WE3E-3

Fully-Reconfigurable Non-Reciprocal Bandpass Filters

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Introduction: Non-reciprocity

**Non-reciprocal devices:** *key enabling elements of various communication & radar systems*

I. Tx/Rx separation in full duplex

II. Reflection cancellation

III. High-power protection
Introduction: Research goals

**Conventional non-reciprocal devices:**
- Break reciprocity: bias a ferromagnetic material
- Cannot be integrated with ICs, MMICs

**Bulky: external magnetic biasing**

Example RF front-end chain: need for isolators & filters

**Goal: 2-stage miniaturization**
- Magnet-less non-reciprocity
- Filter/isolator co-design
Introduction: State of Art - Circulators

Angular momentum biasing [1]
- Small size
- Can be integrated
- Filtering
- High IL
- Low RL
- Strong IM products

Transistor-based stages [2]
- Small size
- Can be integrated
- Low RL
- Strong nonlinearity
Introduction: State of Art - Filters

3rd Order BPF [3]

No tuning
Low selectivity (no TZs)

3rd Order BPF [4]

Only tunable in freq.
Low selectivity (no TZs)
Theoretical Foundations: Concept

Coupling-routing diagram

- Multi-resonant cell
  - 1 pole and 2 TZs

4 resonators modulated in time
- \( f_M \) – frequency of modulation signal (<< \( f_{RF} \))
- \( \phi \) – phase of modulation signal
- Resonators must be modulated out of phase

Conceptual power transmission

- \( f_0 \) and BW
- Modulating signals
- VDC
- \( S=1, 2 \)
- |S11|, |S21|, |S12|
- Amplitude (dB)
- TZ1, TZ2, P1-3
- Voltage
- \( 2^*\Delta \Phi \), \( \Delta \Phi \), 0°
Theoretical Foundations: Schematic

- Multi-resonant cell: 2 series LC resonators
- 2 parallel LC resonators
- Capacitive coupling
- Resonator capacitors are modulated

DC block
Varactor diodes
Bias networks
Theoretical Foundations: Schematic

\[ D_v = \text{Skyworks SMV1413} \]
\[ C_{12} = C_{67} = 4.03 \, \text{pF} \]
\[ C_{23} = C_{36} = 4.47 \, \text{pF} \]
\[ L_P = 20.32 \, \text{nH} \]
\[ L_N = 29.60 \, \text{nH} \]
\[ L_{Z1} = 59.85 \, \text{nH} \]
\[ L_{Z2} = 35.33 \, \text{nH} \]
\[ V_{DC} = 0.56 \, \text{V} \]
Theoretical Foundations: Modulation

Parametric studies - $f_M$

- $f_M = 10$ MHz – Low isolation
- $f_M = 14.9$ MHz – Maximum isolation
- $f_M = 20$ MHz – Low isolation
Theoretical Foundations: Modulation

Parametric studies - $\Delta \Phi$

$\Delta \Phi = 47^\circ$ – High IL, asymmetric response
$\Delta \Phi = 67^\circ$ – Low IL, symmetric response
$\Delta \Phi = 87^\circ$ – Asymmetric response
Theoretical Foundations: Modulation

Parametric studies - $V_M$

$V_{M,P} = 420 \text{ mV}_{PP}$
$V_{M,Z1} = 180 \text{ mV}_{PP}$
$V_{M,Z2} = 120 \text{ mV}_{PP}$

$0.5V_M$ – Low isolation
$V_M$ – *High isolation, Low IL*
$1.2V_M$ – High IL
Theoretical Foundations: Modulation

Parametric studies – $D_V$ loss

Varactor introduces $\sim$0.5 dB loss.

Remaining loss ($\sim$1 dB) result of lost power to IM products.
Experimental Validation: Prototype

-Filter prototype-

-Experimental setup-
Experimental Validation: Sim vs Meas

- Measurements -

Amplitude (dB)
Frequency (MHz)

\[ |S_{11}|, |S_{21}|, |S_{12}| \]

- Simulated
- Measured

- Measurements -

- Measured:
  - \( f_{\text{cen}} \): 300.6 MHz
  - \( \text{BW} \): 25.8 MHz (8.6%)
  - Minimum IL: 2.5 dB
  - Maximum isolation: 23.8 dB
Experimental Validation: Tuning

- Bandwidth tuning -

Switched off

BW: 15 – 41.5 MHz (2.77:1)

- Frequency tuning -

Freq.: 270 – 310 MHz (1.15:1)
### Experimental Validation: Comparison

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$f_{cen}$ (MHz)</th>
<th>BW (MHz)</th>
<th>IL (dB)</th>
<th>Roll-off (dB/oct)</th>
<th>IS (dB)</th>
<th>$f_{cen}$ tuning</th>
<th>BW tuning</th>
<th>Intrinsic switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>187</td>
<td>33</td>
<td>1.5</td>
<td>90</td>
<td>23</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>[4]</td>
<td>136-163</td>
<td>27.5</td>
<td>3.7-4.1</td>
<td>120</td>
<td>52.8</td>
<td>Yes (1.2:1)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>[5]</td>
<td>1000</td>
<td>65</td>
<td>5.5</td>
<td>160</td>
<td>11.7</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td><strong>270-310</strong></td>
<td><strong>15-41.5</strong></td>
<td><strong>1.7-4.3</strong></td>
<td><strong>360</strong></td>
<td><strong>30.9</strong></td>
<td><strong>Yes (1.15:1)</strong></td>
<td><strong>Yes (2.77:1)</strong></td>
<td><strong>Yes</strong></td>
</tr>
</tbody>
</table>

- ✓ Multiple levels of tuning
- ✓ Highest selectivity in forward direction
- ✓ Low IL
Conclusion

Fully-reconfigurable non-reciprocal bandpass filters:

– *Magnet-less non-reciprocity!*

– *Filter/isolator co-design*

– *Non-reciprocal behavior ➔* modulating resonators with progressively shifted AC signals

– *Three-pole, two-TZ prototype ➔* 1.15:1 frequency tuning, 2.77:1 BW tuning, intrinsic switching, low IL, high selectivity
Thank you!

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References


