Lecture #3

Radio Frequency Microelectromechanical Systems (RF MEMS)

The main objective of this lecture is to give a basic overview of RF MEMS. Emphasis will be placed on the potential applications and technological limitations of this relatively new technology.

Radio Frequency Engineering
Lecture #3 RF MEMS

OSD Group MEMS Activities

Micromachining Technologies

- Surface micromachining methods
  - in essence, this technology is a basic extension to multilayer microfabrication, except that sacrificial layers are incorporated
- Bulk micromachining methods
  - anisotropic etching techniques on silicon wafers
  - isotropic chemical etching techniques on GaAs wafers
- Wafer-bonding methods
  - Transmission lines can achieve incredibly low losses, making superconducting technologies unnecessary is some cases

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OVERVIEW

- OSD Group MEMS Activities
- Commercial Applications
- What is (not) RF MEMS?
- RF MEMS Components
  - switches and variable capacitors
- Reconfigurable Systems
  - phase shifters, impedance tuners, filters and antennas
- Commercialization
- Conclusions

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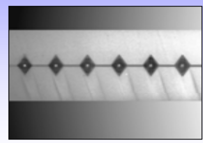
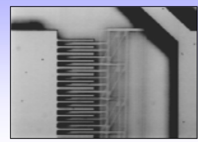
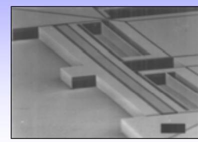
Silicon-based:



- bulk micromachining

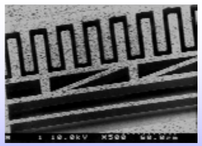


- surface machining boron etch-stop

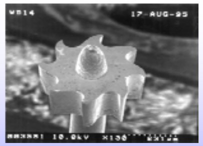


- BSOI + DRIE

Metal-based:

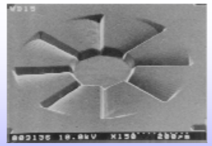


- multi-level electroplating



- UV- and laser-formed molds

Polymer-based:



- laser machining

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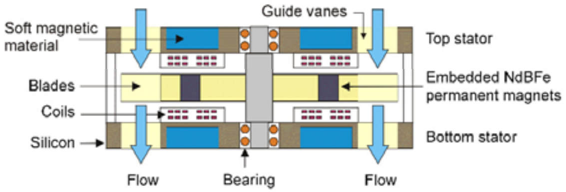
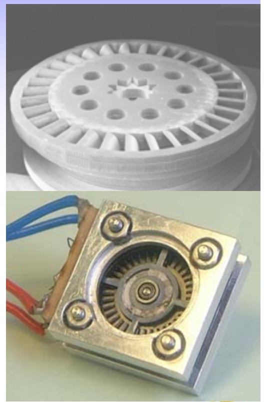
Turbogenerators (A. S. Holmes)

- mm-scale axial flow turbogenerator
- Polymer rotor, embedded magnets
- Energy scavenging from ambient air stream for remote sensors





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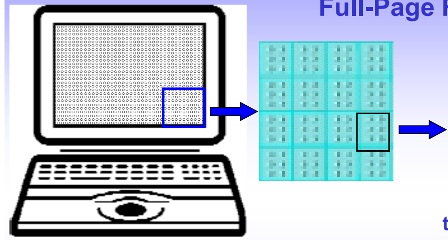
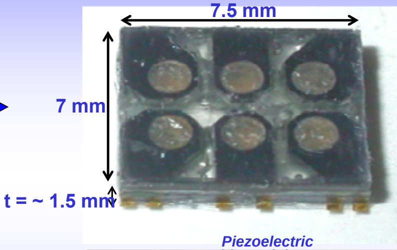
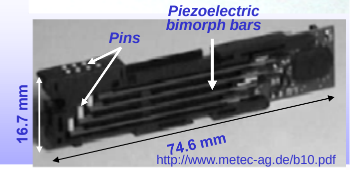
Full-Page Refreshable Braille Display





J. S. Lee and S. Lucyszyn, "A micromachined refreshable Braille cell", *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 14, no. 4, pp. 673-682, Aug. 2005



http://www.metec-ag.de/b10.pdf

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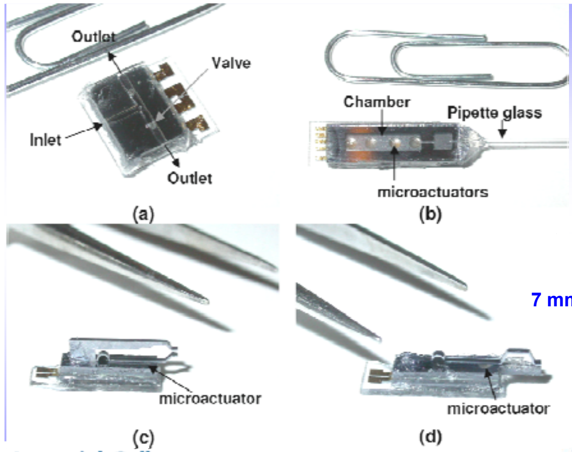
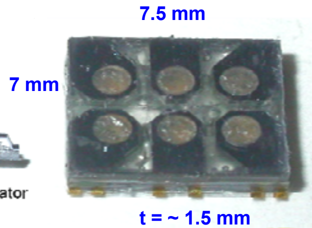
Packaging of Electrothermal Hydraulic Paraffin Wax Microactuator Based Devices



(e) Braille cell



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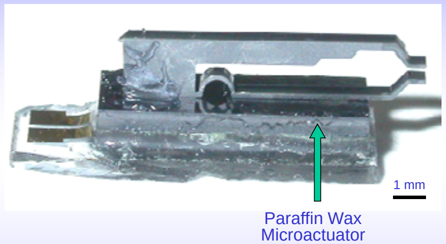
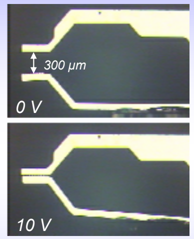
Micro-gripper Technology





J. S. Lee and S. Lucyszyn (Invited Paper), "Bulk-micromachined hydraulic microactuator", *3rd International Conference on Materials for Advanced Technologies 2005 (ICMAT 2005) and 9th International Conference on Advanced Materials (IUMRS-ICAM 2005)*, Symposium F (Nano-Optics & Microsystems), Technical Session 7 – Actuator, Singapore, pp. 115-118, Jul. 2005

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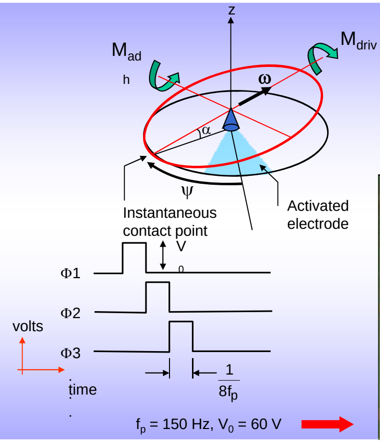
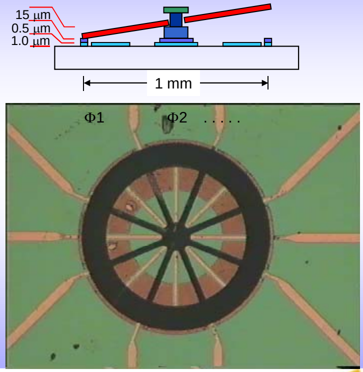
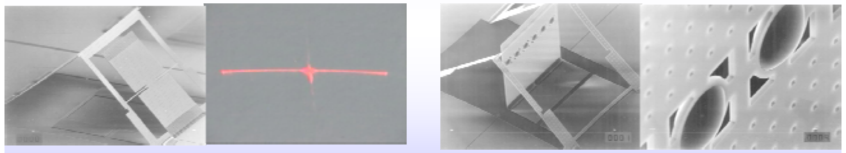
Wobble Motors (A. S. Holmes)





3D MOEMS (R. R. A. Syms)

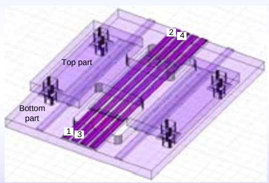
- Devices formed by surface tension self-assembly
  - Mirrors, mirror scanners, microlens arrays
  - Collaboration with BCO Technologies



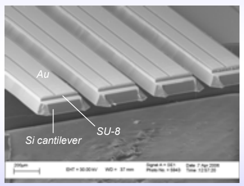
200 µm Pitch RF Connectors

Part-funded by Taiko Denki Co.

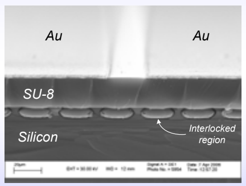
- ACPS (signal-ground) transmission lines on SU-8 on LRS substrate.
- Compliant Si cantilevers generate contact force on each pin.



Test Device



Compliant Si/SU-8/Au Cantilever Pins

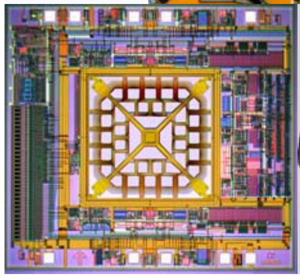


Mechanical Interlocking Prevents Dielectric Peeling

Commercial Applications

- **Car airbag sensors**
- **Accelerometers in handsets (e.g. iPhone and Wii)**
- **Disk drives**
- **Ink-jet print-heads**
- **Digital Micromirror Device (DLP™) Chip**

Car Airbag Sensors

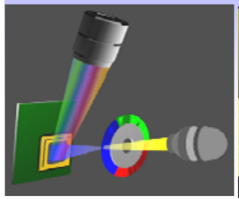


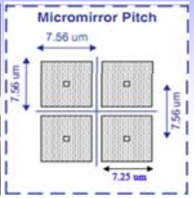
©MEMSIC

What is (not) RF MEMS?

- RF refers to frequencies operating beyond DC to sub-mm wavelengths
  - lumped-element components
  - distributed-element transmission lines
  - quasi-optical techniques
- Microsystems refer to everything from micro-fluidics to self-assembly to micro-electromechanical systems (MEMS)
  - Employ functional components that are controlled under various methods of actuation (e.g. electrostatic, piezoelectric, electromagnetic, electrothermal)
  - Micromachined structures are <u>not</u> MEMS unless they incorporate moving parts

Digital Light Processing (DLP™) Chip





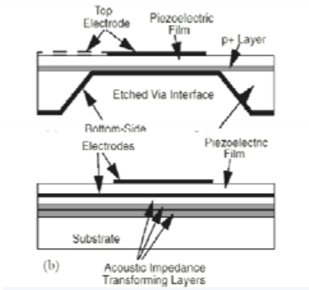
DLP
A TEXAS INSTRUMENTS TECHNOLOGY

Invented by Dr Larry Hornbeck of Texas Instruments in 1987.

The DLP™ chip is probably the world's most sophisticated light switch.

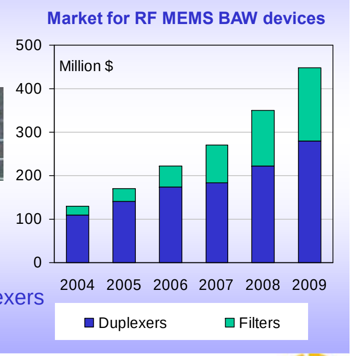
2 million hinge-mounted 7.25 x 7.25 micron^2 mirrors.

Each mirror switches on and off up to **several thousand times per second**.



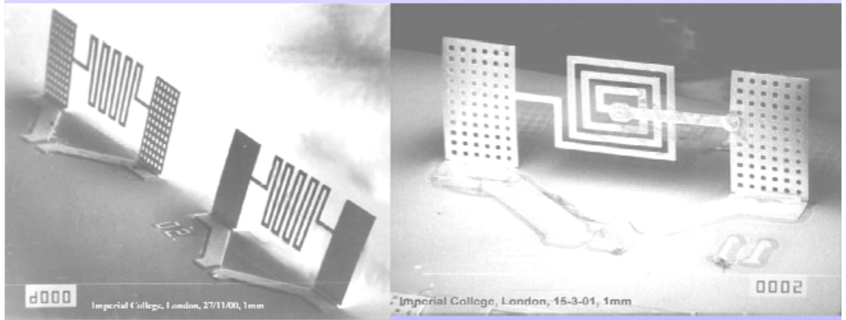
- Thin-<u>F</u>ilm <u>B</u>ulk <u>A</u>coustic Wave <u>R</u>esonator (FBAR)

WTC



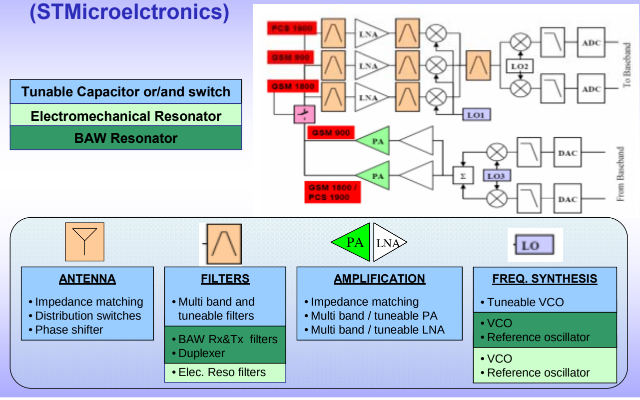
Agilent (US) and Infineon (D):
CDMA replacement of ceramic and SAW duplexers
CDMA and 3G replacement of SAW filters

G. W. Dahlmann, E. M. Yeatman, P. R. Young, I. D. Robertson and S. Lucyszyn, "Fabrication, RF characteristics and mechanical stability of self-assembled 3D microwave inductors", ***Sensors and Actuators A-Physical***, Elsevier Science, vol. 97-98, pp. 215-220, Apr. 2002



• meandered inductors (up to 2 nH)   • spiral inductors (up to 5.5 nH)

Potential Applications of RF MEMS in Mobile Phones (STMicroelctronics)

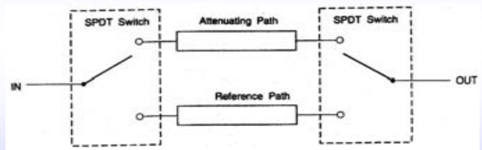


RF MEMS Components

- The first RF MEMS papers started to appear around *circa* 1979
  e.g., within an IBM journal, a paper was published on electrostatically actuated cantilever-type ohmic contact switches
- There are very few examples of a complete RF system
- Notable RF microsystems include: self-assembly inductors, variable capacitors, switches, phase shifters, tuners, antennas and transceivers
- Switches and tuneable capacitors are the most important RF MEMS components and this has important applications in reconfigurable architectures

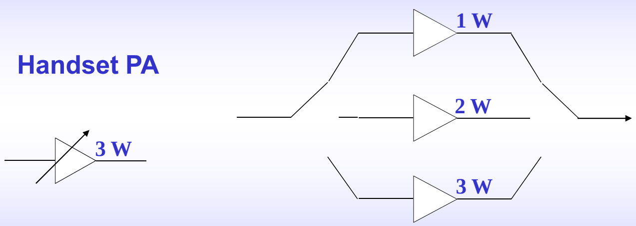
Switches

- Microwave switches are essential for routing an RF signal from one path to another path, and are employed in:
  - T/R switches within T/R modules
  - implementing smart antennas (switched diversity)
  - high performance variable attenuators



  - high performance impedance matching networks and phase shifters
  - providing subsystem redundancy
  - power amplifier selection

✍ Changing the bias points can reduces the output power BUT also the impedance matching conditions. One solution is to have RF MEMS tuners.



$$\eta_{add} = \eta\left(G_{OUT} - \frac{1}{G_{IN}G}\right).100\%$$

Electromechanical and Ferrite Switches

✍ High power handling, bulky, slow

PIN Diode Switches

✍ Compared to conventional mechanical counterparts**,** PIN diode microwave switches result in a significant improvement in mass, size and speed, but at the expense of complex drive circuitry

✍ PIN diodes can handle medium to large RF power levels

✍ On-state requires high forward current

✍ Off-state requires large reverse bias voltage

✍ Switching characteristics are dependent on the individual PIN diodes

Switch Requirements

✍Systems' architectures can be greatly enhanced, in terms of greater performance and functionality and reduced complexity and cost, if switch performance can be improved even further.

✍ Relaxed specifications on HPA on TX side and LNA on RX side.

✍ General requirements for an RF switch include:

✍ High "performance figure-of-merit", $fc = 1/(2\pi R_{ON}C_{OFF})$ with good return loss

✍ High operational bandwidth

✍ Low control power

✍ Small real-estate

For the past few decades, RF integrated circuit switching has been performed by PIN diodes within HMICs and cold-FETs within RFIC/MMICs.

The latter is the result of the inherent compatibility with active-FET processing, but the performance is worse than that obtained with PIN diodes.

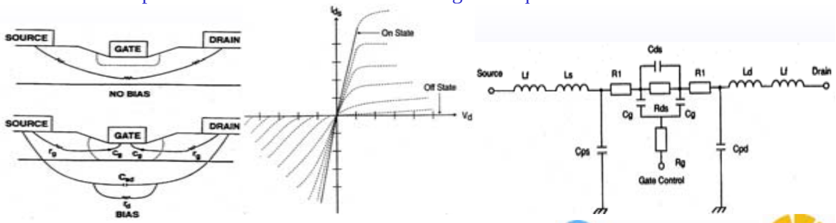
With both PIN diodes and cold-FETs, intermodulation distortion presents serious limitations at higher RF-power levels, however, general PIN diode performance is still formidable.

e.g, M/A-COM's MA4AGSW1 AlGaAs SPST reflective PIN diode switch:

✍ **ON state insertion loss of less than 0.4 dB, from DC to 50GHz**
✍ **OFF state isolation better than 45 dB, from 18 to 50GHz**
✍ **Return losses better than 15 dB, from DC to 50GHz**

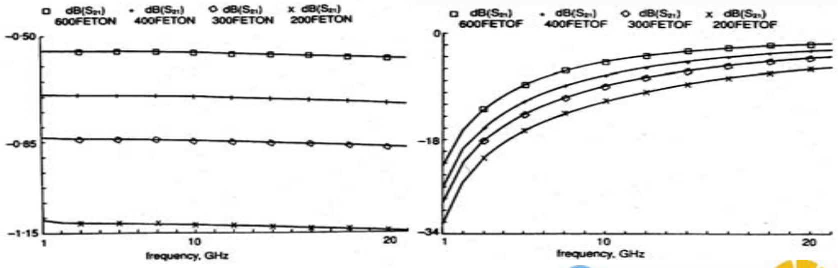
GaAs FET Switch

- The FET switch is a 3-terminal device, with the gate-source bias voltage controlling the states of the switch
  - the cold-FET acts as voltage-controlled resistor, where the drain-to-source channel resistance is varied
  - the intrinsic gate-to-source and drain-to-gate capacitances and other parasitics limit the performance of the FET switch at higher frequencies



Series FET Switch Insertion Loss Performance

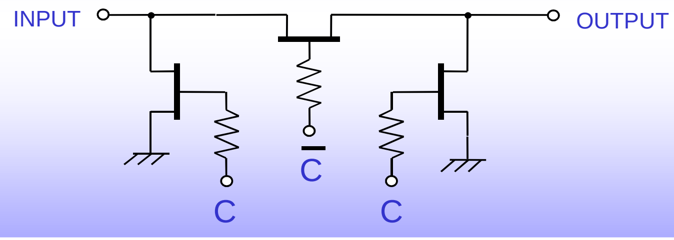
- on-state insertion loss decreases as total gate periphery increases (low channel resistance dominates and this is frequency independent)
- off-state isolation decreases as total gate periphery increases (equivalent capacitance dominates, thus very frequency dependent)



- In recent years, PIN diode switches have been increasingly replaced by GaAs FET based monolithic switches
- GaAs FETs are ideal for low to medium power applications:
  - simple control biasing
  - low DC control power
  - faster switching speeds (nanoseconds)
- SPnT switches, with on-chip control circuits, have made possible the realisation of new architectures for wireless applications
- MMIC switches capable of handling an RF power of more than **100 W** at high switching speeds have been reported by Katzin *et al*.
- Intrinsic parasitic components within its equivalent circuit model kills performance

- Difficult to achieve high isolation with low insertion loss by scaling size
- Another approach is to resonates-out the parasitic drain-source capacitance with a shunt inductor, to provide isolation of the order of 40 dB
- Higher-order series-shunt configurations are necessary to achieve the desired low insertion loss, high isolation and good return loss characteristics

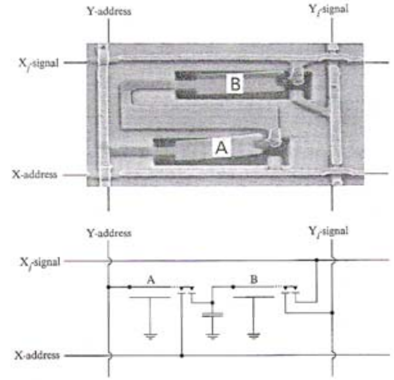
Improved Isolation Reflective SPST Switch using Series/Shunt Combination



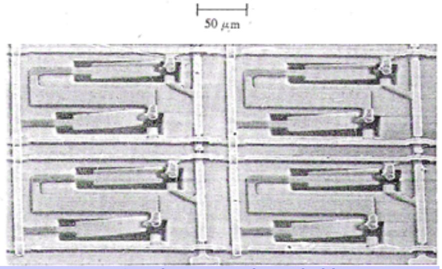
PE42671 UltraCMOS™ SP7T RF Switch

- Industry's first monolithic 3GPP IMD-compliant SP7T switch
  - 2 GSM/PCS/EDGE TX ports
  - 2 WCDMA TX/RX ports
  - 3 RX ports
- World's most linear SP7T switch (IP3 = +68 dBm)
- Operating voltage = 2.75 V
- Meets dual-band WCDMA and GSM requirements

Peregrine Semiconductor Co.



in the beginning … K. E. Petersen invented RF MEMS, (IBM Res. Div. Lab., San Jose) Published in 1979



Cr-Au-coated 0.4 μm thick SiO_2 membrane cantilevers over 6 μm deep silicon cavity

4-node cross-point switching array. Ohmic contact switches require 48 V bias and exhibit 5 Ω contact resistance

MEMS Switches
Electrodes (Two generic types)

✍ Ohmic contact switch has:
- high open-state isolation
- low closed-state insertion loss
- considerable force is required to create a good contact
- microscopic bonding of the metal surfaces
- highly susceptible to corrosion and stiction

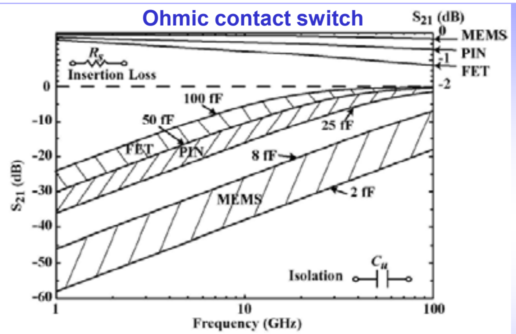
e.g. single-pole single-throw suspended beam-type switch can have a performance figure-of-merit of 90 THz, *Rockwell*

✍ Switched capacitance switch has:
- compromise is made between insertion loss and isolation
- insertion loss is independent of the contact force
- electrode separation need to be maximised
- higher lifetime (typically several orders of magnitude)

RF MEMS vs. PIN AND MESFET SWITCH COMPARISON

	MESFET	PIN Diode	MEMS
Series resistance (Ω)	3 to 5	1	< 1
Loss at 1 GHz (dB)	0.5 to 1.0	0.5 to 1.0	0.1
Isolation at 1 GHz (dB)	20 to 40	40	> 40
IP3 (dBm)	40 to 60	30 to 45	> 66
1 dB compression (dBm)	20 to 35	25 to 30	> 33
Size (mm^2)	1 to 5	0.1	< 0.1
Switching speed	~ ns	~ μs	~ μs
Control voltage (V)	8	3 to 5	3 to 30
Control current	< 10 μA	10 mA	< 10 μA

Ohmic contact switch



- Extremely low insertion loss and amazing isolation up to 120 GHz

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✍ Piezoelectric actuation:
- based on a bimorph cantilever or membrane
- differential contraction causes the structure to bend
- fast switching speeds can be obtained
- usually a differential thermal expansion of different layers
- integrating piezoelectric materials
  - – films are difficult to pattern
  - – processing requires high crystallising temperature

✍ Magnetic actuation:
- low actuation voltage
- high contact force
- consumes significant power in the actuated state
- large and slow structures
- requires a 3D coil with a soft-magnetic core

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✍ Once the choice of electrode has been decided, appropriate methods of actuation can be investigated

✍ Various conflicting parameters need to be considered:
physical size, switching speed, actuation voltage/power and *RF power, etc.*

✍ Electrostatic actuation:
- small switches that are robust and simple to fabricate
- fast and tolerant to environmental changes
- consume power only when switching between states
- residual power is required to hold in the actuated state
- low actuation voltage with good isolation is difficult
  - – typical MEMS capacitive membrane switches can have C_{ON}/C_{OFF} of 10 to 100 but an actuation voltage of 40 to 75 V
- self-actuation by the RF signal can also be a problem

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Summary of Actuation Mechanisms

	Actuation voltage	Actuation power	Displacement	Transition time	Remarks
Piezoelectric	✓	✓	✓	✓	**Difficult to fabricate & parasitic movement due to temp. variations**
Electrostatic	✗	✓	✗	✓	
Magnetic	✓	✗	✓	-	
Thermal	✓	✗	✓	-	**Parasitic movement due to temperature variation**

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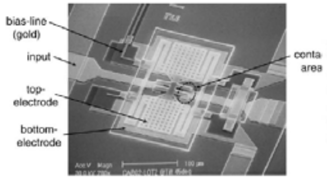
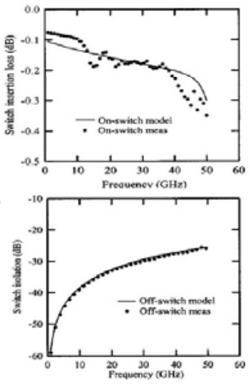
Rockwell Ohmic Contact Series Switch

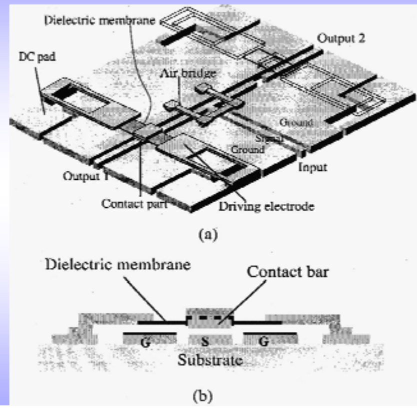




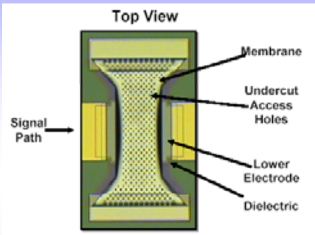
- Biasing circuits decoupled from RF Circuits.
- Dimples for improved contact.
- Actuation voltage = 70V
- R_s=1-2 Ω, C_u=1.75 fF
  $f_T = 1/(2\pi R_s C_u)$ = 90 THz
- RF Performance:
  Loss = -0.12 dB at 10 GHz
  Isolation = -40 dB at 10 GHz

The University of Michigan

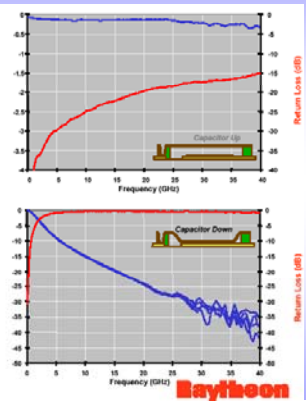
3 V ohmic contact switch, *Park et al.*



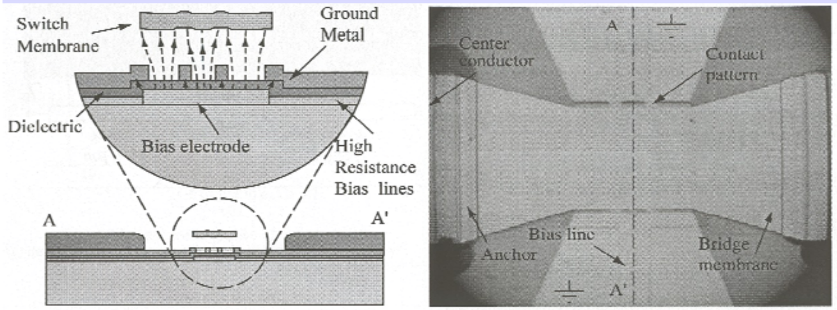
Raytheon Capacitive Membrane Shunt Switch



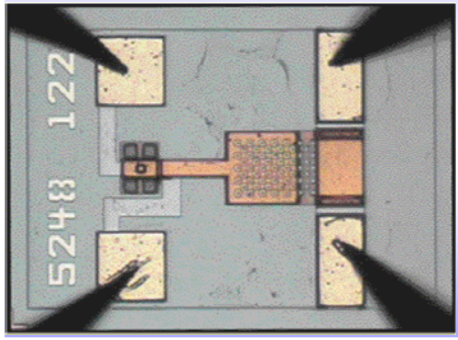
Capacitance Ratio	70-110	
Cutoff Frequency	18,000	GHz
Switching Speed	< 10	µs
Intercept Point	> +66	dBm
Switching Voltage	30-50	volts
Size	280 × 170	µm



Low stiction ohmic contact switch, *Muldavin et al.*



Commercial RF MEMS switch, *HRL Laboratories*



Electrostatically-actuated cantilever-type metal contact switch for microstrip:

Insertion Loss < 0.2 dB

Isolation > 20 dB

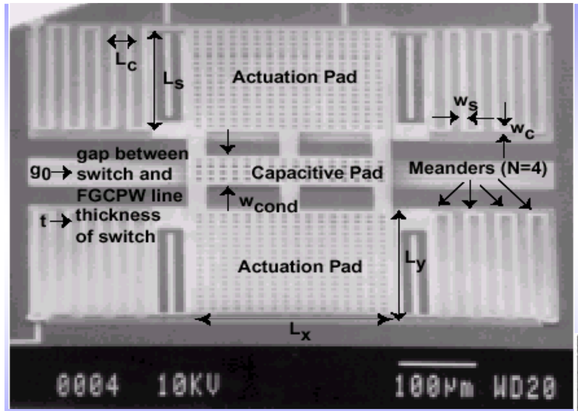
On state Return Loss > 20 dB

Switching Voltage < 5V

Switching Time < 1 ms

DC Actuating Power < 1 µW

Switching Energy Dissipation < 1 µJ

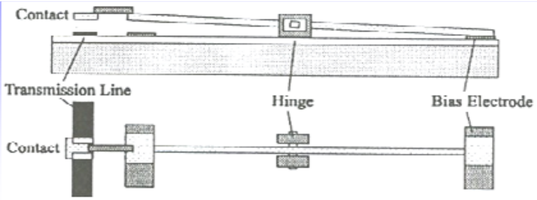


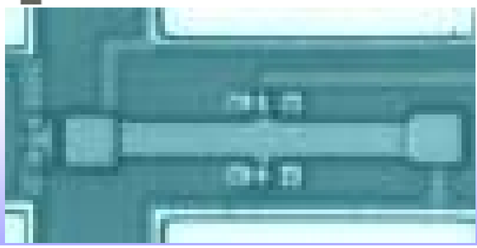
Pacheco, et al. University of Michigan:

9V actuation with N = 5
Capacitance ratio
= 2.5 pF/47 fF = 48

Insertion Loss
= 0.16 dB at 40 GHz
Isolation
= 26 dB at 40 GHz

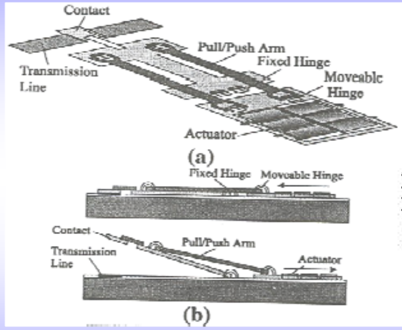
Number of meanders	V_{pi} - Design	V_{pi} - Measured
1	3.90 V	35 V
2	2.75 V	28 V
3	2.24 V	20 V
4	1.94 V	15 V
5	1.74 V	9 V

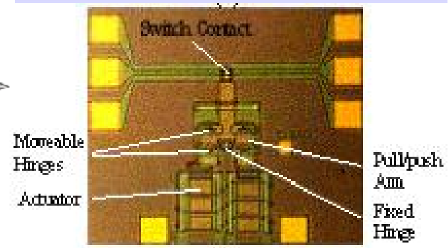




See-saw-bar Ohmic contact switch, *Chiao et al.*

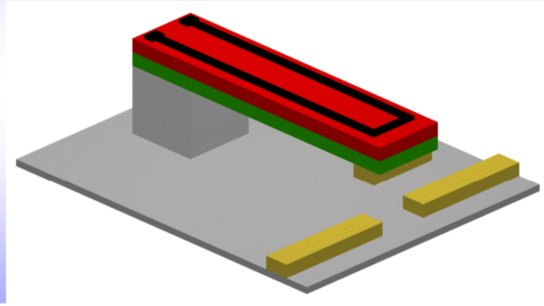
A linear-actuator driven Derrick-type ohmic switch, Chiao et al.





✍ Lateral movement of the microactuators (20 nm per 70 V to 120 V biasing pulse) is translated to rotational movement of the arms

- Thermal actuation:
  - relatively very slow
  - consumes significant control power



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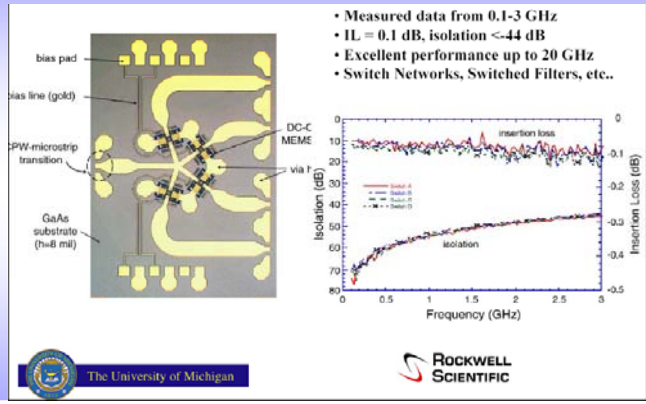
S4PT MEMS Switch



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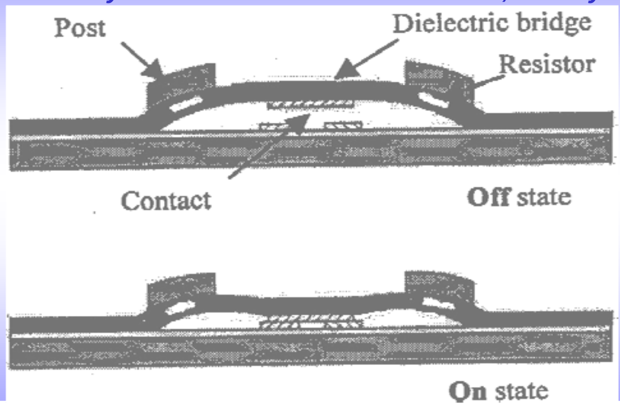
5 V thermally actuated ohmic contact switch, Blondy et al.



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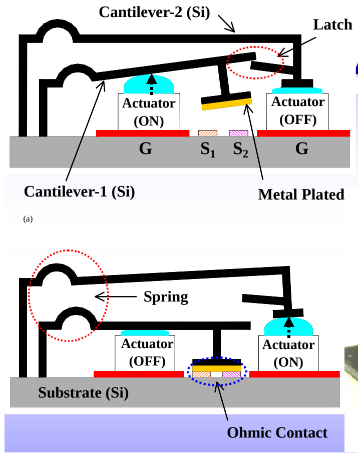
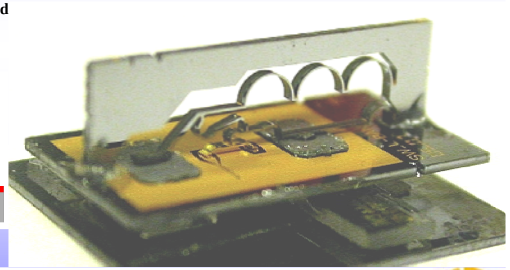
40-60 GHz SPST Switch



AMICOM

High Isolation/Power 3D MEMS Switches

roke
Roke Manor Research Ltd
a Siemens company



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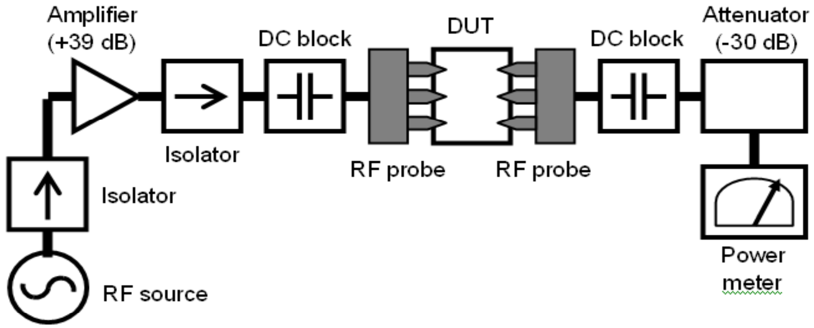
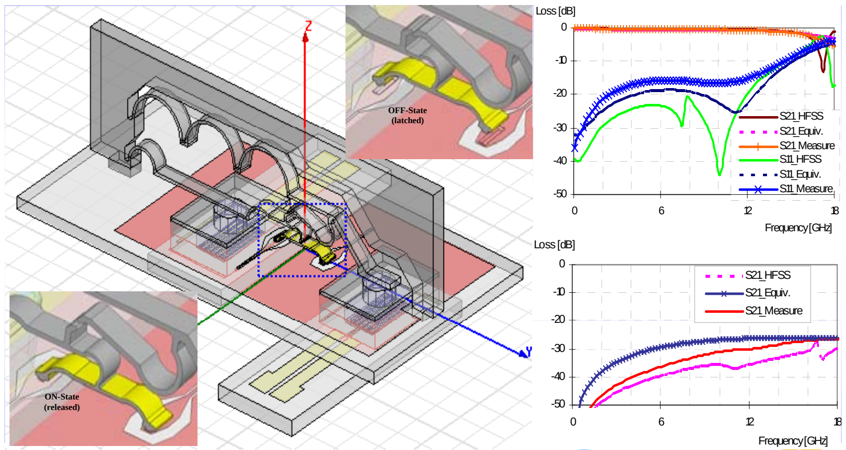


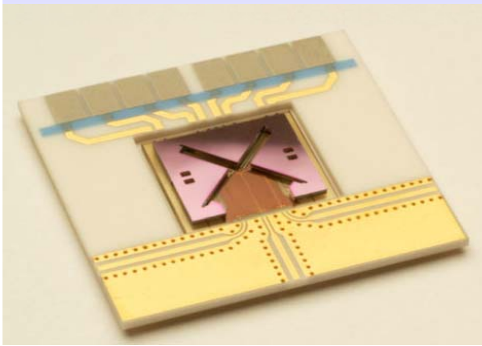
Measurement setup for high power testing at 10 GHz: Under HOT switching, it was found that the switch can operate with 4.6 W of RF power at 10 GHz, without any observable degradation in performance.



DC-6 GHz SPDT Switch

Low Power, Low Voltage MEMS Switch for Space Communication Systems

Microsaic Systems Ltd

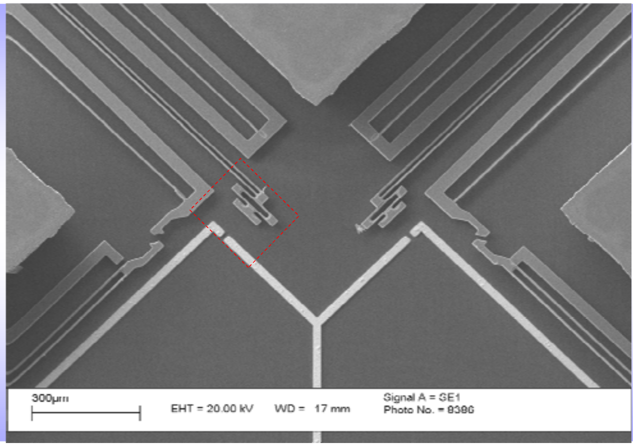


Requirements:

- SPDT switch for operation to 6 GHz
- Low switching power and low actuation voltage (3 V)
- Latching for zero holding power in either state
- Broadband operation
- High isolation

In collaboration with EADS-Astrium Ltd

EADS ASTRIUM



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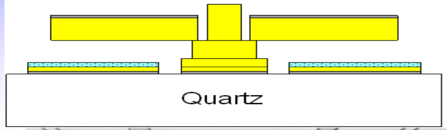
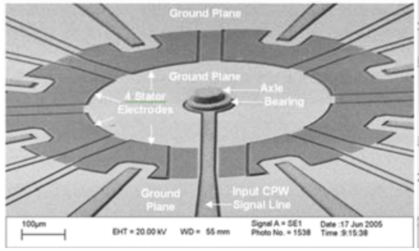
DC to 20 GHz SP8T Switch

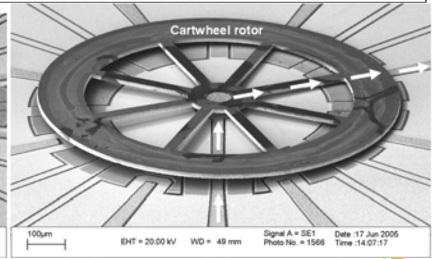
RF MEMS Rotary Switch

EPSRC

Rotor release from the sacrificial layer and assembly onto stator







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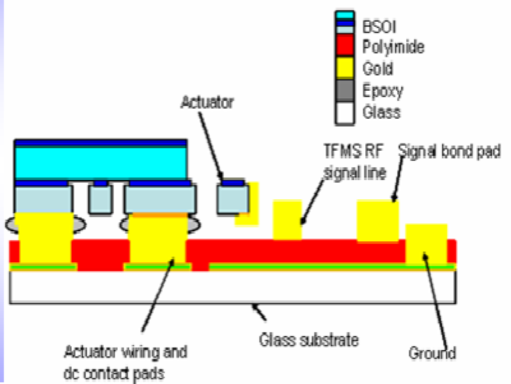
- TFMS transmission lines on glass
  - Laterally compact
  - High field confinement
  - High isolation
- Thermal actuation
  - High contact force
  - Low voltage
  - Latching needed
- Bonded silicon-on-insulator (BSOI)
  - Mechanical reproducibility
  - Long life-time
  - High-aspect-ratio structures

Microsaic Systems Ltd



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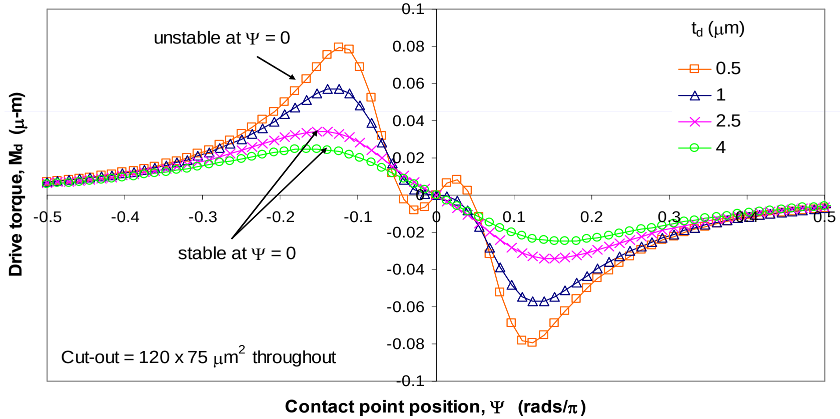

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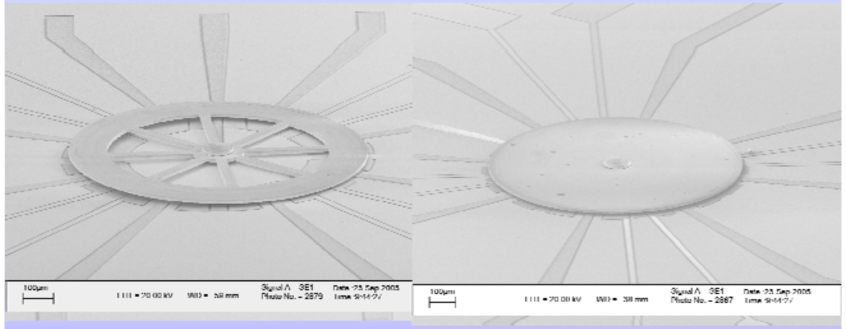
Capped cartwheel and solid disc rotors



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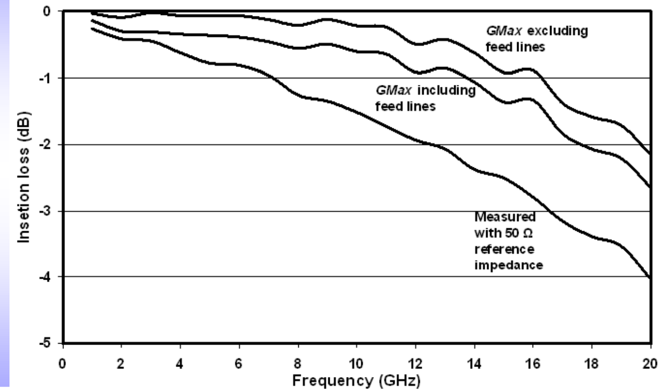
Measure Performance of the SP8T Switch



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Rotating Switch Contacts: 60 V Bias at 30 Hz

3 2

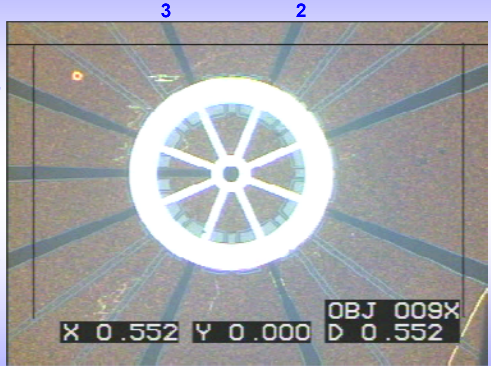
(FOUR) 4

1 (TWO)

Input

(THREE) 5

8 (ONE)



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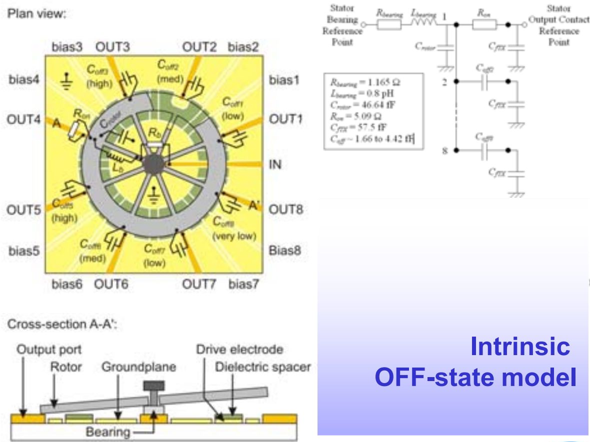
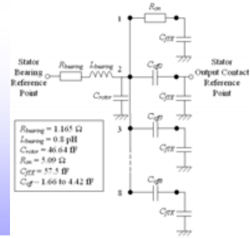


Intrinsic ON-state model

Intrinsic OFF-state model



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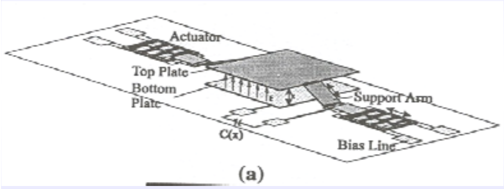
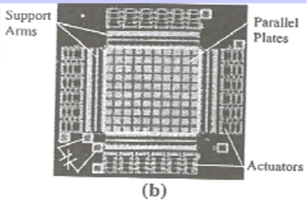
Variable Capacitors

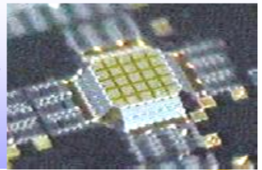
Variable Plate Separation Capacitors

✍ MEMS parallel-plate capacitors with microactuators to vary the plate separation

1 x 1 mm^2 MEMS capacitor, *Chiao et al.*

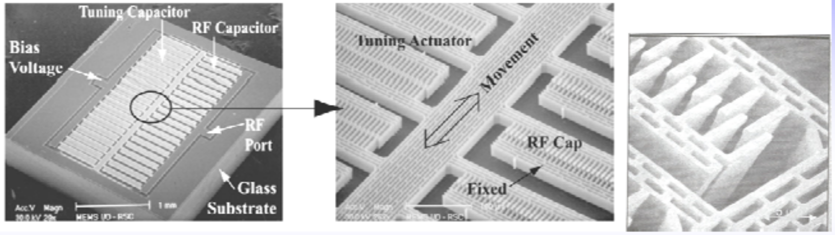






- gap spacing can vary between 1 µm and 100 µm, in 20 nm steps
- capacitance varied between 0.5 pF and 35 pF
- the >200 V breakdown is higher than for varactor diode

Bulk-machined silicon variable capacitor, *DeNatale*

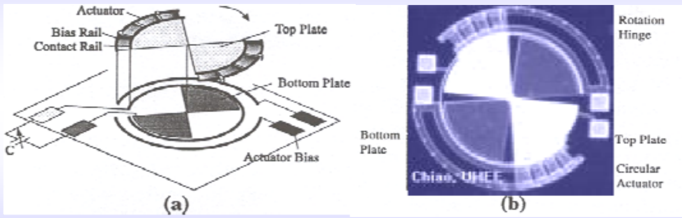


- Rockwell has implemented MEMS tuneable capacitors, using high aspect ratio single-crystal bulk-machined silicon
- high linearity, reduced part count, smaller size and low power consumption
- e.g. Q-factor was 265 at 500 MHz and maximum capacitance was 6 pF; the 5.3 V tuning voltage gave a 4:1 capacitance tuning ratio

Variable Plate Area Capacitors

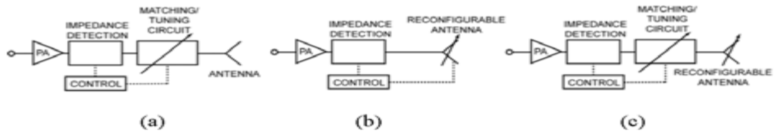
✍ MEMS parallel-plate capacitors with microactuators to vary the overlapping plate area

MEMS capacitor, *Chiao et al.*

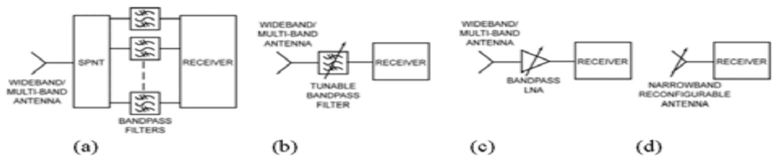


- tuning linearity can be more importance than dynamic range, so circular plates are used
- circular scratch drive actuators are on the edges and move in the opposite direction
- the gap between the plates was 2 µm and a 0.5° increment in angular rotation was achieved

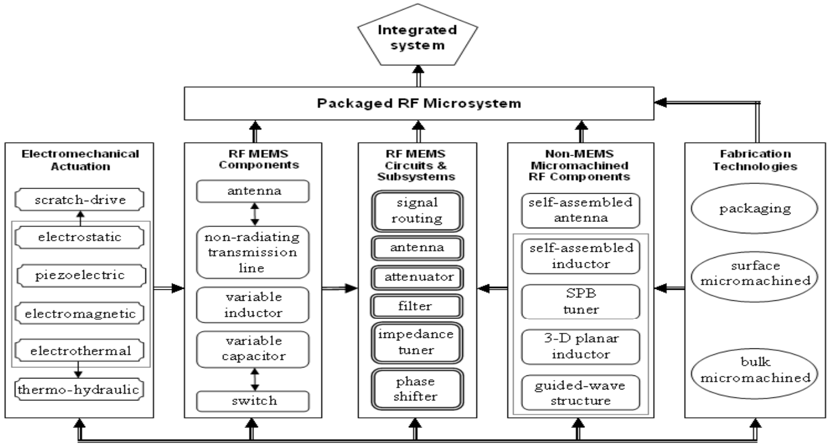
Reconfigurable Systems



Transmitter antenna architectures with impedance/matching detection and control circuits: (a) fixed frequency antenna with impedance matching tuner; (b) reconfigurable antenna; and (c) reconfigurable antenna with impedance matching tuner



Band-selection receiver architectures with filtering realized with: (a) a switched filter bank, employing SPnT switches; (b) a tuneable BPF; (c) a tuneable bandpass LNA; and (d) narrowband reconfigurable antenna selectivity



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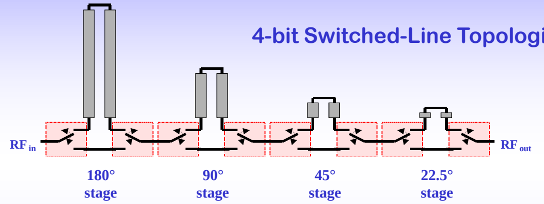
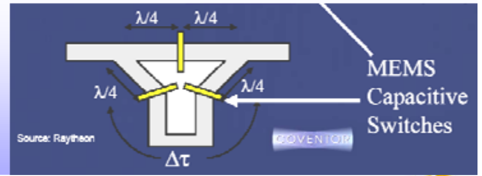
Digital Phase Shifter Topologies

4-bit Switched-Line Topologies



4-stage implementation, requiring 8 SPDT switches



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Phase Shifters

✍ A phase shifter is a **control circuit** found in many microwave communication, radar, sensor and measurement systems

✍ MMIC were developed so that phase shifters could be miniaturised for phased antenna array applications (MiMiC Programme in the US)

✍ In principle, **sub-1 dB worst-case losses** would relax both transmitter power amplifier and receiver low noise amplifier specifications

✍ For phased-array applications, low DC control power and **repeatable batch processing** is important

✍ In order to understand the subtle differences between the two main generic types of phase shifters, both the true phase shifter and the true delay line must be defined

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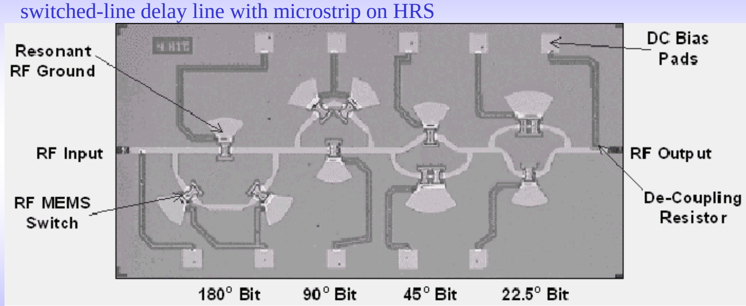
MEMS Digital Phase Shifters

Pillians et al. (**RAYTHEON SYSTEMS CO.**) reported a 4-bit monolithic 32-36 GHz switched-line delay line with microstrip on HRS



• MEMS capacitive membrane switches were used with C_{ON}/C_{OFF} ~ 100 and an actuation voltage of 45 V

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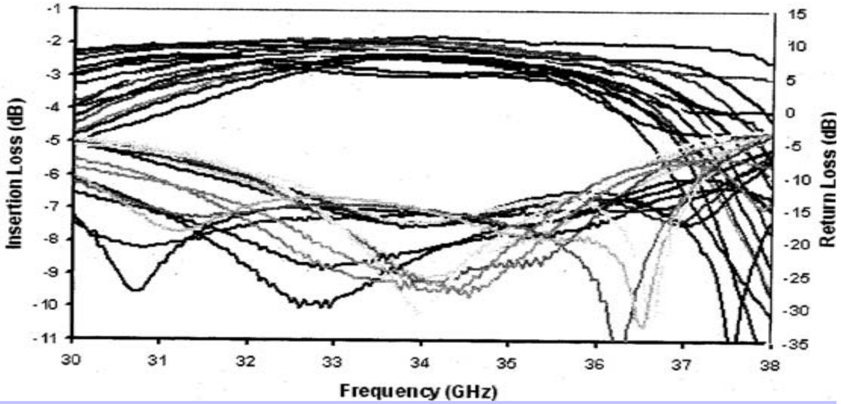

- at 34 GHz, the insertion loss was low at ~ 2.5 dB and the return loss was > 15 dB

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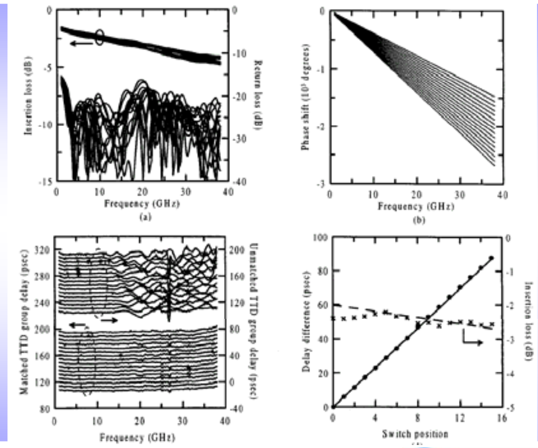

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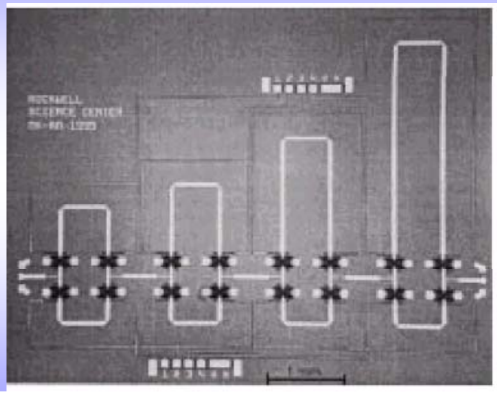
Kim *et al.* reported a DC to 40 GHz 4-bit true time delay network on GaAs



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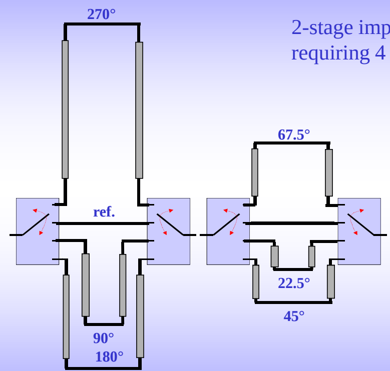
2-stage implementation, requiring 4 SP4T switches



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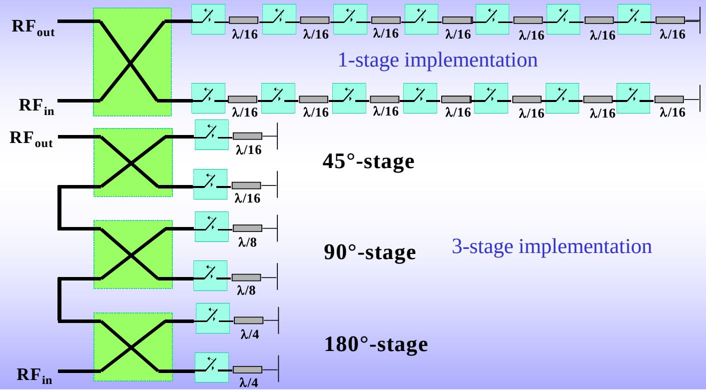
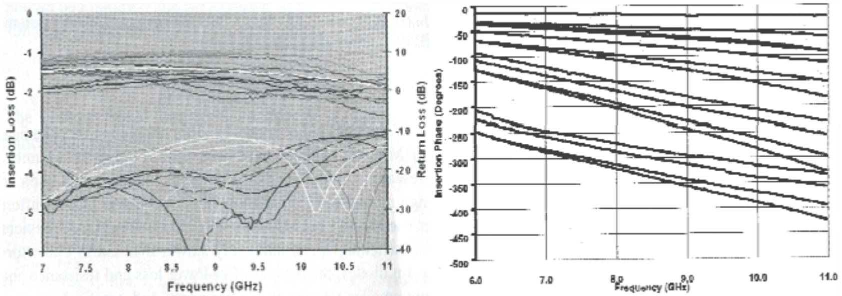
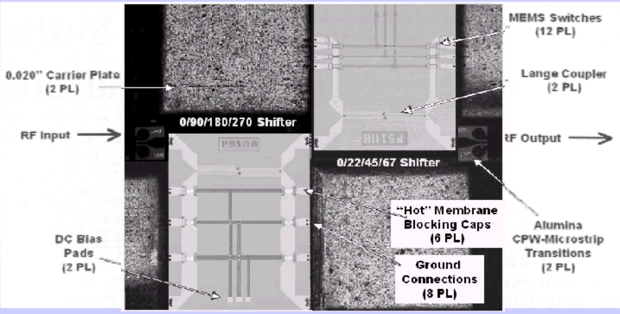
3-bit Distributed Line Reflection Topology





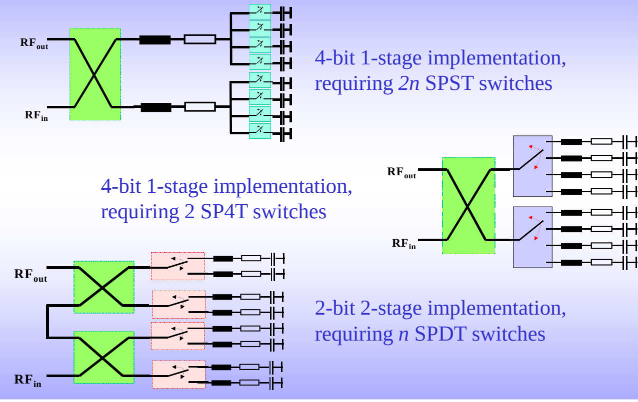
- at X-band, the measured insertion loss was around 1.5 dB, with 60% of this loss being attributed to the Lange couplers

✍*Malczewski et al.* (**RAYTHEON SYSTEMS CO.**) reported a 7-11 GHz 2-stage 2-bit reflection-type delay line (i.e. 4-bit in total), with tapped delay line reflection terminations



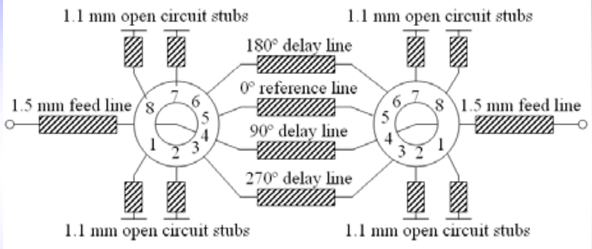
- the same transmission line medium, substrate and MEMS switches were used as with the previous **RAYTHEON SYSTEMS CO.** switched-line example

4-bit Lumped-Element Reflection Topology

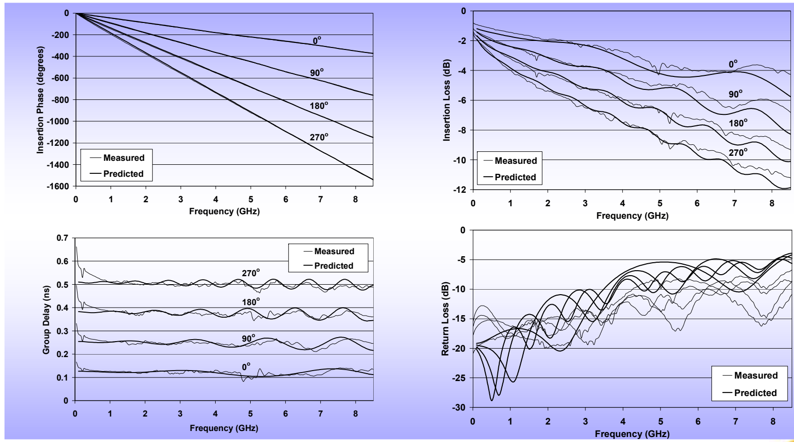


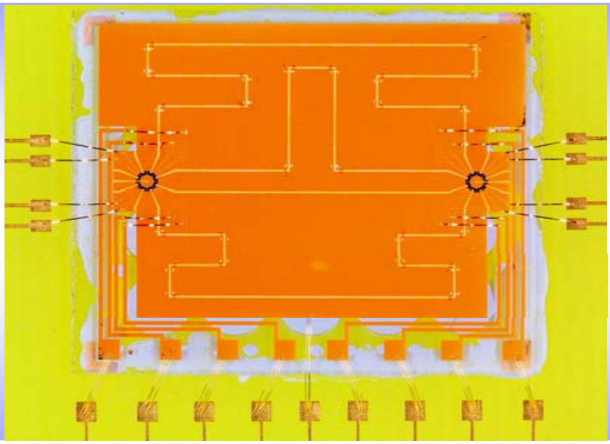
DC-4 GHz 2-Bit Phase Shifter

2-Bit 2 GHz Switched-Line Phase Shifter



TLINP model parameters:	Delay line lengths for 2 GHz design:
$Z_o = 50\ \Omega$	$L_0 = 16.20$ mm
$E_{eff} = 2.3$	$L_{90} = 41.52$ mm
$Loss = 0.09$ dB/mm	$L_{180} = 66.84$ mm
$f_o = 10$ GHz	$L_{270} = 92.16$ mm

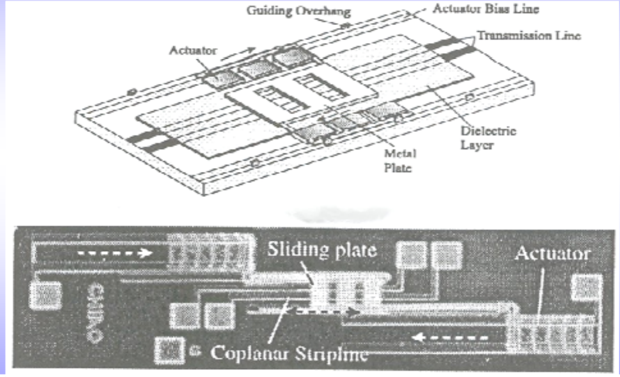




Impedance Tuners

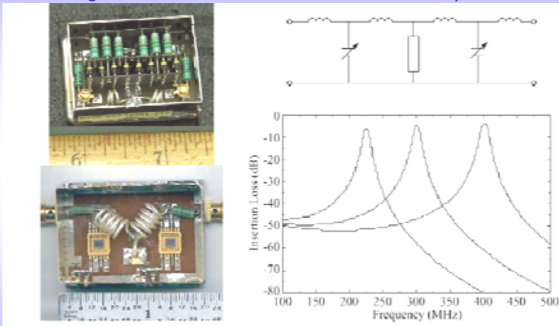
- A sliding planar back-short plate on top of the planar transmission line forms a variable position short circuit
  - in 1996, *Lubecke et al*. demonstrated a CPW MEMS tuner (under mechanical actuation) in a monolithic integrated circuit at 620 GHz
  - *Chiao et al*. reported a similar planar impedance tuner in coplanar strip technology (under electrostatic actuation)

Sliding back-short impedance tuner, *Chiao et al.*



Radio Frequency Engineering
Lecture #3 RF MEMS

Rockwell 2-pole 240-360 MHz Tuneable Filter,
using the bulk-machined silicon variable capacitor



- Dramatic (90%) parts count reduction validated for MEMS circuit
- Higher loss at low frequency due to reduced capacitor Q

Rockwell Scientific

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Filters

- Lumped-element is most common
- Distributed-element, with capacitive membrane switches
- Distributed-element

- Low intermodulation distortion products
- Cheaper than the better YIG tuneable-filters
- While planar RF MEMS filters have demonstrated a Q > 40,
  Wireless communications (e.g. GSM/CDMA) require Q > 250

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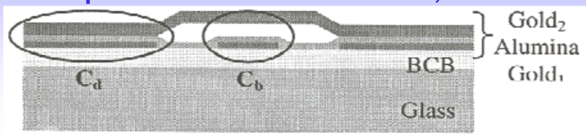
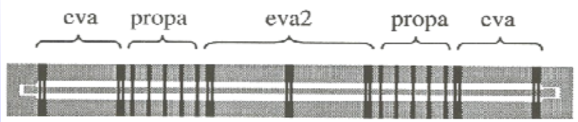
Distributed MEMS tuneable filter,
with capacitive membrane switches, *Mercier et al*.



CPW line (W=G=100 µm, ground conductor=300 µm) loaded by a micro-electromechanical bridge.



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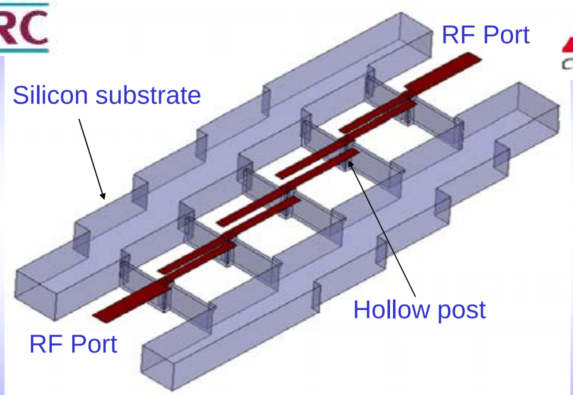
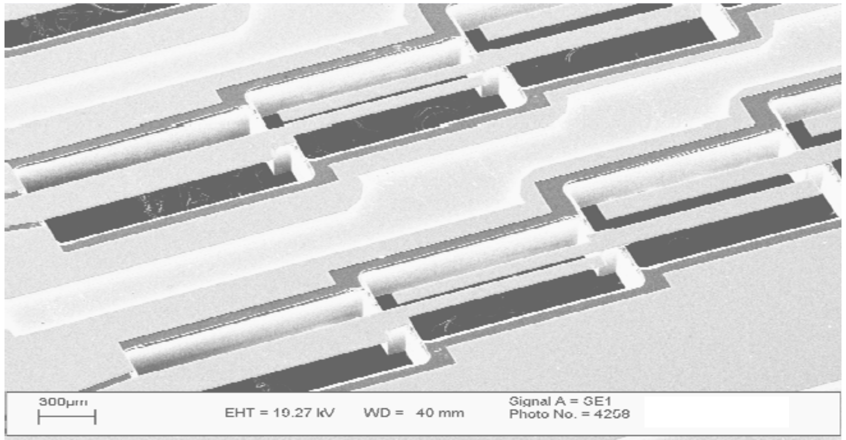
60/76.5 GHz MAMS Line Filters

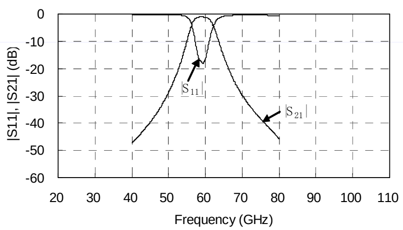
EPSRC

MITSUBISHI ELECTRIC *Changes for the Better*

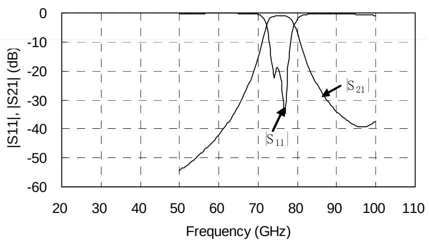


(Another silicon substrate with upper ground plane is not shown)

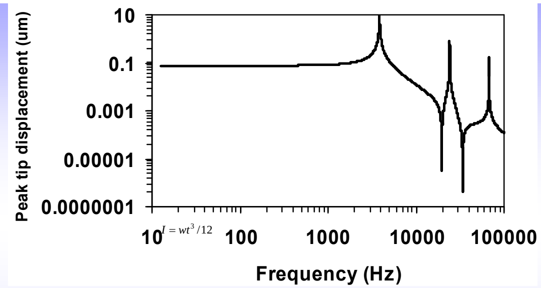




Predicted performance for the 60 GHz filter (without feed structures)



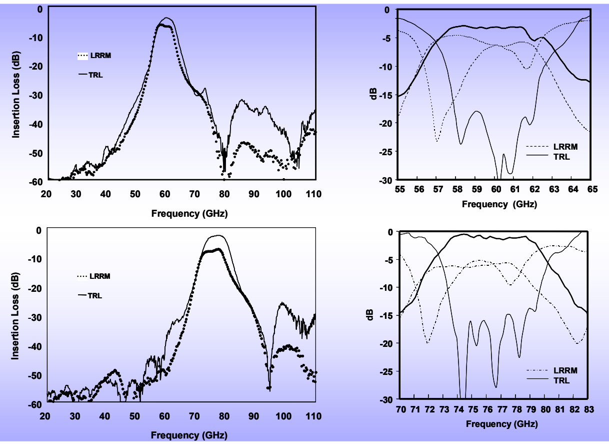
Predicted performance for the 76.5 GHz filter (without feed structures)



It can be show, that the angular resonant frequencies for a clamp:free beam is given by the following expression:

$$\omega_i = \beta_i \sqrt{\frac{EI}{\rho A}} \qquad I = wt^3/12$$

- *ρ is the density of the beam material*
- *E is Young's modulus for the beam material*
- *A is the cross-sectional area of the beam*
- *I is the second moment of area*
- *w is the width of the beam*
- *t is the thickness of the beam*
- *β1 is the phase constant of the lowest-order resonant mode*



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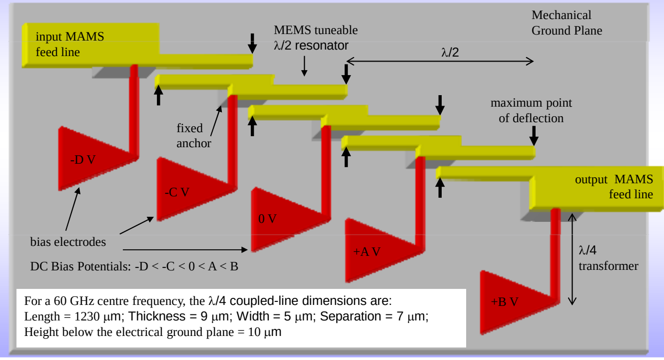
Novel MEMS coupled-line filter concept (electrical ground plane has been removed)



For a 60 GHz centre frequency, the $\lambda/4$ coupled-line dimensions are:
Length = 1230 μm; Thickness = 9 μm; Width = 5 μm; Separation = 7 μm;
Height below the electrical ground plane = 10 μm

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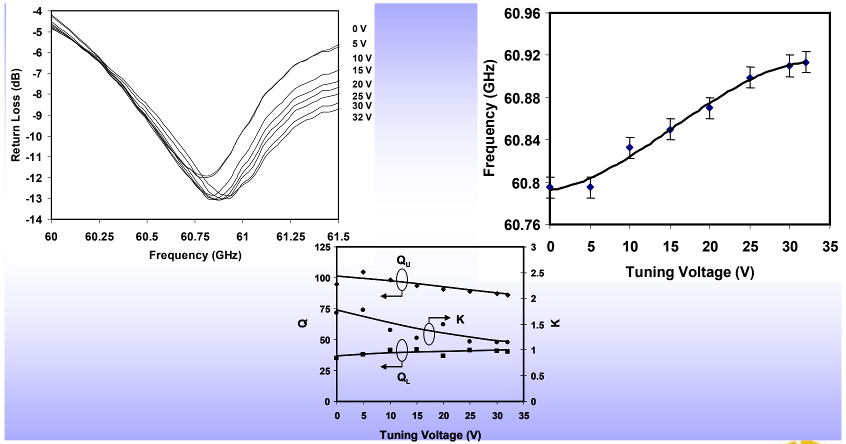

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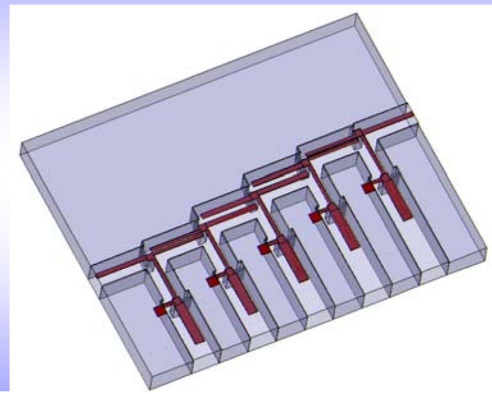
Isometric View of a Tunable 62.5-64.0 GHz MEMS Filter



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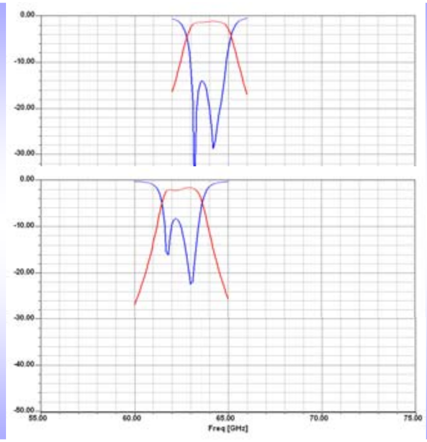
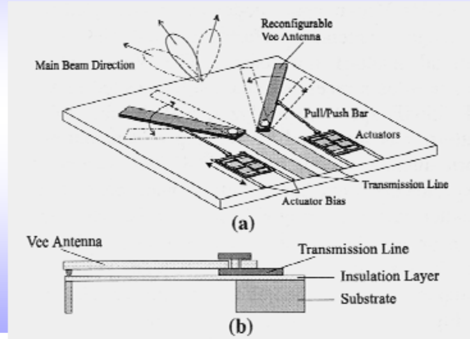


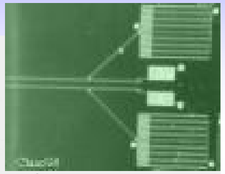
20 μm height MAMS line with no deflection

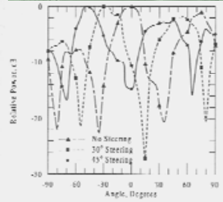
3 μm deflection with ~150 V bias on all cantilevers

MEMS V-Antenna, Chiao *et al.*

- The 17.5 GHz antenna uses a 3-layer polysilicon surface micromachining process
- The directivity for the antenna was estimated to be about 38







Antennas

- A planar MEMS reconfigurable V-antenna has its far-field radiation pattern altered under electrostatic-control
- The 17.5 GHz antenna uses a 3-layer polysilicon surface micromachining process
- Each antenna arm is capable of independent movement, for beam-steering and beam-shaping
- Lateral movement of the microactuators (20 nm per 70 V to 120 V biasing pulse) is translated to rotational movement of the arms
- The directivity for the antenna was estimated to be about 38

60 GHz 2D Beam Steering using Magnetically Actuated Polymer-Based Hinges, *Baek et al.*

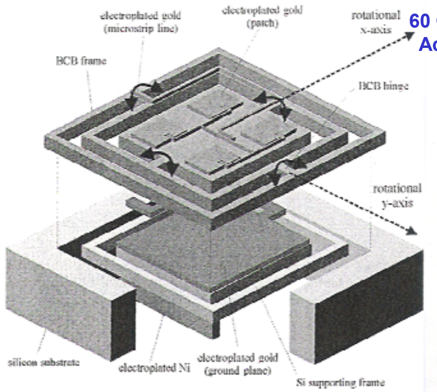


Fig. 2. Schematic view of the 2-D beam-steering antenna.

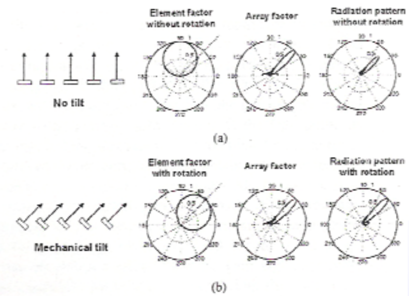
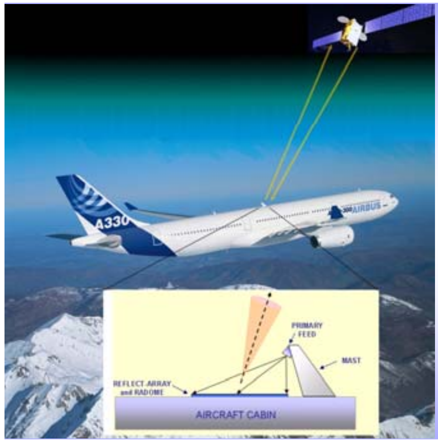


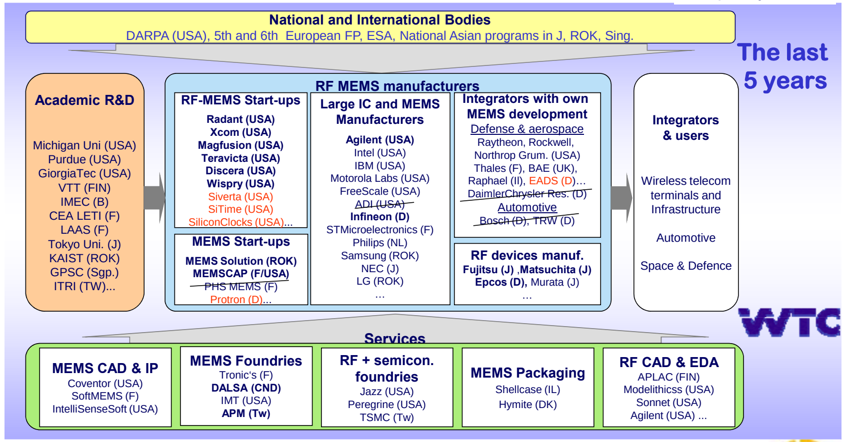
Fig. 1. Simulation results of the element factor, array factor, and radiatic pattern when: (a) the antenna elements are fixed and (b) when the antenn elements are mechanically rotated to 45°.



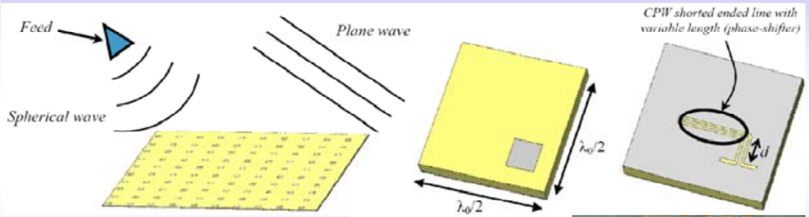
Flying Office concept using a reflectarray antenna, as proposed in the RETINA project (EADS)

Commercialization

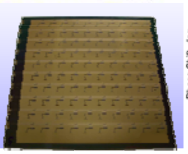
~~ ~~: stopped RF MEMS
Red: New
Bold: prod by end 2005

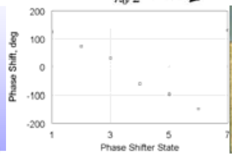


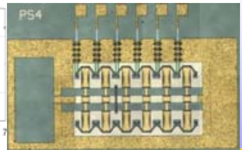
Reconfigurable RF MEMS Reflectarray Antennas
Roberto Sorrentino, *EuCAP 2007*



10 x 10 reflectarray for 26 GHz Satellite Comms





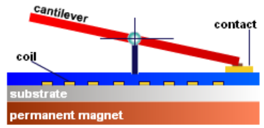


Magfusion

Core Technology - World's First Magnetic Latching (Maglatch™) Switch

Basic Structure

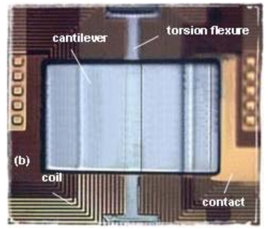
The basic MagLatch™ switch consists of a cantilever, an embedded planar coil, a permanent magnet, and the necessary electrical contacts.



Cross-sectional View

Operation Principle

- Short current pulse through switch coil temporarily aligning magnetization of cantilever to left or right
- Static external magnet field instantly latches switch in open / close position
- Switch maintains state until next switching signal realigns cantilever magnetization
- Relay requires / consumes no power to maintain open / closed position as a result of patent pending latch technology



MagLatch™ Photograph

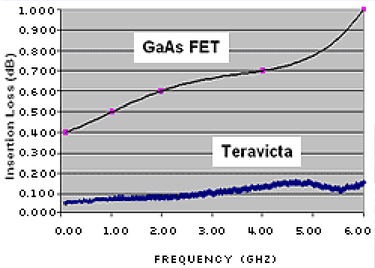
***Magfusion** went bust late in 2005, just after its foundry partner PHS MEMS*

TERAVICTA

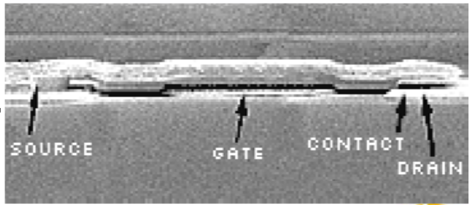
TeraVicta (US, start-up)

- Sampling since 2003.
- Ramping up production with Chinese partner
- Primary high end commercial markets such as ATE

***TeraVicta** closed its business and manufacturing operations, with effect from mid-February 2008*



Packaged part insertion loss comparison
Teravicta RF MEMS switch vs. GaAS FET



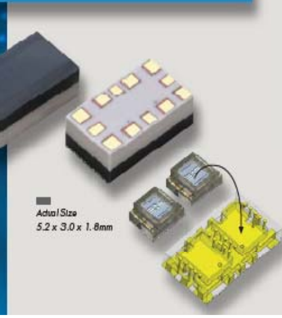
Radio Frequency Engineering
Lecture #3 RF MEMS

OMRON

RF MEMS Switch

Mechanical RF Switching Relay Based on MEMS Technology

Combining its long history of innovative relay products with its MEMS (Micro Electro Mechanical System) expertise, Omron has developed a new RF MEMS Switch to meet the requirements of the ATE market. Using an electrostatic drive mechanism, the switch combines the desirable HF characteristics of electromechanical relays with a life expectancy generally only found in solid state relays. Omron utilizes both 5" and 8" MEMS wafer production lines in its own foundry facilities.



Part Number: 2SMES-01

Load	Resistive Load
Rated Load	0.5mA at 0.5VDC
Rated Carry Current	DC: 100mA RF: 30dBm
Max. Switching Voltage	0.5VDC
Max. Switching Current	0.5mA DC
Max. Switching Capacity	0.25mW

Item	2GHz	8GHz	12GHz
Isolation	–	30dB	–
Insertion Loss	–	1dB	3dB
Return Loss	–	10dB	–
Max. Peak Power	36dBm	–	–
Max. Carry Power	30dBm	–	–

Notes:
1. The impedance of the measurement system is 50Ω.
2. The above values are initial values.
3. The values are for a load with VSWR of ≤1.2.

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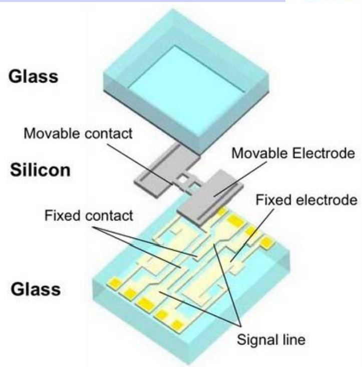
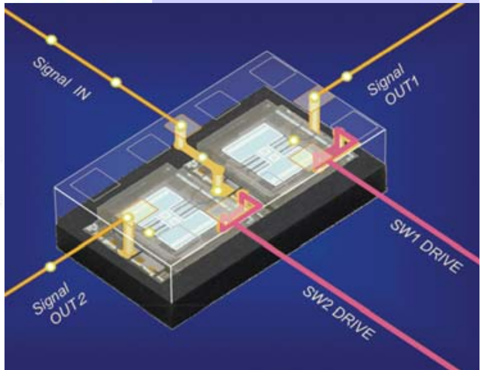
OMRON





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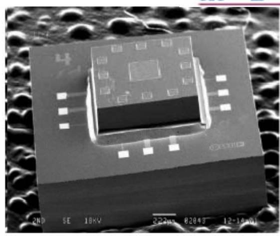
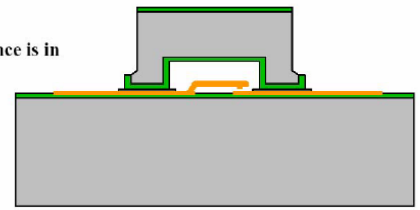
Lecture #3 RF MEMS

Ohmic Contact Switches

RADANT MEMS

- Wafer-to-Wafer Bonding via a Glass Frit Process is Employed to Cap the Individual Switch Die
  - Provides Hermetic Environment
  - Low-Cost Packaging Solution
  - Optimization is in Process
- RMI has Produced Fully Functional Devices with Promising RF Results
  - High-Lifetime: $>10^{11}$ Cycles
  - Optimization of RF Performance is in Process





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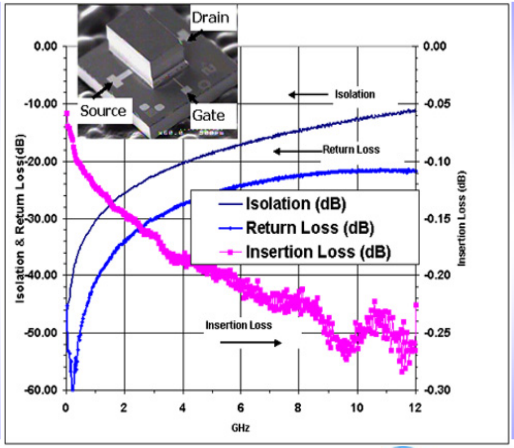

Radio Frequency Engineering
Lecture #3 RF MEMS

Typical specifications for commercially available Radant MEMS switches
(C and H refer to the "cold-switching" and "hot-switching" modes of operation, respectively)

Functionality	Model Number	Frequency Range [GHz]	ON-state Insertion Loss [dB]	OFF-state Isolation [dB]	Switching Life Cycles	Maximum Dimensions [mm³]
SPDT	RMSW221™ **(high isolation)**	dc to 20	< 0.8 at 18 GHz	**> 25 at 18 GHz**	10^{11} at +27 dBm (C) 10^3 at +33 dBm (C) +20 dBm (H)	1.96 x 1.66 x 0.60
	RMSW220HP™ **(high power)**	dc to 40	< 0.8 at 35 GHz	> 12 at 35 GHz	**10^{10} at +36 dBm (C) 10^3 at +42 dBm (C)** +20 dBm (H)	1.45 x 1.40 x 0.65
SP4T	RMSW240™	dc to 20	< 0.7 at 18 GHz	> 25 at 18 GHz	10^{11} at +27 dBm (C) 10^3 at +33 dBm (C) +20 dBm (H)	1.96 x 1.96 x 0.60
SP6T	RMSW260™	dc to 20	< 0.8 at 18 GHz	> 22 at 18 GHz	10^{11} at +27 dBm (C) 10^3 at +33 dBm (C) +20 dBm (H)	1.96 x 1.96 x 0.60

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Typical specifications for commercially available Radant MEMS switches
(C and H refer to the "cold-switching" and "hot-switching" modes of operation, respectively)

Functionality	Model Number	Frequency Range [GHz]	ON-state Insertion Loss [dB]	OFF-state Isolation [dB]	Switching Life Cycles	Maximum Dimensions [mm³]
SPST	RMSW101™	dc to 12	< 0.32 at 10 GHz	> 12 at 10 GHz	10^{11} at +30 dBm (C) 10^3 at +36 dBm (C) +20 dBm (H)	1.90 x 1.85 x 0.60
	RMSW100™ **(low loss)**	dc to 12	**< 0.28 at 10 GHz**	> 11 at 10 GHz	10^{11} at +30 dBm (C) 10^3 at +36 dBm (C) +20 dBm (H)	1.42 x 1.37 x 0.65
	RMSW201™ **(high isolation)**	dc to 20	< 0.6 at 18 GHz	**> 18 at 18 GHz**	10^{11} at +27 dBm (C) 10^3 at +33 dBm (C) +20 dBm (H)	1.90 x 1.85 x 0.60
	RMSW200™ **(broadband)**	**dc to 40**	< 0.5 at 38 GHz	> 12 at 38 GHz	10^{11} at +27 dBm (C) 10^3 at +33 dBm (C) +20 dBm (H)	1.42 x 1.37 x 0.65
	RMSW200HP™ **(high power)**	dc to 40	< 0.5 at 38 GHz	> 12 at 38 GHz	**10^{10} at +36 dBm (C) 10^3 at +42 dBm (C)** +20 dBm (H)	1.42 x 1.37 x 0.65

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Lecture #3 RF MEMS

Preliminary

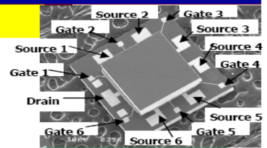
RADANT MEMS

SP6T RF-MEMS Switch
DC to 20 GHz

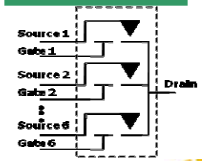
RMSW260™

Features

- High Isolation (>22 dB typical @ 18 GHz)
- Low Insertion Loss (<0.5 dB @ 10 GHz, <0.8 dB @ 18 GHz)
- Near Zero Harmonic Distortion
- No Quiescent Power Dissipation
- Long Life (typical lifetime >100 billion cycles @ 27 dBm, >1 billion cycles @ 30 dBm)
- Hermetically sealed die designed for die-attach and wire-bond to board. Please contact us for other packaging options.



RMSW260™



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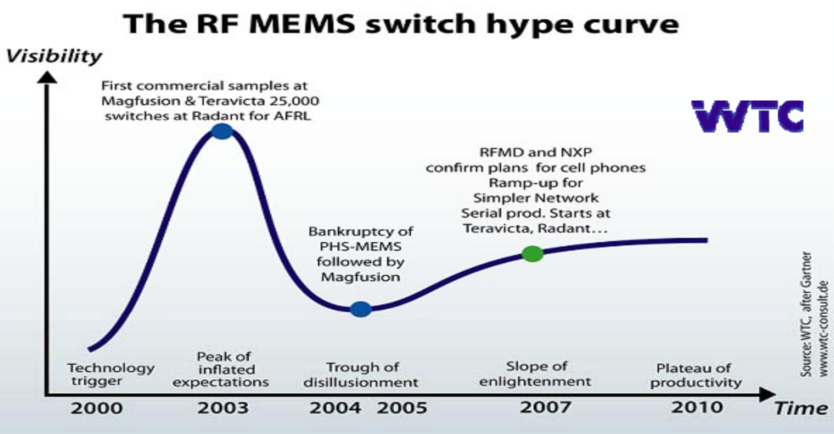
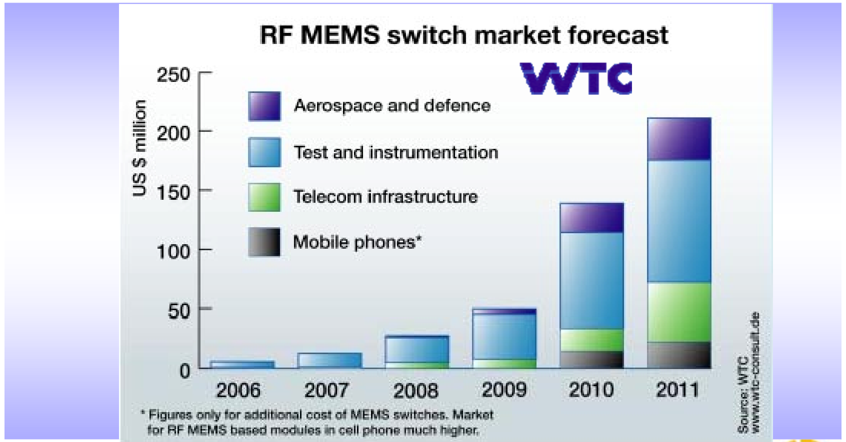


Radio Frequency Engineering
Lecture #3 RF MEMS



Radio Frequency Engineering
Lecture #3 RF MEMS

Existing RF MEMS switch companies: Radant, Advantest, Matsushita and Omron

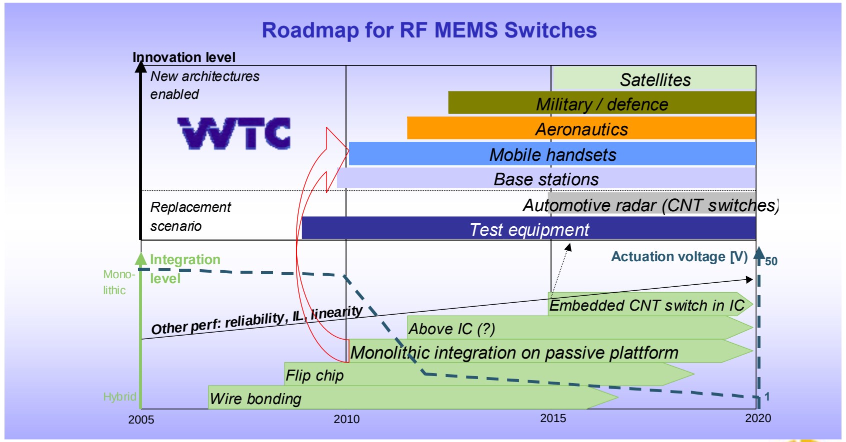
Companies sampling switches for selected customers include WiSpry for mobile handsets and MEMTronics and XCOM for high-end applications like defence.

$5 million worth of RF MEMS switches were sold in 2006, but is expected to surge to $210 million by 2011. Nearly half of that total will go into test and instrumentation applications.

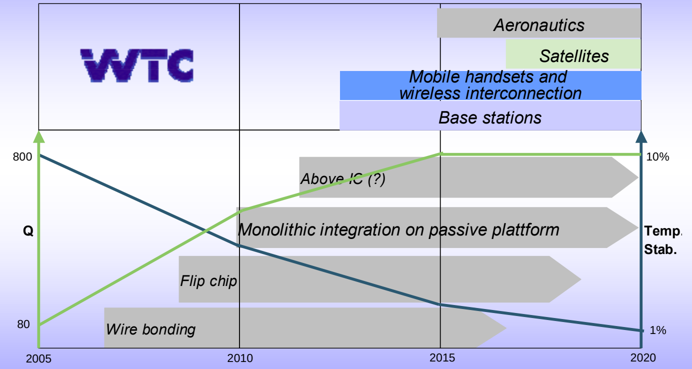
At the module level, reconfigurable power amplifiers and antenna modules for cell phones should exceed $150 million in 2011.

WTC

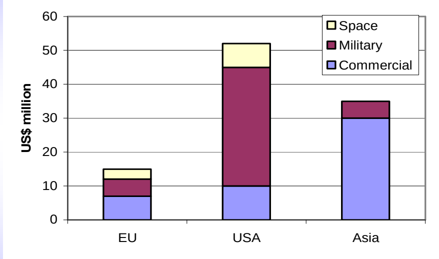
Radio Frequency Engineering
Lecture #3 RF MEMS



Roadmap for RF MEMS Tuneable Capacitors



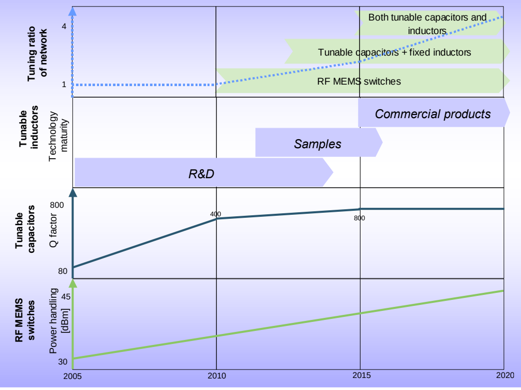
Comparison of RF MEMS funding in Europe, USA and Asia



- Increasing of RF MEMS funding since 2000
- More funding in the USA
  - **Military driven**
  - Commercial and space applications are followers and benefit from military investments
  - Europe and Asia have been slow to follow
  - **Now priority is given to packaging and reliability**

Estimated RF MEMS funding back in 2004

Roadmap for Switches, Tuneable Capacitors & Inductors



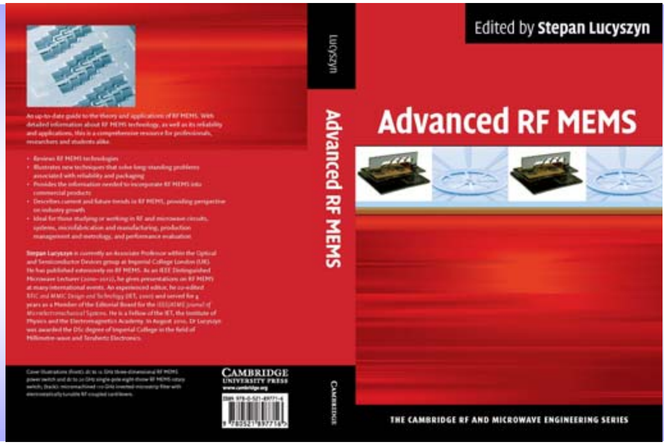
Conclusions

✍ RF MEMS Technology is still far behind conventional MEMS within commercial markets

✍ The first commercially available devices are switches. Even with the failings of Magfusion and TeraVicta, companies like Radant MEMS, Matsushita, Omron, Advantest are in a better position to successfully commercialise RF MEMS in test and instrumentation applications.

✍ Within the US, RF MEMS phase shifters are already being employed within military systems and instrumentation, but reconfigurable matching networks in PAs and LNAs will soon be found in mobile phone applications.

✍ A great deal of R&D is being pursued within Europe, BUT Japan and China will be the challenger to the US for commercialization in the future.



MEMS for Micro Optics and Radio Frequency Applications — Ee302

TOSHIYOSHI LAB.

[Optical MEMS & RF-MEMS]

Centre for International Research on MicroNano Mechatronics

http://toshi.iis.u-tokyo.ac.jp

Micromachine System Engineering (IIS), Micro Device Engineering (RCAST)

Dept. Electrical Engineering and Information Systems (EEIS), School of Engineering

Also with Dept. Department of Advanced Interdisciplinary Studies (AIS), School of Engineering

S. Lucyszyn (Editor), "Advanced RF MEMS", *Cambridge University Press*, Oct. 2010

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FrontPage

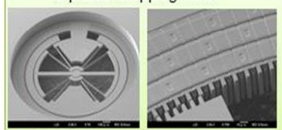
WELCOME TO FUJITA LABORATORY

Our research activity on Micro Electro Mechanical Systems (MEMS).

Novel MEMS technology

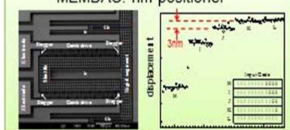
High performance microactuations for alternative electronic devices

3-phase stepping motor



Rotate +/- 15 degree in steps of 1/6 degree

MEMDAC: nm positioner



Generate nm-level displacement according to 12-bit digital input