Digitally-Controlled Gm-C Band-pass Filter

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Outline

• Research Objective

• Switched Gm-C Band-pass Filter

• Center Frequency Tuning

• Q-Value Tuning

• Conclusion
Outline

• **Research Objective**

• *Switched Gm-C Band-pass Filter*

• *Center Frequency Tuning*

• *Q-Value Tuning*

• Conclusion
Background

Wireless LAN, Bluetooth, etc.

IF Receiver

Gm-C filters are needed

Center frequency & Q-value adjustment is a challenge
Research Objective

Fine CMOS process → Low voltage

Analog band-pass filter

• Switched Gm-C integrator

• Digital schemes
  ➢ Center Frequency
  ➢ Q-value
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Proposed Switched Gm-C Integrator

\[ I_o = I_{o+} - I_{o-} = gm(V_{i+} - V_{i-}) \]

\[ V_{o+} = \frac{I_{o+}}{sC} = \frac{gm}{2sC} (V_{i+} - V_{i-}) \]

\[ V_{o-} = \frac{I_{o-}}{sC} = -\frac{gm}{2sC} (V_{i+} - V_{i-}) \]

\[ V_o = V_{o+} - V_{o-} = \frac{gm}{sC} V_i \]
Proposed Switched Gm-C Integrator

**Conventional approach**

**Proposed method**

**Analog adjustment of Gm using $I_{bias}$**

Difficult for fine CMOS with low voltage

**Digital adjustment of Gm by switch**

low voltage control
Continuous Adjustment of Switched Gm-C Integrator

Noise characteristics

C → Constant
Gm → Adjustable

Continuous Adjustment

Switched Gm-C Integrator

- Low-voltage
- Digital control
Switched Gm-C Integrator

Integral Part Adjusting

Factional part tuning

Gm

Gm \(^{N-2}\)

Gm \(^{N-1}\)

Gm \(^N\)

Gm \(^{N-2}\)

Gm \(^{N-1}\)

Gm \(^N\)

0

2Gm
Adjust Fractional Part by PWM

Switched Gm-C Integrator

\[
\frac{I_{\text{out}}}{V_{\text{in}}} = D \cdot Gm
\]

\[
D = \frac{T_{\text{on}}}{T_{\text{on}} + T_{\text{off}}}
\]

PWM control
Adjust Fractional Part by $\Delta\Sigma$

1bit $\Delta\Sigma$ converter for high accuracy

Switched Gm-C Integrator

1bit $\Delta\Sigma$ converter
Input and Output Waveforms of Switched Gm-C Integrator

\[ V_{in} = 500mV \]
\[ f = 598kHz \]
\[ C = 1pF \]
\[ 1/Gm = 2 \times 10^6 S \]
Input Voltage Amplitude and Pulse Density with ΔΣ Adjustment
Gm-C Second-order BPF

\[ H(s) = \frac{Gm_1C_2s}{s^2C_1C_2 + sC_2Gm_2 + Gm_3Gm_4} \]

\[ \omega_0 = \sqrt{\frac{Gm_3Gm_4}{C_1C_2}} \]  

\[ Q = \sqrt{\frac{C_1Gm_3Gm_4}{C_2Gm_2^2}} \]  

\[ K = \sqrt{\frac{C_2Gm_1^2}{C_1Gm_3Gm_4}} \]
Another node of the filter

\[ H''(s) = \frac{V_m}{V_{in}} = \frac{Gm_1Gm_3}{s^2C_1C_2 + sC_2Gm_2 + Gm_3Gm_4} \]

\[ H(s) = \frac{K\omega_0}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \]

\[ \omega_0 = \sqrt{\frac{Gm_3Gm_4}{C_1C_2}} \]

\[ Q = \sqrt{\frac{C_1Gm_3Gm_4}{C_2Gm_2^2}} \]

\[ K = \sqrt{\frac{Gm_1^2Gm_3}{C_1C_2Gm_4}} \]
Proposed Digitally-controllable BPF and LPF

\[ V_{BP} \]

\[ V_{LP} \]

\[ Gm_1 = N_1 gm \]
\[ Gm_2 = N_2 gm \]
\[ Gm_3 = N_3 gm \]
\[ Gm_4 = N_4 gm \]
\[ C_1 = M_1 C \]
\[ C_2 = M_2 C \]

\[ \omega_0 = \frac{N_3 N_4}{\sqrt{M_1 M_2}} \frac{gm}{C} \]
\[ Q = \sqrt{\frac{M_1 N_3 N_4}{M_2 N_2}} \]
\[ K = \sqrt{\frac{M_2 N_1^2}{M_1 N_3 N_4}} \]
Outline

• Research Objective

• Switched Gm-C Band-pass Filter

• **Center Frequency Tuning**

• Q-Value Tuning

• Conclusion
• Suitable for **digital low voltage** implement
• Require a reference frequency
Center Frequency Tuning Part

Diagram showing a circuit with labels such as Vin, Vref, Sin(ω₀t), VCNST, VLPF, VBPF, V1, V2, and VC. The circuit includes a PFD, Gm-C Filter, Register, Charge pump, and 4bit ADC.
Proposed Center Frequency Tuning Method

**Magnitude characteristics**

\[ H(s) = \frac{Gm_1 C_2 s}{s^2 C_1 C_2 + s C_2 Gm_2 + Gm_3 Gm_4} \]

**Phase characteristics**

\[ \theta = \frac{\pi}{2} - \arctan \frac{\omega_i \omega_0}{Q(\omega_0^2 - \omega_i^2)} \]

\( \omega_0 \): Center Frequency
\( \omega_i \): Input Frequency

\( \theta = 0 \rightarrow \) Center frequency tuning is done
Principle for Using Phase Characteristics

\[ \theta = \frac{\pi}{2} - \arctan \frac{\omega \omega_0}{Q(\omega_0^2 - \omega_i^2)} \]

\[ \omega_0 = \sqrt{\frac{Gm_3 Gm_4}{C_1 C_2}} \]

1. \( \theta < 0 \rightarrow \omega_0 < \omega_i \) \hspace{1cm} Gm_3, Gm_4 \text{ bigger} \hspace{1cm} \omega_0 \text{ is adjusted bigger}

2. \( \theta = 0 \rightarrow \omega_0 = \omega_i \) \hspace{1cm} \text{Done}

3. \( \theta > 0 \rightarrow \omega_0 > \omega_i \) \hspace{1cm} Gm_3, Gm_4 \text{ smaller} \hspace{1cm} \omega_0 \text{ is adjusted smaller}
\[ V_{\text{ref}} = \sin(\omega_0 t) \]

\( \omega_0 \) is desired center frequency.

**PFD (Phase Frequency Detector)**

- **Comparator**
- **BPF (Bandpass Filter)**
- **Charge pump**
- **4bit ADC**

**Signals of PFD**

- Phase Lag
Operation of Charge Pump

Adjust the $Gm_3, Gm_4$ values

Output of charge pump $V_c$

Output of PFD
Input and Output Waves of BPF

Vout

Vref

Transient state

Adjusted state

Phase is aligned
Center Frequency Tuning Simulation Result of BPF

Simulation parameters

\[ Gm = 5 \times 10^{-5} \text{S} \quad C = 1.59 \text{pF} \]

\[ N_1 = N_2 = 2 \quad M_1 = M_2 = 1 \quad 0 \leq N_3 = N_4 \leq 15 \]


Center Frequency Tuning Simulation Results of LPF

Simulation parameters

\[ G_m = 5 \times 10^{-5} \text{S} \quad C = 1.59 \text{pF} \]

\[ N_1 = N_2 = 2 \quad M_1 = M_2 = 1 \quad 0 \leq N_3 = N_4 \leq 15 \]
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• \textit{Q-Value Tuning}

• Conclusion
Q-value Tuning Part

The diagram illustrates a circuit with a Gm-C filter, a PFD (Phase Frequency Detector), and components for signal processing, including a charge pump and a 4-bit ADC.
Q-value Tuning Method

The proposed method is given by:

\[ H(\omega_0) = \frac{G_{m1}}{G_{m2}} = \sqrt{\frac{G_{m1}^2 C_2}{G_{m3} G_{m4} C_1}} \cdot \sqrt{\frac{G_{m3} G_{m4} C_1}{G_{m2}^2 C_2}} = KQ \]

where

\[ \omega_0 = \sqrt{\frac{G_{m3} G_{m4}}{C_1 C_2}} \]

\[ Q = \sqrt{\frac{C_1 G_{m3} G_{m4}}{C_2 G_{m2}^2}} \]

\[ K = \sqrt{\frac{G_{m1}^2 G_{m3}}{C_1 C_2 G_{m4}}} \]

\[ \omega_0 \text{ determined by } G_{m3}, G_{m4} \]

\[ K \text{ determined by } G_{m1}, G_{m3}, G_{m4} \]

Fix Center frequency and K

Q-value is proportional to gain

\[ |H(j\omega_0)| = K \cdot Q \]
In Case Q is Smaller than Desired Value

\[ V_1 > V_2 \quad \rightarrow \quad V_{cp} \text{ is tuned bigger} \quad \rightarrow \quad Gm_2 \text{ is tuned smaller} \]

\[ Q = \sqrt{\frac{C_1 Gm_3 Gm_4}{C_2 Gm_2^2}} \]

\[ Q \propto \frac{1}{Gm_2} \]

Q → bigger

\( \omega_0 \) has been adjusted
$\omega_0$ has been adjusted

Output of Comparator

COMP UP

COMP DOWN
$\omega_0$ has been adjusted

Output of Charge pump

$V_{cp}$

$V_{ref} = \sin(\omega_0 t)$

$V_{clk}$ Constant voltage

Gm-C Filter

$1/A$

CLK

\begin{align*}
V_1 \\
V_2 \\
V_{cp}
\end{align*}

4 bit ADC

\begin{align*}
S1 \\
S2 \\
S3 \\
S4
\end{align*}
$\omega_0$ has been adjusted

Output of ADC

$V_{\text{ref}} = \sin(\omega_0 t)$

$V_{\text{clk}}$ Constant voltage

$V_1$

$V_2$

$V_{\text{cp}}$

$\propto \left( \frac{1}{Gm_2} \right)$

$Q \propto \frac{1}{Gm_2}$
In Case Q is Bigger than the Desired Value

\[
Q = \sqrt{\frac{C_1 Gm_3 Gm_4}{C_2 Gm_2^2}}
\]

\[Q \propto \frac{1}{Gm_2}\]

\[V_1 < V_2 \rightarrow V_{cp} \text{ is tuned smaller} \rightarrow Gm_2 \text{ is tuned bigger}\]

\[\omega_0 \text{ has been adjusted}\]
Algorithm of Q-value Tuning

When $V_1 = V_2$

$V_1 = V_{ref}$

$V_2 = Q \cdot KV_{ref} / A$

$\omega_0$ has been adjusted

$K$ is fixed

$Q = \frac{1}{K} A$

$Q \rightarrow$ Determined by A
Input and Output Waves of BPF

\[ |H(j\omega_0)| = Q \]

\[ V_{\text{ref}} \]

\[ V_{\text{out}} \]

Phase is aligned
Q-value Tuning Simulation Result of BPF

Simulation parameters

\[ \begin{align*}
G_m &= 5 \times 10^{-5} \, S \\
C &= 1.59 \, \text{pF} \\
\omega_0 &= 600 \, \text{kHz} \\
M_1 &= M_2 = 1
\end{align*} \]
Q-value Tuning Simulation Result of LPF

Simulation parameters

\[ G_m = 5 \times 10^{-5} \, S \]
\[ C = 1.59 \text{pF} \]
\[ f_0 = 600 \text{kHz} \]
\[ M_1 = M_2 = 1 \]
Outline

- Research Objective
- Switched Gm-C Band-pass Filter
- Center Frequency Tuning
- Q-Value Tuning
- Conclusion
• Propose a digitally-controlled Gm-C band-pass filter using switched Gm arrays
  - Fine CMOS → Low voltage

• Digital tuning schemes
  - Center Frequency → Phase property
    - Orthogonal
    - Determined by Gm3, Gm4
  - Q-value → Gain property (Center frequency has been adjusted)
    - Determined by Gm2

• Present SPICE simulation results