An RF Tunable LC Bandpass Filter with small Passband Ripple and transformer emulator

Department of Electrical Engineering
Analog and Mixed-Signal Center
Texas A&M University
http://amsc.tamu.edu/
Material Courtesy of Ahmed Mohieldin
Outline

- Introduction
- High-Order filters
- Dual resonator bandpass filter
- Design Considerations
- Measurement Results
- Conclusions
Introduction

- Replace off-chip filters
- Eliminate need of impedance matching
- Reduce power, area, and cost
- Integrated spiral inductors are lossy
- Positive feedback is needed for Q-enhancement

\[ \omega_0 \equiv \frac{1}{\sqrt{LC}} \sqrt{1 - \frac{1}{Q_0^2}} \]
\[ Q \equiv \frac{Q_0}{1 - (G_m / G_{loss})} \sqrt{1 - \frac{1}{Q_0^2}} \]
\[ G_{loss} \equiv R_L (\omega_o C)^2 \]
High-Order Filters

- Needed to provide acceptable IR
- Classic LC filter synthesis techniques can be used with Q-enhancement
- No guarantee that the filter frequency response will be preserved
- To avoid large element value spread, especially for narrow band, coupled filters are used
- Consists of reactive tank circuits coupled by capacitors, inductors, or magnetically
Dual Resonator Bandpass Filter

- Two magnetically coupled resonators
- 4th order filter
- \( \omega_0 \) is fixed by the LC product
- Coupling coefficient \( k \) is used to tune \( Q \)

\[
R = R_1 = R_2 = K_2 Q \sqrt{L / C}
\]

\[
LC = \frac{1}{\omega_0^2}
\]

\[
k = \frac{K_1}{Q}
\]
Effect of tuning $k$

$K = \{K_1/2Q, K_1/Q, 2K_1/Q\}$

- Minimum passband ripple at critical coupling
- Tuning $k$ and $R$ simultaneously to keep $k \times R$ constant

ECEN 665 (ESS) Analog & Mixed
Signal Center, Texas A&M University

11/17/2008
Transformer Models

- Transformer can be replaced by induced currents
- Due to losses, induced currents are not in phase
- Severe passband ripples
- Coupling neutralization to maintain a flatband response
- Emulate the transformer action by electric coupling
Emulation of Magnetic Coupling

- \( k = G_k R_s (\approx 0.01) \)
- Provide possibility of BW tuning while maintain flatband
- Placing inductors apart to diminish magnetic coupling
Circuit Implementation

\[ V_{DD} \]

\[ V_{1} \]  
\[ V_{2} \]  
\[ G_{k} \]  
\[ R_{s} \]  
\[ L \]  
\[ C \]  
\[ R_{L} \]  
\[ I_{1}^{+} \]  
\[ I_{1}^{-} \]  
\[ I_{2}^{+} \]  
\[ I_{2}^{-} \]  
\[ V_{f} \]  
\[ V_{Q} \]  
\[ V_{DC} \]  
\[ k = R_{s} G_{k} \]  

ECEN 665 (ESS) Analog & Mixed  
Signal Center, Texas A&M  
University
Design Considerations

- **Noise Analysis**

\[ v_{noise}^2 = \frac{1}{A_v^2} \left( \frac{KT}{C} \right) \left[ \frac{Q}{Q_0} + \zeta \frac{Q}{Q_0} + \zeta A_v \right] = \frac{1}{A_v^2} \left( \frac{KT}{C} \right) \left( \frac{Q}{Q_0} \right) \left[ 1 + \zeta + \zeta \frac{G_{in}}{G_{loss}} \right] \]

\( \zeta \) is a noise factor that depends on the implementation

- For low peak gain \( A_v < (Q/Q_0) \), contribution of the input transconductance can be neglected
Design Considerations

- **Nonlinearity Analysis**

- To isolate nonlinear effects, each nonlinear element is considered separately:

  \[ V_{1-dB, in}^2 = V_{1-dB}^2 \bigg|_{G_{in}} \]

  \[ V_{1-dB}^2 \bigg|_{G_{in}} = 1.077 \times (V_{GS} - V_T) = 1.077 \times \sqrt{\frac{2I_{SS}}{K_n (W / L)_{in}}} \]

  \[ V_{1-dB, Gm}^2 = \frac{V_{1-dB}^2 \bigg|_{G_m}}{A_v^2} \cdot \frac{Q_0}{Q} \]

- For high Q narrowband or high gain applications, the negative OTA dominates linearity performance.

- A differential pair based OTA
Nonlinearity Analysis

Starting inductor’s quality factor $Q_0$ has a considerable effect on linearity.

$$Q_0 \uparrow \quad G_{\text{loss}} \downarrow \quad G_m = \sqrt{2K_n I_{SS} \frac{W}{L}} \downarrow \quad (V_{GS} - V_T) = \sqrt{\frac{2I_{SS}}{K_n (W/L)}}$$

$\uparrow$ $G_{\text{in}}$  $A_v$  $V_{\text{noise}}$  $V_{1\text{-dB}}$  $\downarrow$

For a fixed $I_{SS}$

Noise-Linearity Trade-off

Constant DR

Design Considerations
Design Considerations

- **Dynamic range**

\[
DR = \frac{V_{1-dB}^2}{V_{\text{noise}}^2} = \frac{V_{1-dB}^2}{KTC} \cdot \left(1 + \frac{\zeta + \frac{G_{\text{in}}}{G_{\text{loss}}}}{G_{m}}\right) \cdot C \left(\frac{Q_{0}}{Q}\right)^2
\]

- Selectivity-DR trade-off

- Factor of \(Q^2_0\) improvement over OTA-C counterpart

\[CQ^2_0 = \frac{L}{R_L^2} \quad \Rightarrow \quad DR \quad \Rightarrow \quad L \text{ and } R_L \text{ scale proportionally}
\]

- DR is maximized by minimizing the losses of the inductor

- Technology issue TSMC 0.13\(\mu\)m \(Q>10\) @5GHz
Design Considerations

- Power Consumption

\[ G_m = G_{\text{loss}} = \frac{R_L}{(\omega_0 L)^2} \]

How to maximize DR?
Choose minimum L to meet the power budget.

DR-Power Trade-off

Tuning-Power Trade-off
Effect of $R_S$ on filter power consumption

For a fixed $R_L$

For a fixed $k$
Effect of $R_S$ on filter noise performance

For a fixed $R_L$:

- $R_S$
- $G_{loss}$

For a fixed $k$:

- $R_S$
- $G_k$
Power and Noise optimization

\[ R_S \approx R_L \left( \frac{Q_0^2}{2.5\sqrt{2Q}} \right)^{1/2} \]

Optimize Noise

\[ Q_0 = 3, \quad Q = 100 \]

\[ \text{NF} + 1.76\text{dB} \]

\[ R_S \approx R_L \left( \frac{Q_0^4}{2Q^2} \right)^{1/3} \]

Optimize Power

\[ P^* 1.15 \]
Filter Tuning

Tuning the coupling coefficient

ECEN 665 (ESS) Analog & Mixed
Signal Center, Texas A&M
University

11/17/2008
Filter Tuning

\[ \frac{V_2}{V_1}(j\omega_0) = j \frac{1}{\sqrt{1-(1/Q^2)}} \approx j \]

Frequency and Q tuning
Chip Micrograph

X=500\mu m, Y=300\mu m

ECEN 665 (ESS) Analog & Mixed
Signal Center, Texas A&M
University
Measurement Results

Upper trace $|V_1/V_{in}|$ (dB)
Lower trace $|V_2/V_{in}|$ (dB)
Measurement Results

Frequency tuning
\[ f_0 = \{1.77\text{GHz}, 1.86\text{GHz}\} \]

Bandwidth tuning
\[ \text{BW} = \{70\text{MHz}, 100\text{MHz}\} \]
### Measurement Results

**Two Tone intermodulation distortion -34dBm each**

- **ECEN 665 (ESS) Analog & Mixed**
- **Signal Center, Texas A&M University**

---

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Power (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.83005910</td>
<td>-08.64 dBm</td>
</tr>
<tr>
<td>1.8400816</td>
<td>-50.39 dBm</td>
</tr>
<tr>
<td>1.85010020</td>
<td>-50.65 dBm</td>
</tr>
<tr>
<td>1.86012020</td>
<td>-90.51 dBm</td>
</tr>
</tbody>
</table>

---

**Graph:**

- Start 1.825GHz
- Stop 1.865GHz
- 4 MHz/
Measurement Results

1 dB Compression Dynamic Range

ECEN 665 (ESS) Analog & Mixed
Signal Center, Texas A&M
University
### Comparison with previously published work

<table>
<thead>
<tr>
<th></th>
<th>[4]</th>
<th>[5]</th>
<th>[6]*</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter order</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>( f_0 ) (GHz)</td>
<td>0.85</td>
<td>1.9</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>BW (MHz)</td>
<td>18</td>
<td>150</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Passband gain (dB)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Ripple in passband (dB)</td>
<td>&lt; ±1</td>
<td>+1.6</td>
<td>±0.35</td>
<td>&lt; ±0.25</td>
</tr>
<tr>
<td>( Q_{\text{ind}} )</td>
<td>&lt; 3</td>
<td>?</td>
<td>?</td>
<td>2.7</td>
</tr>
<tr>
<td>1dB compression DR</td>
<td>61</td>
<td>63</td>
<td>63</td>
<td>42</td>
</tr>
<tr>
<td>Current drain/pole (mA)</td>
<td>19.25</td>
<td>4.5</td>
<td>1.17</td>
<td>4</td>
</tr>
<tr>
<td>Technology</td>
<td>0.8( \mu )m CMOS</td>
<td>0.25( \mu )m BiCMOS</td>
<td>0.25( \mu )m CMOS</td>
<td>0.5( \mu )m CMOS</td>
</tr>
<tr>
<td>Area/pole (mm(^2))</td>
<td>0.5</td>
<td>0.25</td>
<td>0.585</td>
<td>0.0375</td>
</tr>
<tr>
<td>Supply voltage (V)</td>
<td>2.7</td>
<td>2.7</td>
<td>2.5</td>
<td>2.7</td>
</tr>
</tbody>
</table>

ECEN 665 (ESS) Analog & Mixed Signal Center, Texas A&M University

11/17/2008
Remarks

- A 4th Order tunable LC filter is presented in 0.5μm CMOS process
- The architecture uses electric emulation of the magnetic coupling
- Electric coupling provide the capability of BW tuning with small passband ripple
- Design trade-offs have been demonstrated
- The filter achieves 42dB of DR with ±0.25dB passband ripple and consumes 16mA

Reference: