Lecture 23: OTA-C Filters

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Agenda

• OTA-C Filters
• Material is related primarily to Project #3
• Full class on filters offered (458, 622)
OTA-C Filter Applications

- Hard-disk drives require linear phase filters (>100MHz)
- RF systems require filters in the GHz range
- Wireless xcvrs intermediate frequency (IF) filters (>100MHz)
- Often used with variable gain amplifiers (VGAs) for automatic-gain control (AGC) to maximize dynamic range
- Low noise, low power, and high linearity are required
OTA-Based Active Resistor

\[ I_i = I_o = g_m V_i \]

\[ R = \frac{V_i}{I_i} = \frac{1}{g_m} \]
OTA-Based Active Resistors

[Schaumann]

\[
\begin{align*}
V_i &\quad I_1 \\
I_0 &\quad g_m \\
R = (1/g_m) &\quad V_i \\
\end{align*}
\]

\[
\begin{align*}
V_1 &\quad V_2 \\
R = (1/g_m) &\quad V_i \\
\end{align*}
\]

\[
\begin{align*}
V_i &\quad V_i \\
R = -(1/g_m) &\quad V_i \\
\end{align*}
\]
OTA-Based Integrator

- Finite OTA $r_o$ causes a non-zero pole
- OTA $C_o$ reduces integration constant

\[
\frac{V_2}{V_1} = \frac{g_m}{sC}
\]

\[
\frac{V_2}{V_1} = \frac{g_m}{s(C + C_o) + g_o}
\]
### Lossy $g_m$-C Integrator (1st-Order LPF)

**[Schaumann]**

Consider an OTA with finite output resistance and non-zero input and output capacitance. The transfer function of the integrator can be expressed as:

Ideally, \[ \frac{V_2}{V_1} = -\frac{g_{m1}}{sC + g_{m2}} \]

Considering finite OTA output resistance and non-zero input and output capacitance, the transfer function becomes:

\[ \frac{V_2}{V_1} = -\frac{g_{m1}}{s(C + 2C_o + C_i) + g_{m2} + 2g_o} \]
Fully Differential Lossy $g_m$-C Integrator

- Pseudo-Differential

[Schaumann]

- Fully Differential
  - 2C because full $g_m$ current goes to each side

- Why just C here?
I_1 = g_{m2}V_2
I_2 = g_{m1}V_1

From these two equations
\[
\frac{V_1}{I_1} = \frac{1}{g_{m1}g_{m2}} \frac{I_2}{V_2}
\]
\[
Z_1 = \frac{1}{g_{m1}g_{m2}} Y_2
\]
If \( Y_2 = sC \)
\[
Z_1 = \frac{sC}{g_{m1}g_{m2}} = sL_{\text{eff}}
\]
\[
L_{\text{eff}} = \frac{C}{g_{m1}g_{m2}}
\]
Differential Grounded Inductor

\[ L = \frac{C}{(g_m^2)} \]
Second-Order Filter

\[ \frac{V_{BP}}{V_{in}} = \frac{s \left( \frac{g_{\text{min}}}{C_1} \right)}{s^2 + s \left( \frac{1}{R_Q C_1} \right) + \frac{g_{m1} g_{m2}}{C_1 C_2}} = \frac{s \left( \frac{g_{\text{min}}}{C_1} \right)}{s^2 + s \left( \frac{\omega_o}{Q} \right) + \omega_o^2} \]

\[ \frac{V_{LP}}{V_{in}} = -\frac{\left( \frac{g_{\text{min}} g_{m1}}{C_1 C_2} \right)}{s^2 + s \left( \frac{1}{R_Q C_1} \right) + \frac{g_{m1} g_{m2}}{C_1 C_2}} = -\frac{\left( \frac{g_{\text{min}} g_{m1}}{C_1 C_2} \right)}{s^2 + s \left( \frac{\omega_o}{Q} \right) + \omega_o^2} \]

\[ \omega_0 = \sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}} \]

\[ Q = \sqrt{\frac{C_1}{C_2} \left( g_{m1} g_{m2} R_Q^2 \right)} \]

\[ A_{\text{Vpeak}} = g_{\text{min}} R_Q \]
Differential Second-Order Filter

[Mohieldin]
OTA Output Resistance Effects

\[ \omega_0 \equiv \omega_{0\text{ideal}} \sqrt{1 + \frac{1}{Q_{\text{ideal}} A_V}} \]

**CENTER FREQUENCY IS LITTLE SENSITIVE TO** \( A_V \)

\[ BW \equiv BW_{\text{ideal}} \left(1 + 2 \frac{Q_{\text{ideal}}}{A_V}\right) \]

**BW IS QUITE SENSITIVE TO** \( A_V \)

\( A_V \equiv g_{m1} R_1 \) (\( R_1 = R_2 \) OTA output resistance)
OTA Non-Dominant Pole Effects

Single pole model:

\[ g_m \approx \frac{g_m 0}{1 + \frac{s}{\omega_{p1}}} \]

\[ \omega_0 = \omega_{0\text{ideal}} \sqrt{\frac{1}{1 + \frac{2BW_{\text{ideal}}}{\omega_{p1}}} } \]

\[ \text{error} \approx -\frac{BW_{\text{ideal}}}{\omega_{p1}} \]

\[ BW \approx BW_{\text{ideal}} \left( 1 - 2Q_{\text{ideal}} \frac{\omega_{0\text{ideal}}}{\omega_{p1}} \right) \]

\[ \text{error} \approx -2Q_{\text{ideal}} \frac{\omega_{0\text{ideal}}}{\omega_{p1}} \]

Sensitive

Quite sensitive !!!
OTA Parasitic Capacitor Effects

\[ \omega_0 = \omega_{0\text{ideal}} \left(1 + \frac{g_{m2} - g_{m1}}{g_1} \right) \left(1 + \frac{C_f}{C_2} \right) \]

\[ BW = BW_{\text{ideal}} \left(1 + \frac{C_{in} + C_f}{C_1} + \frac{C_f}{C_2} \left(1 + \frac{C_{in}}{C_1} \right) \right) \]

C1 and C2 are affected by the grounded parasitic capacitors (partially corrected by the automatic tuning system).

Cin introduces a high frequency zero.

Filters are little sensitive to miller effects !!!
OTA-C BPF Modeling Simulations

[Silva]

- Little sensitive to OTA output resistances
- Very sensitive to second poles
- Parasitic capacitors should be accounted in the ATS (matching)

4th-Order BPF
4th-Order Filter Example

[Diagram of a 4th-order filter circuit with CMFB and CMFF components.]

[Mohieldin]
Magnitude, Phase, and Group Delay

Magnitude and phase response for the 4th order filter

Group delay: Effects of the parasitic poles
Optimization: Non-Dominant Pole & DC Gain

Best response: fnp = 1 Ghz, Av = 40 dB
Useful References

A CMOS 140-mW Fourth-Order Continuous-Time Low-Pass Filter Stabilized With a Class AB Common-Mode Feedback Operating at 550 MHz

Pankaj Pandey, Jose Silva-Martinez, and Xuemei Liu

Brief Papers

A Fully Balanced Pseudo-Differential OTA With Common-Mode Feedforward and Inherent Common-Mode Feedback Detector

Ahmed Nader Mohieldin, Student Member, IEEE, Edgar Sánchez-Sinencio, Fellow, IEEE, and José Silva-Martinez, Senior Member, IEEE

• “Design of Analog Filters” by R. Schaumann (Filters Textbook)
Next Time

- Analog Applications
  - Variable-Gain Amplifiers
  - Switch-Cap Filters, Broadband Amplifiers
- Bandgap Reference Circuits
- Distortion