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Metamaterial-based MEMS Ultra-compact
Non-dispersive Phase Shifters

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• Phase-array Antennas
• Metamaterials
• MEMS Phase Shifters
• Tunable/Reconfigurable RF Front Ends
Phased-array Antennas
Compact, Light, Low Power Consumption, Low Cost, Conformal, Multifunction, Reconfigurable
Phase Shifters Critical to Phased-array Antennas

• UAVs need conformal and multi-function phased-array antennas for radar & communications
• Nondispersive phase shifters allow frequency hopping and broadband modulation
• Switching between right-handed and left-handed transmission lines minimizes dispersion
• MEM-switched phase shifters have low loss, compact size, light weight, low power consumption and low cost
• Slow-wave structure tightly wraps around MEM switches further reduces loss, size, weight and cost
• Low-loss phase shifters allow new system architecture and integration with antenna Metamaterial + MEMS + Slow-wave
Composite Right-/Left-Handed Metamaterials

Compact Switched CRLH

CRLH

Switched CRLH
## Solid-State Switches

<table>
<thead>
<tr>
<th></th>
<th>Insertion Loss</th>
<th>Power Consump.</th>
<th>Linearity</th>
<th>Integration</th>
<th>Speed</th>
<th>Power Handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diodes</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Fast</td>
<td>High</td>
</tr>
<tr>
<td>Transistors</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>MEMS</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
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</table>
**MEMS Capacitive Switch**

- 25V actuation voltage
- 10V release voltage
- \((100\mu m)^2\) MIM capacitor
- 1pF closed, 0.1pF open
- 15dB isolation @ 35GHz
- 0.1dB insertion loss @ 35GHz
- 10µs switching time
- Hot switching of 1W RF power
- Packaging/reliability improved under DARPA HERMIT Program
- Hero lifetime of 300 billion cycles
**MEMS Ka-band 3-bit Phase Shifter**

Transmission Line

Phase Delay $\Delta \Phi = \omega \ell \sqrt{LC}$

Characteristic Impedance $Z = \sqrt{L/C}$

<table>
<thead>
<tr>
<th>Organization</th>
<th>Rockwell</th>
<th>MEMtronics</th>
<th>U. S. Florida</th>
<th>Lehigh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Switched Line</td>
<td>Loaded Line</td>
<td>Slow Wave</td>
<td>Slow Wave</td>
</tr>
<tr>
<td>Variable</td>
<td>$\ell$</td>
<td>$C$</td>
<td>$L &amp; C$</td>
<td>$L &amp; C$</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>2 dB</td>
<td>3 dB</td>
<td>1 dB</td>
<td>1 dB</td>
</tr>
<tr>
<td>Return Loss</td>
<td>15 dB</td>
<td>7 dB</td>
<td>20 dB</td>
<td>20 dB</td>
</tr>
<tr>
<td>Length</td>
<td>5 mm</td>
<td>5 mm</td>
<td>5 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>No. Switches</td>
<td>12</td>
<td>9</td>
<td>50</td>
<td>12</td>
</tr>
</tbody>
</table>
Metamaterial-based MEMS Phase Shifter
Novel, Compact, Low-Loss, Wideband, Non-dispersive, Reliable

- Compact switched composite right-/left-handed metamaterial transmission line
- Left-handed nature through gap in bottom electrodes of side switches, resembling defected ground structure (DGS)
- Compact slow-wave structure tightly wraps around three MEM capacitive shunt switches

<table>
<thead>
<tr>
<th></th>
<th>Thru</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Switch</td>
<td>Up</td>
<td>Down</td>
</tr>
<tr>
<td>Side Switches</td>
<td>Down</td>
<td>Up</td>
</tr>
<tr>
<td>$C_S$ (fF)</td>
<td>990</td>
<td>40</td>
</tr>
<tr>
<td>$C_P$ (fF)</td>
<td>18</td>
<td>80</td>
</tr>
</tbody>
</table>
Ku-band 45° Unit Cell

- $S_{11}$ in dB vs. Frequency (GHz)
- $S_{21}$ in dB vs. Frequency (GHz)
- Phase $\Delta \Phi$ vs. Frequency (GHz)
**Ka-band 3-bit Phase Shifter**

- **Resistors (5 pl)**
- **Blocking Caps (2 pl)**
- **Bit bias inputs**
  - 0V = delay state
  - -V = zero phase state

**Graphs:**
- **Insertion Loss < 1 dB**
- **Return Loss > 20 dB**
- **Insertion Phase ~ 360° /dB loss**

**Specifications:**
- **Frequency (GHz):** 25.75 GHz
- **Insertion Loss:** < 1 dB
- **Return Loss:** > 20 dB
Reconfigurable RF Front-End

WiSpry

Tunable PA/Filters
Remaining Switching
Tunable Impedance Matching Network

OEM Develop
Future

Tunable Antenna
Tunable Capacitors
**Conclusion**

• Combination of MEMs, metamaterial, and slow-wave structure results in low-loss, broadband and non-dispersive phase shifters with compact size, light weight, low power consumption, and low cost

• MEMS have low loss hence high quality factor

• MEMS are ideal for tuning/reconfiguration

• Electro-statically actuated MEMS consume little power

• MEMS can be readily integrated with antenna or CMOS

• Antenna tuning/matching imminent

• Reconfigurable RF front end next
RF MEMS Last Frontier of MEMS