LOW COST, LOW POWER, MULTI-STANDARD Flexible Baseband Filter

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Flexible Baseband Filter

- Analog baseband filter for multi-standard or software-defined radios
  - Digitally assisted filters
  - Programmable BW
  - Selectable Type (filter approximation)
  - Selectable order
  - Highly linear
  - Adjustable power
Motivation

- Multi-standard applications
- IP reuse
- Variety of applications in 1-20 MHz range

<table>
<thead>
<tr>
<th>Standard</th>
<th>BW [MHz]</th>
<th>IIP3 [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluetooth</td>
<td>1</td>
<td>17.3</td>
</tr>
<tr>
<td>UMTS TDD</td>
<td>1.28</td>
<td>18.4</td>
</tr>
<tr>
<td>UMTS FDD</td>
<td>3.84</td>
<td>20.42</td>
</tr>
<tr>
<td>DVB-H</td>
<td>7.6</td>
<td>17.9</td>
</tr>
<tr>
<td>WLAN 802.11a/b/g/n</td>
<td>10/20</td>
<td>21.5</td>
</tr>
</tbody>
</table>
Key Filter Aspects

- System Level
  - Architecture
  - Stability Theory
- Circuit Level
  - Reconfiguration (type selection)
  - Continuous Frequency Tuning
  - Power Adjustable opamp
  - Low-voltage operation
- Layout level
  - Layout techniques to block cross-talks
Cascaded Architecture

- Cascaded architecture
  - Ease of tuning
- Three stages (1\textsuperscript{st}, 3\textsuperscript{rd}, 5\textsuperscript{th} orders)
  - One mono
  - Two biquads

\[ H_{tot}(s) = \frac{1}{\left(1 + \frac{s}{\omega_{o0}}\right)} \frac{\omega_{o1}^2}{\left(s^2 + \frac{\omega_{o1}}{Q} s + \omega_{o1}^2\right)} \frac{\omega_{o2}^2}{\left(s^2 + \frac{\omega_{o2}}{Q} s + \omega_{o2}^2\right)} \]

- 1st-order
- 3rd-order
- 5th-order
Stability Analysis

- Ensure stability of the filter
  - Through variation of
    - Biquad’s bandwidth ($\omega_0$)
    - Biquad’s Quality factor (Q)
    - Opamp’s GBW
    - Opamp’s PM

- Analyzing the denominator of the transfer function

\[
H_{\text{biquad}}(s) \equiv \frac{V_4}{V_{\text{in}}} = \frac{-G^2}{D_{\text{tot}}(s)}
\]
Stability Theory

- MAPM increases with
  - Higher $Q$
  - Higher $\omega_0$
  - Lower GBW

- With certain high Qs and higher $\omega_0$/GBW, impossible stability
Overall Filter Architecture
Reconfiguration

- Chebyshev vs. Inverse Chebyshev
- Normalized Filter
- Scale $R \Rightarrow$ Scale Frequency
- Adding zeros in Inverse Chebyshev
- Zeros will scale exactly with poles keeping a constant ratio

\[ \text{Normalized } R_{\text{CHEB}} \]
\[ \text{Normalized } R_{\text{INV. CHEB}} \]
\[ V_{\text{CTRL}} \]
Continuous Impedance Multiplier (CIM)

\[ R_{eff} = \frac{V_1}{I_2} \approx R_{disc}(k + 1) \]

- \( V_G \) should be a good AC ground
- \( V_c \) should be larger than \( V_{\text{common-mode}} \)
- Always in triode
- Size such that parasitic at highest frequency is negligible compared to \( R_{disc} \)
Opamp and Power Adjustment

(a) Opamp schematic

(b) GBW of opamps in diff. stages vs. Power

(c) PM of opamps in diff. filter stages vs. Power
Outline

1) Introduction
2) Direct-Modulation Transmitter
3) Self-Tuning System
4) Experimental Results
5) Continuously-tunable Active-RC Filter
6) Experimental Results
7) Conclusion
Filter Measurement setup/Die photo
Frequency Response

Discrete Freq. Selection : Solid line
Continuous Freq. Tuning: Dashed line
Filter Type selection

Magnitude Response

Group Delay
Order Selection
In-band Linearity

- IIP3 = 31.3 dBm
- Two-tone test

\[ \Delta P = 60.77 \text{ dB} \]
\[ P_m = 1 \text{ dBm} \]
\[ IIP3 = 31.3 \text{ dBm} \]
Out of band linearity

- An extra filter was implemented to purify signal generators
Out of band linearity

LF mode:
- $I_{IP2}=89.5 \text{ dBm}$
- $I_{IP3}=52.8 \text{ dBm}$

HF mode:
- $I_{IP2}=23.5 \text{ dBm}$
- $I_{IP3}=8 \text{ dBm}$
# Comparison to Recently Published Works

<table>
<thead>
<tr>
<th>Topology</th>
<th>Order</th>
<th>Type</th>
<th>Power [*]</th>
<th>Power/pole</th>
<th>$V_{DD}$</th>
<th>$f_c$ Range</th>
<th>Continuous Tuning?</th>
<th>Noise [mV/$\sqrt{Hz}$]</th>
<th>DR [dB]</th>
<th>IIP3 [dBm]</th>
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</thead>
<tbody>
<tr>
<td>[D’Amico’06]</td>
<td>4</td>
<td>-</td>
<td>4.1</td>
<td>1.02</td>
<td>1.8</td>
<td>6-14</td>
<td>No</td>
<td>7.5</td>
<td>79</td>
<td>17.5</td>
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<tr>
<td>[Kousai’07]</td>
<td>5</td>
<td>C</td>
<td>11.25</td>
<td>2.25</td>
<td>1.5</td>
<td>19.7</td>
<td>No</td>
<td>30</td>
<td>69</td>
<td>18.3</td>
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<tr>
<td>[Vasilopoulos’06]</td>
<td>Active-RC</td>
<td>5(C)/3(E)</td>
<td>C/E</td>
<td>4.6</td>
<td>0.92</td>
<td>1.2</td>
<td>5, 10</td>
<td>85, 143</td>
<td>73</td>
<td>18.8-21.3</td>
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<tr>
<td>[Giannini’06]</td>
<td>Active-$G_m$-RC</td>
<td>4</td>
<td>-</td>
<td>3.4</td>
<td>0.85</td>
<td>1.45-3.6</td>
<td>No</td>
<td>24.8</td>
<td>81</td>
<td>21</td>
</tr>
<tr>
<td>[Chamla’05]</td>
<td>$G_m$C</td>
<td>3</td>
<td>B</td>
<td>2.5-3.1</td>
<td>0.83-1.03</td>
<td>0.05-0.35</td>
<td>5.87-19.44</td>
<td>Yes</td>
<td>35-700</td>
<td>-</td>
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<tr>
<td>[Lo’07]</td>
<td>$G_m$C</td>
<td>3</td>
<td>B</td>
<td>1.57-1.92</td>
<td>0.52-0.64</td>
<td>0.05-0.35</td>
<td>5.87-19.44</td>
<td>Yes</td>
<td>65</td>
<td>-</td>
</tr>
</tbody>
</table>

This Work: Active-RC | 1/3/5 | C/I | 3.0-7.5 | 0.6-1.5 | 1.0 | 1-20 | Yes | 85, 52 | 71.4 | 31.3, 26 |

*B-Butterworth, C-Chebyshev, I-Inverse Chebyshev, E-Elliptic

**All the implementations are realized in 0.13\mu m CMOS technology except for [Chamla’05] which is fabricated in 0.25\mu m SiGe BiCMOS and [Lo’07] which is fabricated in 0.18\mu m CMOS.