ECEN474: (Analog) VLSI Circuit Design
Fall 2010

Lecture 24: OTA-C Filters

Sam Palermo
Analog & Mixed-Signal Center
Texas A&M University
Announcements

• Project
  • Preliminary report due Nov 19
  • No layout
  • Focus is on good circuit design

• No Class on Monday 11/15
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

Hard-Disk Drive Receiver Front-End
OTA-Based Active Resistor

\[ I_i = I_o = g_m V_i \]
\[ R = \frac{V_i}{I_i} = \frac{1}{g_m} \]

[Schaumann]
OTA-Based Active Resistors

[Schaumann]

\[ R = \frac{1}{g_m} \]
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 (1\textsuperscript{st}-Order LPF)

[Ideally]

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

Considering finite OTA output resistance and non-zero input and output capacitance

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

- Pseudo-Differential

- 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 \( Y_2 = sC \)

\[ Z_1 = \frac{sC}{g_{m1}g_{m2}} = sL_{\text{eff}} \]

\[ L_{\text{eff}} = \frac{C}{g_{m1}g_{m2}} \]

\[ L = \frac{C}{(g_{m1}g_{m2})} \]
Differential Grounded Inductor

[Schaumann]
Second-Order Filter

Continuous-time biquad

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

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

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

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

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

Mohieldin

\[V_{BP1}^+ \]

\[CMFF+CMFB\] (Fig. 3)

\[C_{L1}\]

\[V_{LP1}^+\]

\[g_{m1A}\]

\[V_{in}^+\]

\[V_{in}^-\]

\[CMFF\] (Fig. 2)

\[g_{m2A}\]

\[V_{BP1}^-\]

\[CMFF+CMFB\]

\[C_{L1}\]

\[g_{m1A}\]

Common Mode Information
OTA Output Resistance Effects

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

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

CENTER FREQUENCY IS LITTLE SENSITIVE TO \( A_V \)

BW IS QUITE SENSITIVE TO \( A_V \)

\[ A_V = g_{m1} R_1 \quad (R_1 = R_2 \text{ OTA output resistance}) \]
OTA Non-Dominant Pole Effects

Single pole model:

\[ g_m = \frac{g_m_0}{1 + \frac{s}{\omega_{p1}}} \]

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

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

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

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

Sensitive

Quite sensitive !!!
OTA Parasitic Capacitor Effects

\[ \omega_0 = \omega_{0\text{ideal}} \sqrt{1 + \frac{1}{\frac{C_f}{C_1} + \frac{C_f}{C_2} + \frac{C_{in}(C_2 + C_f)}{C_1C_2}}} \]

Little sensitive

\[ BW = BW_{\text{ideal}} \frac{1 + \frac{g_{m2} - g_{m1}}{g_{s1}}}{1 + \frac{C_{in}}{C_1} + \frac{C_f}{C_1} + \frac{C_f}{C_2} \left(1 + \frac{C_{in}}{C_1}\right)} \]

Little sensitive

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

4th-Order BPF

- Little sensitive to OTA output resistances
- Very sensitive to second poles
- Parasitic capacitors should be accounted in the ATS (matching)
4th-Order Filter Example
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: $f_{np} = 1$ Ghz, $A_v = 40$ dB

- $f_{nd}=500M$ (Error=4.8%)
- $f_{nd}=2G$ (Error=1.6%)
- $f_{nd}=1G$ (Error=0.5%)
- $f_{nd}=4G$ (Error=2.7%)
Useful References

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

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