High-performance and Low-cost Capacitive Switches for RF Applications

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DARPA Fame
• Motivation for microelectromechanical (MEM) switches
• MEMS Switch performances and fabrication issues
• MEMS RF applications
• BST interdigital capacitors (IDCs)
• Low-loss BST phase shifters
• Future work and summary
Overview

Ideal switching circuits

Actual switching circuits

\[
IL = -20 \log \left| \frac{V_L}{V_0} \right| = \begin{cases} 
20 \log \left| 1 + \frac{Z_d}{2Z_0} \right|, & \text{series switch} \\
20 \log \left| 1 + \frac{Z_0}{2Z_d} \right|, & \text{shunt switch}
\end{cases}
\]
At present, most commonly used switching devices are PIN diodes, GaAs FETs, and conventional mechanical switches (relays).
Important figures of merit for switches are:

- isolation
- insertion loss
- power consumption
- power handling capability
- switching speed
- cutoff frequency
- cost of fabrication
MEMS (Micro ElectroMechanical Systems)

- Outgrowth of “Micromachining”
  - Creation of unique physical structures through the use of sacrificial layers resulted in miniature mechanical structures on a substrate

**MEMS Switch**

- $V_p = \sqrt[3]{\frac{8K_s g_0}{27\varepsilon_0 WL}}$
- $Z_d = \frac{C_{off}}{C_{on}}$

[Diagram of MEMS Switch]
MEMS Switches in RF Applications

MEMS Switch in a CPW configuration

\[ C_{\text{off}} \approx \frac{\varepsilon_0 Ww}{g} \]
\[ C_{\text{on}} \approx \frac{\varepsilon_0 \varepsilon_r Ww}{h} \]

- acts as RF switch or capacitor (100:1 ratios)
- loss dominated by conductor loss
- controlled by static DC voltage (10 nJ switching energy)
- low cost processing (~4 mask layers)
- high cutoff frequency
- minimum intermodulation distortion
### Why RF MEMS?

**Comparative table**

<table>
<thead>
<tr>
<th>Switch Type</th>
<th>Isolation</th>
<th>Insertion loss</th>
<th>Power handling</th>
<th>Power consumption</th>
<th>Switching speed</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIN diodes</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>GaAs FETs</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Excell</td>
<td>Poor</td>
</tr>
<tr>
<td>MEMS switches</td>
<td>Excell</td>
<td>Excell</td>
<td>Excell</td>
<td>Exell</td>
<td>Poor</td>
<td>Good</td>
</tr>
</tbody>
</table>

**Advantages:**

- Very good isolation and insertion loss.
- Virtually no control circuit power dissipation in either ON or OFF state.
- With proper design, can be capable of broad band and high power switching.
- Switching speed is more than sufficient for RF control circuit applications.
- Relatively low cost (designed and fabricated by standard processing techniques). Essentially on every substrate.

MEMS technology offers superior performance at lower costs and is expected to have tremendous impact on microwave systems.
Critical parameters to be carefully considered:
- the height of the membrane over the central conductor ($\rightarrow C_{OFF}$, $V_{PD}$)
- the thickness and composition of the top membrane ($\rightarrow V_{PD}$, mechanical properties)
- the size and the geometry of the membrane ($\rightarrow$ RF and DC performances)
- the thickness and type of dielectric coating the central conductor ($\rightarrow C_{ON}$, breakdown)
- type of substrate ($\rightarrow$ leakage, parasitic effects)
Typical Fabrication Process
Stiction occurred in an air-dried sample

90° angle view of the released suspended structure after critical point drier
Substrates & Metals

- Silicon
  - Si - Si₃N₄
  - Si - SiO₂
- GaAs
- Glass

**High leakage current**
- Low breakdown voltage

**Lowest leakage current**
- High breakdown voltage

**Membrane:**
- gold
- aluminum
- titanium
- platinum
- nickel

**Strong metal stress (Pt,Ni,Ti)**

**Low metal stress (Al,Au)**
Important Factors:

- compositions of MEMS top membrane $\rightarrow$ low stress deposition
- reflow temperature and surface roughness of sacrificial layer

Conclusions:

- risky design if span length longer than 300$\mu$m
- reflow temperature need to be adjusted for different types of MEMS switch design
- sputtered aluminum and electroplated low-stress nickel are good candidates as MEMS top membrane
DC Measurements

Typical DC measurements

- DOWN state capacitance: 2-7 pF
- UP state capacitance: 0.1-0.5 pF
- Capacitive ratio: 4-70
- Pull-down voltage: 20-100 V
RF Simulations and Measurements

- Good agreements between measurements and HFSS simulations
- Instead of 3-D EM simulation, lump-element model can also fit measurements well, which gives us a simplified way to describe MEMS switch performance
• How do we improve the switch performance?

\[
C_{\text{down}} = \varepsilon_0 \varepsilon_r \frac{A}{h}
\]

• Increasing switching ratio
  (i.e. increasing \( C_{\text{DOWN}} \) for given \( C_{\text{UP}} \))
Pro: Much higher isolation in DOWN state than previous design

Con: Direct metal-to-metal contact → lower switching speed
MEMS RF Applications

• Advantages of RF MEMS
  - High performance, low bias power consumption
  - Potential low cost manufacturing into a variety of substrates

• Limitations of RF MEMS
  - Slower switching speed
  - Potential lifetime limitations

APPLICATIONS

• Phase Shifters
• Filters
• Reconfigurable Antenna
Programmable Delay Lines

Variable Phase Velocity Design
Analog or Digital MEMS Switches

Switched-Capacitor

Variable-Capacitor

4-bit Digital Phase Shifter

RF in

0-22.5°

0-45°

0-90°

0-180°

RF out

V₁

V₂

V₃

V₄
**Distributed Circuit Concepts**

**Transmission-line**

**Equivalent circuit**

\[
Z_0 = \sqrt{\frac{L}{C}} \\
\nu = \frac{1}{\sqrt{LC}}
\]

\[\omega < \sqrt{\frac{2}{LC}}\]

**Loaded Transmission-line**

**Varactor provides variable phase delay:**

\[\Delta \phi = \omega \sqrt{L_l \left( C_l + C_s \right)}\]
MEMS Low-loss Distributed Phase Shifters

Transmission line sections

Equivalent Circuit:

\[ \frac{1}{L_t} \quad \frac{1}{C_t} \quad \frac{1}{C_{\text{MEMS}}} \quad \frac{1}{L_t} \quad \frac{1}{C_t} \quad \frac{1}{C_{\text{MEMS}}} \quad \frac{1}{L_t} \quad \frac{1}{C_t} \quad \frac{1}{C_{\text{MEMS}}} \]

\( L_{\text{sect}} \) : Length of transmission line per section
\( C_t \) : Transmission line capacitance per section
\( L_t \) : Transmission line capacitance per section

Periodic loading of transmission lines with MEMS capacitive switches creates a structure with a variable phase velocity
Optimization – MEMS Phase Shifters

Loading Factor: \[ x = \frac{C_{\text{var}}^\text{max}}{L_{\text{sect}}} \]

Return Loss: \[ S_{11} \leq S_{11,\text{max}} \]

Max phase shift/section:
\[ \delta \phi = 2\pi f \frac{L_{\text{sect}}}{v_i} \left( \sqrt{1 + x} - \sqrt{1 + xy} \right) \]
\[ f_s = \frac{1}{2\pi r_s C_{\text{var}}^\text{max}} \]
\[ \text{Loss} = n_{\text{sect}} \pi f_s^2 C_{\text{var}}^\text{max} Z_L + n_{\text{sect}} L_{\text{sect}} \alpha(Z_i) \]

Min/Max ratio: \[ y_{\min} = \frac{C_{\text{var}}^\text{min}}{C_{\text{var}}^\text{max}} \geq a - \frac{1-a}{x} \]
Challenge:

• Not overload the transmission line with an excessively large MEMS switch capacitance in the DOWN state

Solution:

the ‘series’ configuration design

\[ C_{\text{TOT}} = 2 \frac{C_{\text{var}} C_{\text{fixed}}}{C_{\text{var}} + 2C_{\text{fixed}}} \]

\[
\begin{cases} 
C_{\text{var}} \gg C_{\text{fixed}} \rightarrow C_{\text{TOT}} \equiv 2C_{\text{fixed}} \\
C_{\text{var}} \ll C_{\text{fixed}} \rightarrow C_{\text{TOT}} \equiv C_{\text{var}}
\end{cases}
\]
• The state of the art insertion loss performance, 154°/dB at 25 GHz and 160°/dB at 35 GHz, demonstrates the potential for the implementation of a very low loss multi-bit digital MEMS phase shifter.
Three-bit MEMS Phase Shifters

- Designed for 25GHz operation
- 3dB max. insertion loss
- Phase error less than 8.5° for all switching states
- Capacitively loaded line sets up a slow wave structure
- Resonator electrical length determined by capacitive loading of the line
- Tuning range of the filter determined by the effective capacitance range of varactor
- MEMS varactors have been demonstrated with low loss making them an excellent candidate for filter applications
Simulated Results of Tunable Filters

**Return Loss**

**Insertion Loss**
• 12% bandwidth at 20GHz with 3.6dB insertion loss in passband
• Loss is contributed by conductive loss, substrate leakage and radiation.
• 3.8% tuning range, which is limited by the tuning factor of MEMS varactors (~1.3:1)
• The switch can be used to turn “on” or “off” various conductive paths.
• In this way various virtual antenna states can be realized.

A matrix of RF switches in a metallic grid to control the RF current distribution and hence radiation and impedance characteristics of the antenna structure.

• Multiple frequency band operation
• Possible beam and null steering
• Lends itself to multiple feed locations
• Polarization diversity

Microstrip structure with switches represents over $10^{17}$ possible states.
SQUARE RECONFIGURABLE GRID ANTENNA INCORPORATING MEMS CONTROL SWITCHES
Preliminary Work on MEMS-based Grid Antenna

FULL HFSS MODEL -- ALL MEMS DOWN
SQUARE RECONFIGURABLE ANTENNA INCORPORATING MEMS CONTROL SWITCHES
(switches at 3/4 of each leg length, diagonal trace from feed point)

S11 [dB]

8 8.5 9 9.5 10 10.5 11 11.5

Frequency [GHz]

-15 -10 -5 0 5 10 15 20 25 30 35 40

Radiation Pattern [Electric Field]

0 30 60 90 120 150 180 210 240 270 300 330

simulated

measured
**Motivation**

*Phased Array Antennas*

*The Phase-Shifter: A critical component*

**Thin-Film BST Varactors**

*Parallel Plate vs. Interdigital Capacitors*

*Device Characterizations*

**Phase-Shifters using Thin-Film BST**
Wideband Phased Array

Coarse Delay Control

Fine Delay Control

Sub-Array

Antenna Array

desired phasefront
**Key BST Properties**

- **Large field dependent permittivity** --- *Compact tunable circuits*
- **Intrinsically fast field response** --- *Fast switching speeds*
- **High breakdown fields, >3x10^8 V/cm** --- *High power handling capability*
- **Low drive currents (dielectric leakage)** --- *Low prime power requirement*
- **Simple fabrication** --- *Low cost*

- BST thin film properties differ markedly from those of bulk and much work is focused on low-cost deposition of BST thin film for microwave applications.
Influence of Loss and Tunability on Phase Shifter Performance

Tunability: how much we can vary capacitance of film $C_{\text{max}}/C_{\text{min}}$

**Device loss and tunability are important**
Desirable Features of a Viable Thin-Film Varactor Technology

- Reproducibility
- Inexpensive substrates
- Standard growth/processing steps
- Low loss tangent (\(\tan \delta < 0.01\))
- High tunability (>2:1)
- Compatible with low-cost packaging

- Integrated monolithic capacitors using sputtered/MOCVD material on low-cost substrates
- Sapphire is a cost effective wide area substrate that has excellent microwave and rf properties
Monolithic BST Device Structures

Parallel Plate vs. Interdigitated Capacitor (IDC)

- Vertical polarization
- High tunability, efficient use of BST
- Low breakdown voltage
- Complex fabrication

- Horizontal polarization
- Low tunability, inefficient use of BST
- High breakdown voltage
- Easier fabrication
Tunability

- 1000Å film
- 70-80% of material tunability
- 0-100 V control
- Device tunability limited by finger-to-finger spacings
- Ti/Au metalization
- 3-mask process

**Good choice for low-cost circuits**
RF Parameters Extraction Method

Layout for Parameters Extraction:

Open  Short  Load

Equivalent Circuit Expression:

\[
Y_D \equiv \frac{(Y_L - Y_{op})(Y_{sh} - Y_{op})}{Y_{sh} - Y_L} \equiv G + i\omega C
\]

\[
Q = \frac{\omega C}{G}
\]
Total device loss consists of conductor loss and BST material loss:

\[
\frac{1}{Q_{\text{device}}} = \frac{1}{Q_{\text{cond}}} + \frac{1}{Q_{\text{bst}}}
\]

- \(Q_{\text{bst}}\), inherent to deposited BST film
- \(Q_{\text{cond}}\), determined by \(R_{\text{metal}}\) and \(C_{\text{device}}\)

- Devices with different finger to finger spacings but same other dimension parameters are fabricated on the same wafer

- \(Q_{\text{device}}\) stays the same while \(Q_{\text{cond}}\) varies \(\Rightarrow Q_{\text{bst}}\) dominates the total device \(Q_{\text{device}}\)
100 nm (Ba, Sr) TiO$_3$ thin films deposited on sapphire substrate

- Quality factor rolls off as frequency increases
- Stoichiometry of deposited thin film determines its loss tangent
- $Q > 35$ in X-band for (Ba$_{30}$, Sr$_{70}$) TiO$_3$ thin film

$T_{\text{Surface}} = 700 \, ^\circ\text{C}$: RF power = $2 \times 150$ W (3.3 W/cm$^2$): 90/10 Ar/O$_2$ (sccm): 100 nm
Tuning Factors of BST Interdigital Capacitors

- Finger spacing = 1µm
- 100nm (Ba$_{30}$,Sr$_{70}$)TiO$_3$ thin film on sapphire substrate
- ~2:1 tuning range
- 0-100V DC control

$T_{\text{Surface}} = 700$ °C: RF power = 2*150 W (3.3 W/cm$^2$): 90/10 Ar/O$_2$ (sccm): 100 nm
X-band BST Phase Shifters

Photograph of fabricated X-band BST phase shifter

S-parameter measurements of distributed BST phase shifter
Differential phase shift at 0V, 40V and 100V bias voltage

- 0º-360º phase shift @ 8.2GHz with 5dB insertion loss
- Return loss is better than –10dB from DC to 10GHz
State of Progress

What have been done so far?

- Developed a novel design of MEMS devices
- MEMS-based RF circuits (i.e. phase shifters, filters)
- BST interdigital capacitors and phase shifters

What the plan for future work?

- BST-MEMS switches
- MEMS-based reconfigurable microstrip grid antenna
- MEMS single-controlled single-pole-double-throw (SPDT) switches
BST-MEMS Switches

Barium Strontium Titanate (BST)

Switch up

Switch down

- High dielectric constant of BST (>250)
- >15dB more isolation than conventional MEMS switch in DOWN state

What we will do?

- BST/Pt/Au/Ti/Sapphire
- Reduce pull-down voltage, avoid breakdown in BST thin film
Future Work on Reconfigurable Antenna --- Toyon Project

- Demonstrate the 4-element microstrip grid antenna using standard MEMS fabrication techniques
- RF measurements and simulations accounting for the parasitic effects in the model
- Finally expand this design to a 16-element switching reconfigurable antenna array
MEMS Single-Controlled SPDT Switches

Signal IN

Control 1
Control 2

MEMS Switch 1
MEMS Switch 2

Coplanar Waveguide

Signal OUT 2

Signal OUT 3

Port 1

C_{down}

Port 2

λ/4

Port 3

Isolated

λ/4

(a) Switch Down

(b) Switch Up
• MEMS based switches promise superior performance relative to conventional devices. Through its superior performance characteristics, the MEMS switches are developed in a number of existing circuits, including switches, phase shifters and filters.

• BST thin films have been characterized and used to demonstrate a 0°-360° X-band phase shifter with only 5dB insertion loss.

• Replace Si$_3$N$_4$ with high dielectric constant BST thin film in MEMS switch is expected to further improve the switch performance.

• MEMS technology offers the potential for building a new generation of low loss high-linearity reconfigurable antenna arrays for radar and communications applications.