  \[ A_v = -227 \Rightarrow A_v \times C_{dtot} = 18.9 \, \text{pF} \]
  \[ C_{total} = 19.92 \, \text{pF} \]
  \[ \tau = \frac{C_{total}}{g_{ds} + g_{ds}} = 6.51 \, \mu \text{s} \Rightarrow f_1 = \frac{1}{2\pi \tau} = 24.4 \, \text{kHz} \]
Two stage OTA: ac response analysis

- Diagramme de gain (AOP non compensé)
  - DC gain: 59566 (95.5 dB)
  - Unity-gain frequency: 153 MHz
  \( \rightarrow \) gain @ phase shift equal to -180° > 0 dB

Two stage OTA: impact of an output capacitance

- Gain diagram \( \rightarrow \) 2\textsuperscript{nd} pole is shifted

\[ \tau_s = \frac{C_{\text{out}}}{g_{\text{ds}} + g_{\text{ds}}} \Rightarrow f_s = \frac{4.10^{-6}}{2\pi C_{\text{out}}} \]

Poles of an amplifier

- Simplified model
  - One stage \( \rightarrow \) one pole
  - First stage pole is a dominant pole (Miller effect)
  - A two stage amplifier should be stable

- Simulated behavior, some other poles exist (current source for example)
  - Phase shift increases above 180° @ high frequencies
  - A two stage amplifier is not naturally stable

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**Dominant pole adjustment**

- 1st pole can be shifted down in low frequencies by adding \( C_f \) in parallel with \( C_{gd12} \)

\[
C_f \gg C_{gd12} \\
\Rightarrow C_{tot} = C_f + C_{gd12} \\
\Rightarrow f_1 = \frac{1}{2\pi} \frac{R_{a1} + R_{a4}}{A_v} \frac{1}{2\pi C_f}
\]

\( a.n. \ f_{ue} \approx 50 \Omega \Rightarrow C_f = 3.6 \times 10^{-8} \text{ pF} \)

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**Other dynamic performances**

- Gain-BandWidth product
  \[
  GBW = A_v A_{12} f_1, \quad GBW = \frac{R_{a1} + R_{a4}}{A_v} \frac{1}{2\pi C_f} \\
  a.n. \ g_{m1} = ImV/V \Rightarrow GBW = \frac{ImA/V}{2\pi C_f} = 31.8 \text{MHz}
  \]

- Unity-gain frequency
  - Circuits behave as a 1st order \( f_u = GBW = \frac{g_{m1}}{2\pi C_f} \)

- Slew-rate
  - Maximum swing of the voltage output
  \[
  S.R. = \frac{dV(C_f)}{dt} \bigg|_{t_{max}} = \frac{I_{bias}}{C_f}
  \]

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**OTA dynamic performances: Slew-Rate**

- Let's calculate the SR with \( C_f = 5 \text{pF} \)
  \[
  S.R. = \frac{dV(C_f)}{dt} \bigg|_{t_{max}} = \frac{I_{bias}}{C_f}
  \]

- Impact of \( W/L \) of \( T_1 \) and \( T_2 \)
  - doubling SR without changing \( f_u \) et \( I_{bias} \)

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**OTA dynamic performances: Slew-Rate**

- \( W_1 \), \( W_2 = 94 \)
  - \( 23.5 \) et \( C_f = 2.5 \text{pF} \)

- \( SR = 57.2 \text{V/µs} \)
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2-stage OTA: frequency response analysis

\[ r_1 = g_{m12}/g_{d1} \]
\[ r_2 = g_{m12}/g_{d1}/g_{load} \]
\[ C_1 = C_d + C_{d1} + C_{p12} \]
\[ C_2 = C_{d2} + C_{d1} + C_{load} \]
\[ C_r = C_r + C_{p12} \]

2-stage OTA: frequency response analysis

\[ f = \frac{v_{out}}{r_1} + C_1 p v_{out} + C_2 (v_{out} - v_{load}) \]
\[ \Rightarrow v_{out} = f (v_{in}, v_{out}) \]

2-stage OTA: frequency response analysis

- Increasing \( C_c \)
  - \( f_z \) and \( f_p \) are shifted down accordingly
- Increase of \( g_{m12} \)
  \( \rightarrow \) silicon cost, power consumption

2-stage OTA: frequency response analysis

- Solution: adding a serial resistance
  - 1st and 2nd poles don’t move a lot
  - Additional 3rd pole @ higher frequencies
  - Zero is changed:
    \[ f_z = \frac{2\pi}{\omega} \cdot C_c (1/g_{d1} - R_s) \]
  \( \rightarrow \) zero can be placed
  \( \rightarrow \) to compensate 2nd pole (unreliable)
  \( \rightarrow \) just after the unity gain frequency (reliable)
2-stage OTA: zero positioning

• 1st method
  • Step 1:
    - First simulation with random \( C_f \) (5pF) and \( R_s = 0 \)
    - Choice of a phase margin: extract \( f_u \) and measure \( A_v(f_u) \)
  • Step 2:
    - Calculation of \( C_f = C_f_0 \cdot A_v(f_u) \)
    - Zero positioning @ \( f_u + 20\% \) of \( f_u \)
    - \( R_s \) calculation

\[
\begin{align*}
  f_u &= 10.7 \text{MHz} \\
  f_c &= 520 \text{Hz} \\
  A_v &= 2.6 (8.3 \text{dB})
\end{align*}
\]

\[
\begin{align*}
  f_u &= 21 \text{MHz} \\
  f_c &= 200 \text{Hz} \\
  A_v &= -0.46 \text{dB}
\end{align*}
\]

\[
\begin{align*}
  f_u &= 21 \text{MHz} \\
  \phi &= -180°
\end{align*}
\]

2-stage OTA: zero positioning

• 2nd method:
  - Choice of unity-gain frequency:
    • Example: GBW=18MHz \( \Rightarrow f_u = 18 \text{MHz} \)
  - Calculation of the capacitance:
    \[
    C_f = \frac{R_s}{2 \pi f_u} \approx 8.8 \text{pF}
    \]
  - Zero positioning:
    • \( f_u + 20\% : 22 \text{MHz} \)
    \[
    f_c = \frac{-1}{2 \pi C_f (U_{d12} - R_s)} = 22 \text{MHz} \Rightarrow R_s = \frac{1}{2 \pi f_c C_f} \Rightarrow R_s = \frac{1}{8.8 \text{pF}} \approx 1820 \text{Ω}
    \]
2-stage OTA: zero positioning

- In any case resistor may be replaced by a MOST in the linear regime

\[ I_{ds} = \mu C_{ot} \frac{W}{L} V_{dd} V_{ds} \]

\[ r_{ds} = \frac{1}{\mu C_{ot} \frac{W}{L} V_{dd}} \]

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From 2-stage OTA to Miller OPAMP

\[ A_z = \frac{r_{out}}{r_{out} + r_{in} + C \frac{1}{A_p}} \]

\[ A_2 = \frac{r_{out}}{r_{out} + r_{in} + C \frac{1}{A_p}} \]

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2-stage OTA with PMOS differential pair

\[ V_{dd} = 3.3V \]

A single-stage OTA

\[ V_{out} \]

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