Reconfigurable Front-End Modules Based on Ferroelectric Varactors

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Outline

• Motivation

• Tunable Passive Components

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  – Frequency Agile Power Dividers & Couplers
  – Prototype Implementation & Results

• Part 2
  – Impedance Matching Networks
  – L, Pi, T, and reflection type
  – Prototype Implementation & Results

• Conclusion
Motivation

- Increasing number of communication bands
- Additional wireless services, e.g. GPS, WiMAX
- Demand for reconfigurable front-end solutions
Ferroelectric Thin-Film Varactors

- Nonlinear component
- Compact dimensions
- Induced acoustic resonance
Ferroelectric Thin-Film Varactors

- Metal-Insulator-Metal (MIM)
- Compact dimensions
- Q around 40 @ 2 GHz
- ADS model available
Filter Design – Lowpass

Port 1 \( L_1 \) \( L_3 \) \( L_5 \) Port 2

\[
M_{i=1,3,5} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_i \\ 0 & 1 \end{bmatrix}
\]

\[
M_{j=2,4} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_j & 1 \end{bmatrix}
\]

\[
M_{\text{total}} = M_1 \cdot M_2 \cdot M_3 \cdot M_4 \cdot M_5
\]

- Chebyshev lowpass filter
- Analytical formulas for zero locations

\[
\begin{align*}
    z_2 &= j\omega_2 = \pm \frac{\sqrt{2C L_3(-2L_1 L_3 - 2L_1^2 + Z_0^2 C L_3 + \alpha)}}{2C L_1 L_3} \\
    z_3 &= j\omega_3 = \pm \frac{\sqrt{2C L_3(-2L_1 L_3 - 2L_1^2 + Z_0^2 C L_3 - \alpha)}}{2C L_1 L_3} \\
    \alpha &= \sqrt{-4L_1 L_3^2 Z_0^2 C + 4L_1^4 + 4L_1^2 L_3 Z_0^2 C + L_3^2 Z_0^4 C^2}
\end{align*}
\]
Filter Design – Notch Filter

- Notch filter
- Analytical formulas for zero and pole locations

\[ M_1 = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_1 & 1 \end{bmatrix} \]

\[ M_2 = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y_2 & 1 \end{bmatrix} \]

\[ Y_2 = \frac{1}{2/(pC) + pL_2} \]

\[ \begin{align*}
   z_1 &= j\omega_1 = \pm \sqrt{-2/[C(L_1 + L_2)]} \\
   p_2 &= j\omega_2 = \pm \sqrt{-2/(L_2C)}
\end{align*} \]
Modified Combline Filter

- Second attenuation pole is shifted from DC to lower stopband
Frequency Agile $\lambda/4$ Segments

\[ C_{eq} = \frac{1}{\omega \sqrt{2Z}} = \frac{1}{2\pi f \sqrt{2Z}} \]

- Scalable network
- Slightly detuned $Z$
- Perfect phase shift

Tuning of $C_{eq} \rightarrow$ shifts resonance
Tunable Wilkinson Divider

- Size reduction 50%
- Multiband tuning
- Assumed tunability 60%
Tunable Branch-Line Coupler

- Size reduction 50%
- Perfect phase match
- $C_{eq}$ serves as shunt element for both segments
Tunable Branch-Line Coupler

- Size reduction 50%
- Perfect phase shift
- Multiband operation with tunability of 60% for $C_{eq}$
Tunable Lowpass (1)

- Tuning range of 30%
- 1.5-2GHz multiband
- High losses due to moderate Q and RF isolation
Tunable Lowpass (2)

- Good agreement
- Loss due to varactor imbalances and prototype assembly
- Two-tone test @ 1.95GHz with $\Delta f=5$MHz and Bias=20V
Tunable Notch Filter (1)

- Cascaded varactors simplify biasing
- Notch tuning 1.5-2.1GHz
- Multiband operation
- Low losses
Tunable Notch Filter (2)

- Good agreement between simulation and measurement
- Two-tone test @ 1.95GHz with $\Delta f=5$MHz and Bias=20V
Tunable Combline Filter (1)

- Good agreement
- Compact dimensions
- IL < 3dB and RL > 20dB
- Tuning 1.8-2GHz
Tunable Combline Filter (2)

- Two-tone test @1.95GHz with $\Delta f=5$MHz and Bias=5V
- OIP3=36.5dBm

<table>
<thead>
<tr>
<th>Bias (V)</th>
<th>$f_0$ (GHz)</th>
<th>IL (dB)</th>
<th>RL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.85</td>
<td>2.8</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>1.90</td>
<td>2.7</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>1.97</td>
<td>2.6</td>
<td>26</td>
</tr>
<tr>
<td>15</td>
<td>2.02</td>
<td>2.6</td>
<td>28</td>
</tr>
</tbody>
</table>
Tunable Wilkinson Divider (1)
Tunable Wilkinson Divider (2)

- $\text{IL} < 1.2\text{dB}$, Isolation $> 25\text{dB}$
- Lowpass filtering $S_{21}, S_{31}$
- Attenuation $> 20\text{dB}$ at $2f_0$
- Tuning range 1.7-2.1GHz
Tunable Branch-Line (1)

- Size reduction 50%
- Lowpass filtering
- Attenuation > 30dB at second harmonic

$V_{Bias} = 5V$
Tunable Branch-Line (2)

$V_{\text{Bias}} = 9\text{V}$

$V_{\text{Bias}} = 15\text{V}$

Measured

Simulated
Tunable Branch-Line (3)

- Tuning range 1.8-2.3GHz
- IL < 2.7dB, RL > 15dB
- Amplitude error < 0.4dB, phase error < 5deg
Part 2 – Impedance Matching

- Motivation - Missmatch Conditions
- L Matching Network
- Pi Matching Network
- T Matching Network
- Reflection Type Matching Network
Mismatch Conditions

- Antenna
- Power amplifier
L - Matching Network

- PA Matching
- Tunable L is series LC
- Small matching area
L - Network Gain

- Fixed MN with \( Z_{in}=25\Omega \) SMD 0402 components
- Losses for minor impedance variations

\[
\begin{align*}
\text{Qc}=50 & \\
\text{Qc}=25 & \\
\end{align*}
\]
L - Matching Area

- Excellent agreement
- Dynamically adjustable PA impedance
Π - Matching Network

- High C value
- Suitable for low impedances
- Low IMD
**Π – Network Gain**

- Gain for significant impedance variations

![Graph showing network gain variations](image)
Π – Matching Area

- Excellent agreement
- Losses increase for higher impedances
Assembly Parasitics

Simulated with bond wires

Simulated without bond wires

Measured

Transducer Power Loss (dB)
T – Matching Network

- Low C values
- Suitable for high impedances
- High IMD
T – Network Gain

- Gain for significant impedance variation
T – Matching Area

- Excellent agreement
- Higher losses for low impedances
Reflection – Matching Network

- Total Smith chart area coverage
- Hybrid coupler and phase shifters
- Large circuit dimension
Reflection Type Circuit

- High Q values for varactors lead to large matching area
Reflection – Network Gain

- Gain for significant impedance variation

Qc=100

Qc=75
Reflection – Matching Area

- Excellent agreement
- Symmetric matching area

Bias

Simulated

Measured

Transducer Power Loss (dB)
Conclusion

- Potential of ferroelectrics in tunable front-end
- Tunable microwave circuits
- Prototype implementation & results

Outlook

- Integration of tunable microwave subsystems in front-end architectures