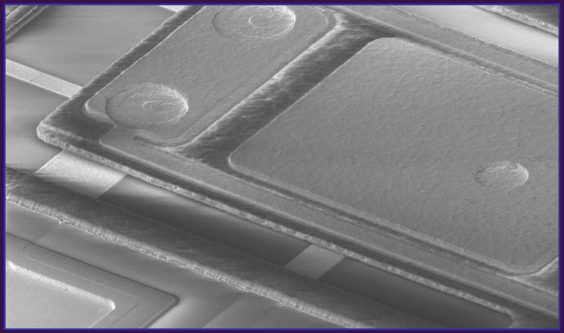
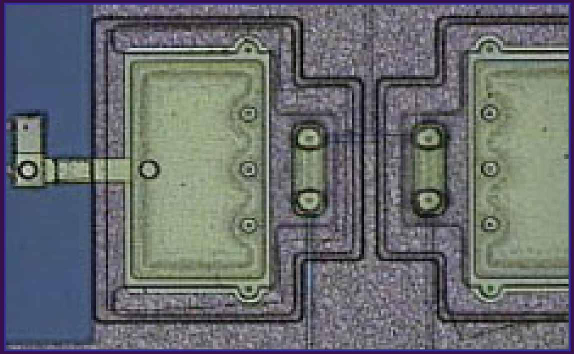
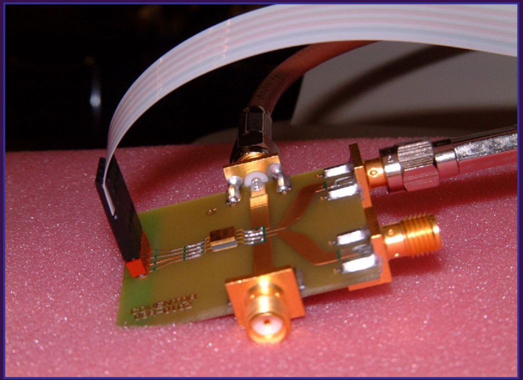
Commercial RF-MEMS: Product Opportunities and Challenges



Arthur S. Morris, III
CTO, VP Eng.





wiSpry

Introduction

- Who is wiSpry?
  - Spun out from Coventor at end of 2002
  - Developing RF-MEMS for services customers since 1999
  - High performance low-cost RF components
  - Broad customer evaluations underway

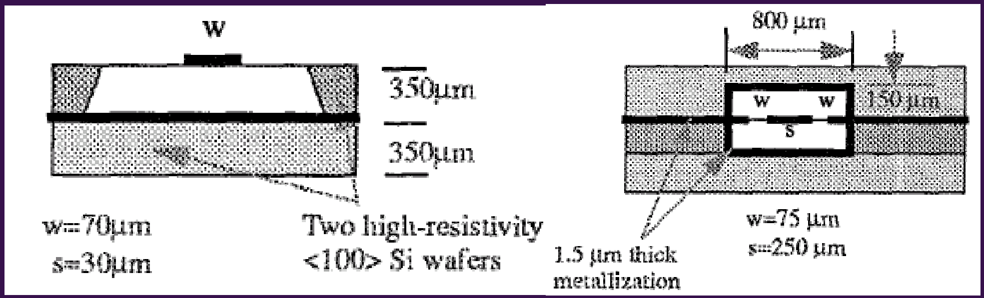
- Agenda
  - MEMS Technology Update
  - Promising Application Opportunities
  - Key Challenges and Solutions
  - Summary

Micromachining

Transmission Lines

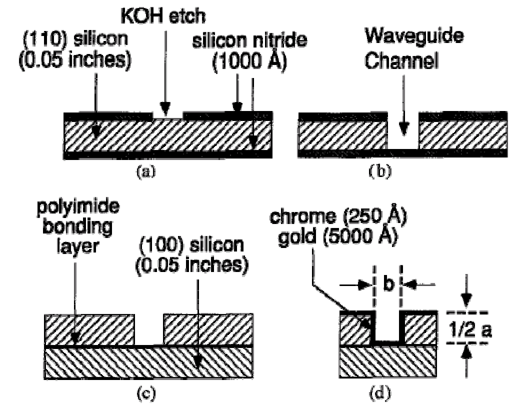
Maintain 50Ω at small dimensions
With losses < 1dB/cm at 10 GHz

Membrane Supported Lines



U Michigan

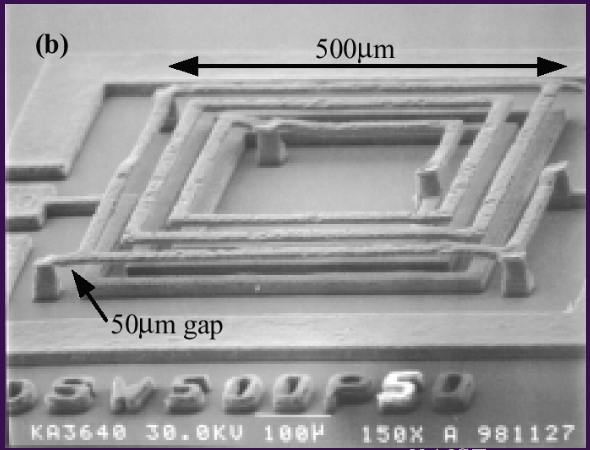
Micromachined Waveguides



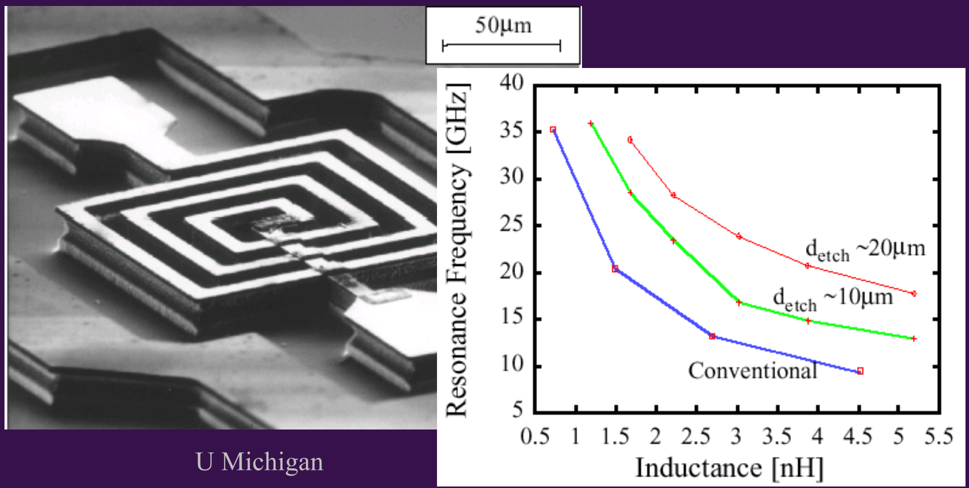
JPL, CIT, IEEE

Inductors

L > 14 nH
Q up to 100 at 2 GHz



KAIST



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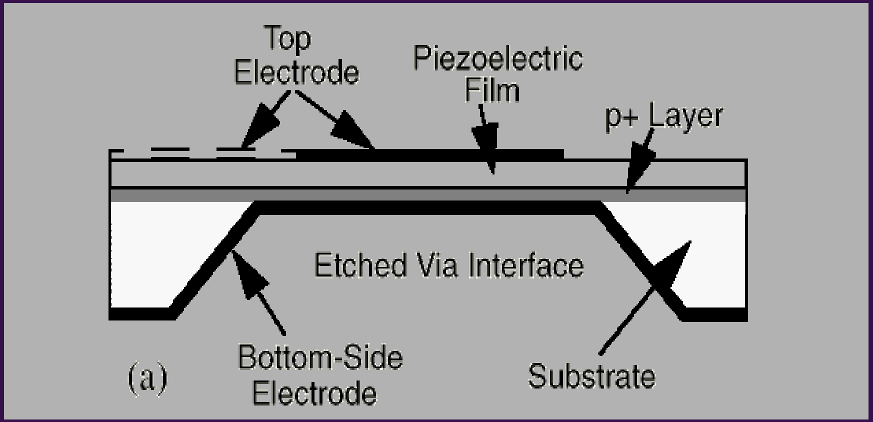
Micromechanical Resonators & Filters

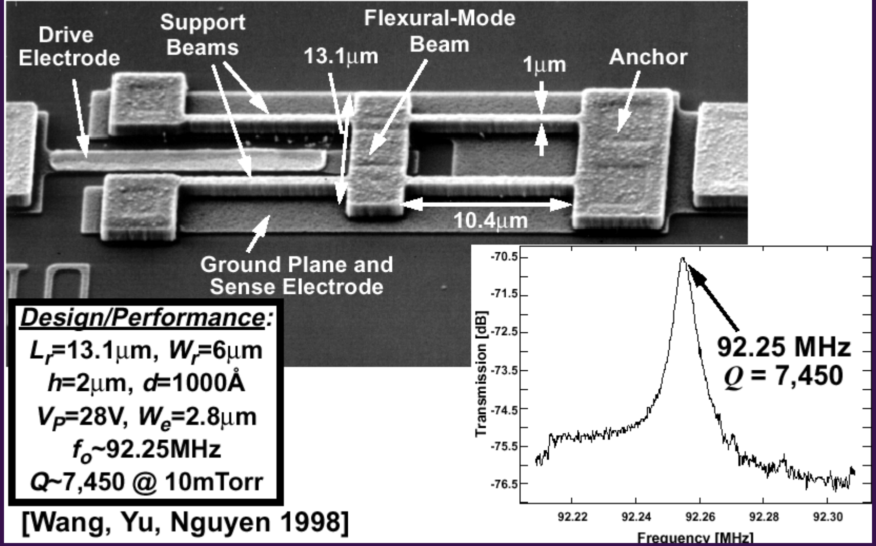
Thin-film Bulk



RF up to 7.5 GHz
Q > 1000

Agilent shipping FBAR-based SAW-replacement filters.

Flexural Mode



[Wang, Yu, Nguyen 1998]

IF above 90 MHz & Q > 7000

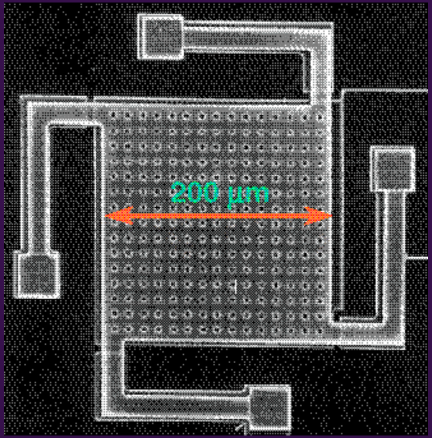
Future >300 MHz & Q > 10000

Discera sampling oscillators stabilized with these resonators.

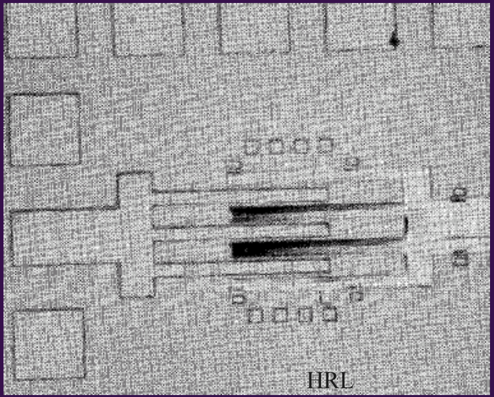
MEMS Varactors and Switches

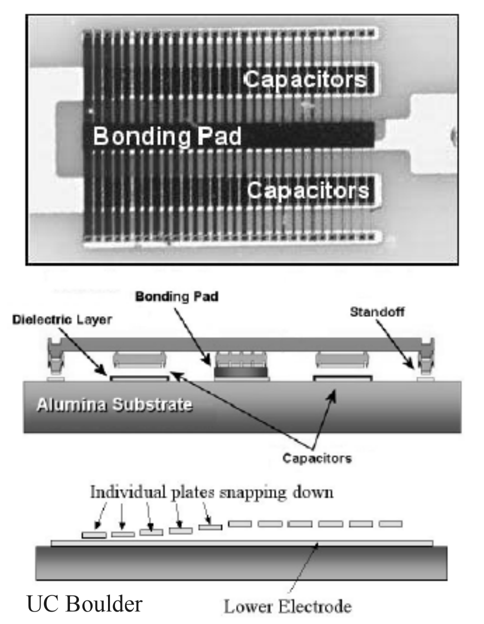
Capacitance > 8 pF
Ratios > 10:1
Q up to 200 at 2 GHz

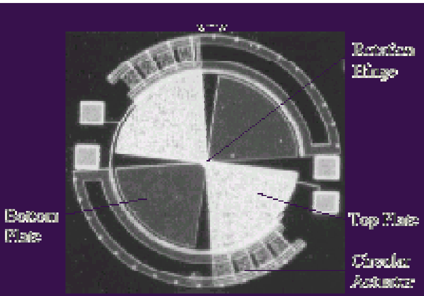
Low Loss < 0.1dB
High Isolation > 50 dB
Ultra-linear



BSAC and LLNL

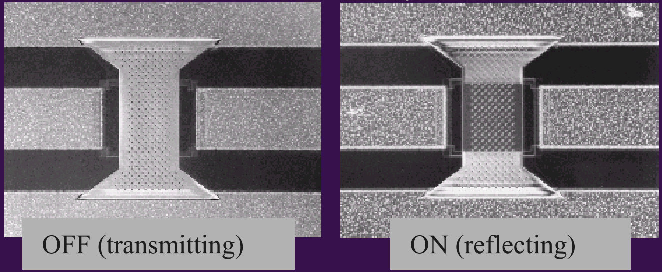


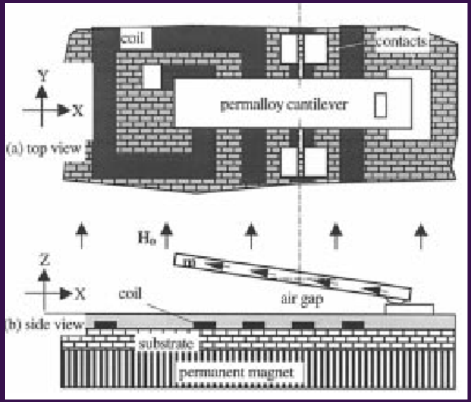




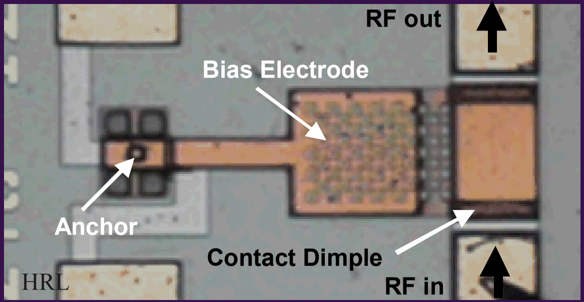
University of Hawaii

Raytheon





Magfusion



RF-MEMS Switches

High Isolation

- *Physical gap*

Low Insertion Loss

- *All metal pathway*

Low Power

- *Electrostatic Actuation (typ.)*

Ultra-linear

- *Metal-Metal contacts*

Property	**MESFET**		**PIN Diode**		**PHEMT**		**MEMS**
Series Resistance	3 Ω	5 Ω	1 Ω	3 Ω	1 Ω	3 Ω	<1 Ω
Loss at 1 GHz	0.5 dB	1.0 dB	0.5 dB	0.8 dB	0.3 dB	0.8 dB	0.1 dB
Isolation at 1 GHz	15 dB	30dB	30 dB	50 dB	20 dB	35dB	>50 dB
IP3	40-60 dBm		30-60 dBm		40-60 dBm		>70 dBm
1 dB comp.	20-35 dBm		25-40 dBm		20-40 dBm		>37 dBm[1]
Size	1-5 mm^2		2-4 mm^2		1-4 mm^2		<0.1 mm^2
Switching Speed	~ns		~ms		~ns		1-100μs
Control Voltage	8 V		3-5V		2.3 to 5 V		2-100V
Control Current	< 10 μA		1 mA		< 30 μA		<<1 μA

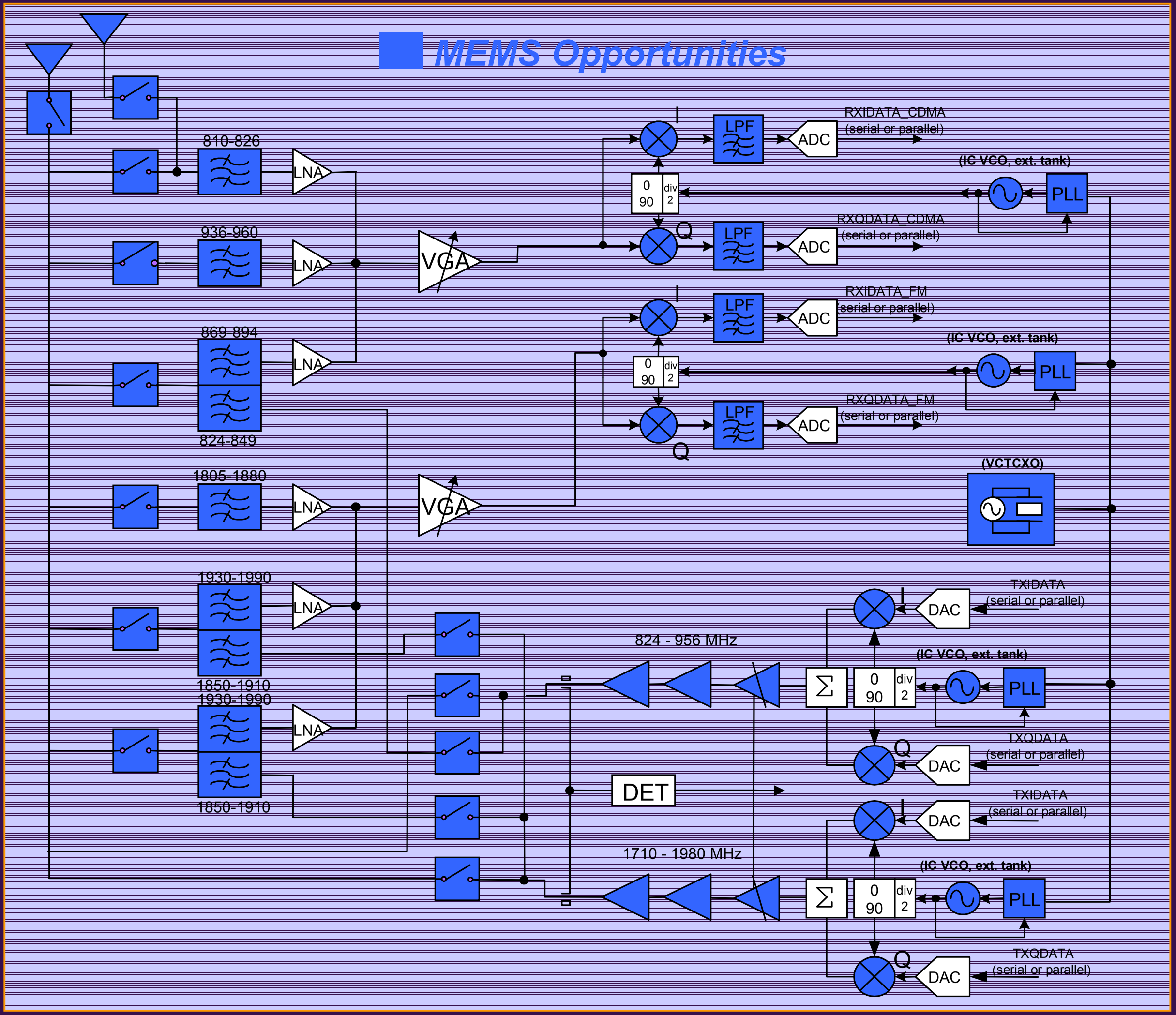
MEMS Provide Low Loss, High Isolation, High Linearity and Small Size Simultaneously!

[1] No compression observed

NB: Typical values

Opportunities Abound in RF Front Ends

- Reconfigurable Filters
- Tracking Filters
- Low-loss Filters
- Filter bank switching
- T/R switching
- Amp stage bypass
- Amp dynamic matching
- Amp band switching
- Antenna tuning
- Antenna reconfiguration
- Antenna phase shifters
- Tunable oscillators
- Mixers



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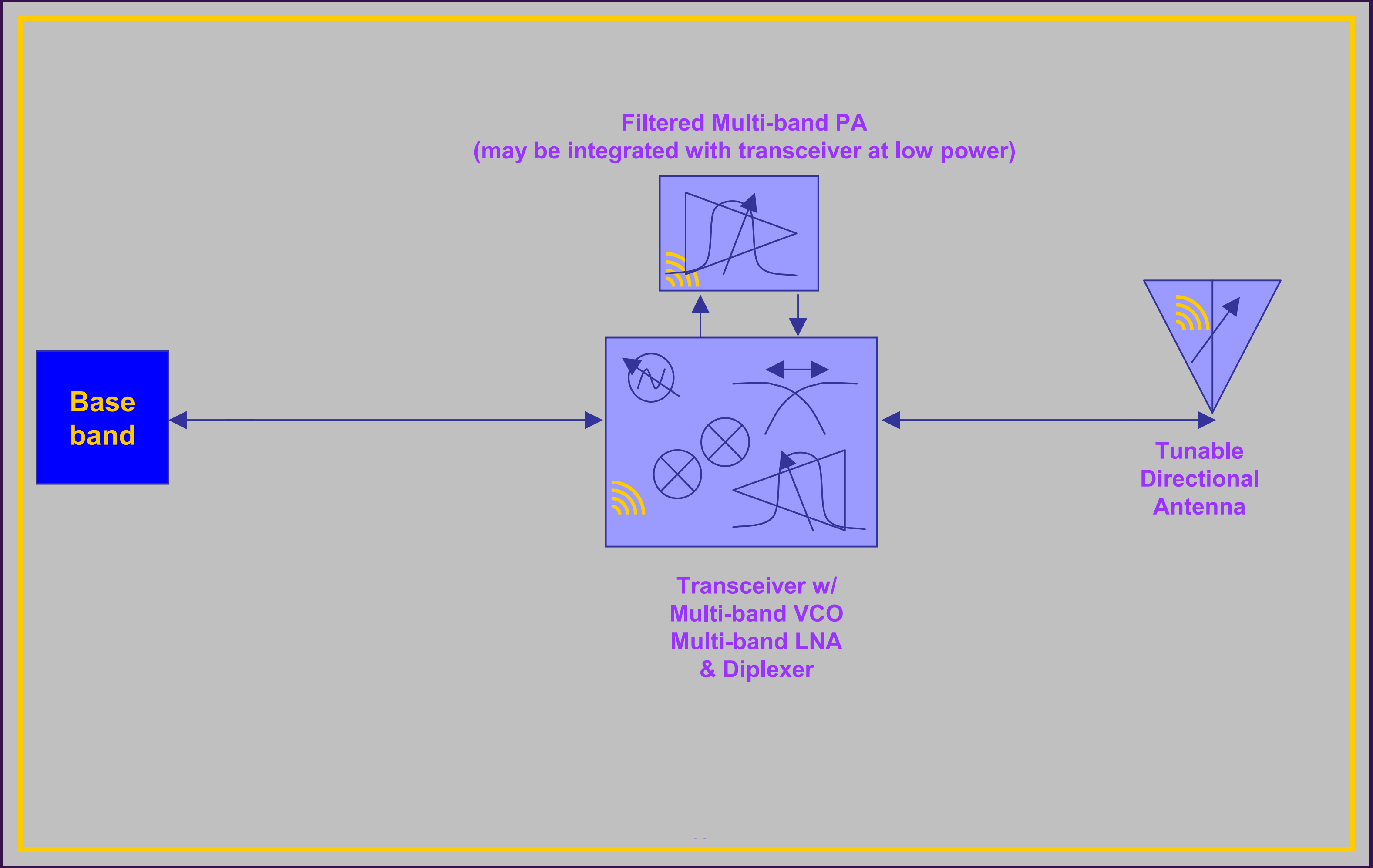
Toward Re-configurable RF Front-Ends

Optimal Integration of RF Architectures



Filtered Multi-band PA
(may be integrated with transceiver at low power)

Base band

Transceiver w/
Multi-band VCO
Multi-band LNA
& Diplexer

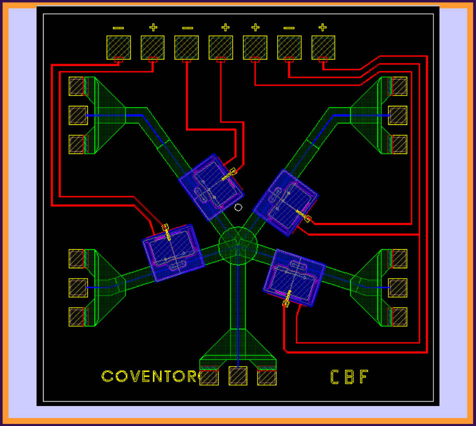
Tunable
Directional
Antenna

wiSpry Benefits

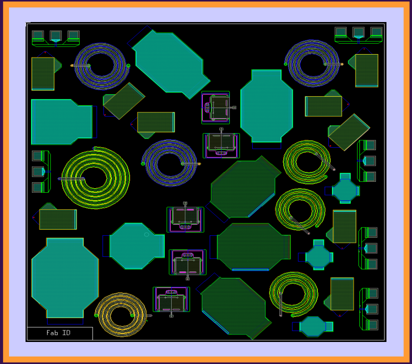
- Lower Overall Cost (Savings of 50-75% Possible)
- Smaller Footprint
- Improved RF Performance
- Faster Time to Market

*wi*Spry's Initial Focus

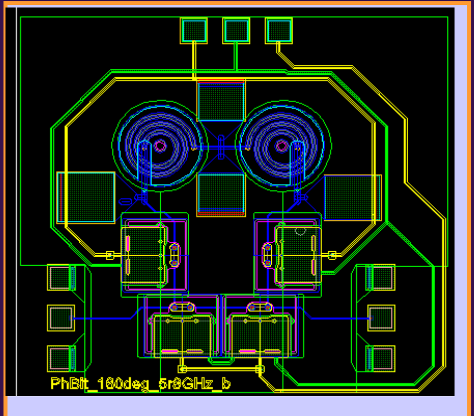
- Switches
  - Band/Mode/Path/Chain Selection
    - Beyond SP6T in < 2 mm^2
  - 2-bit transfer
  - Matrices
  - High-current options



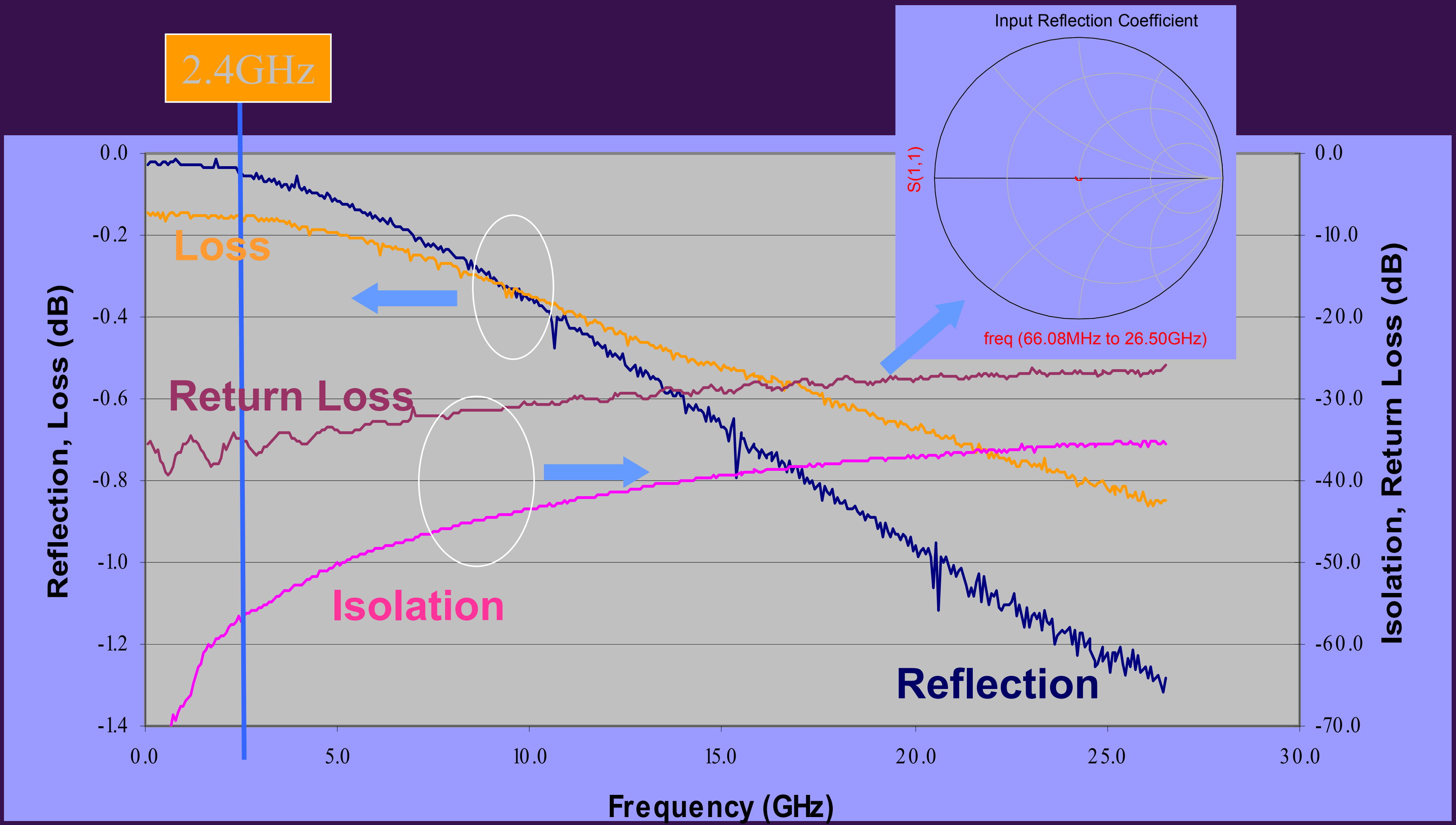
- Monolithic Switchplexer
  - Band Diplexer
  - Transmit / Receive Switching



- Phase Shifter
  - "Smart" Antennas
  - Test and measurement

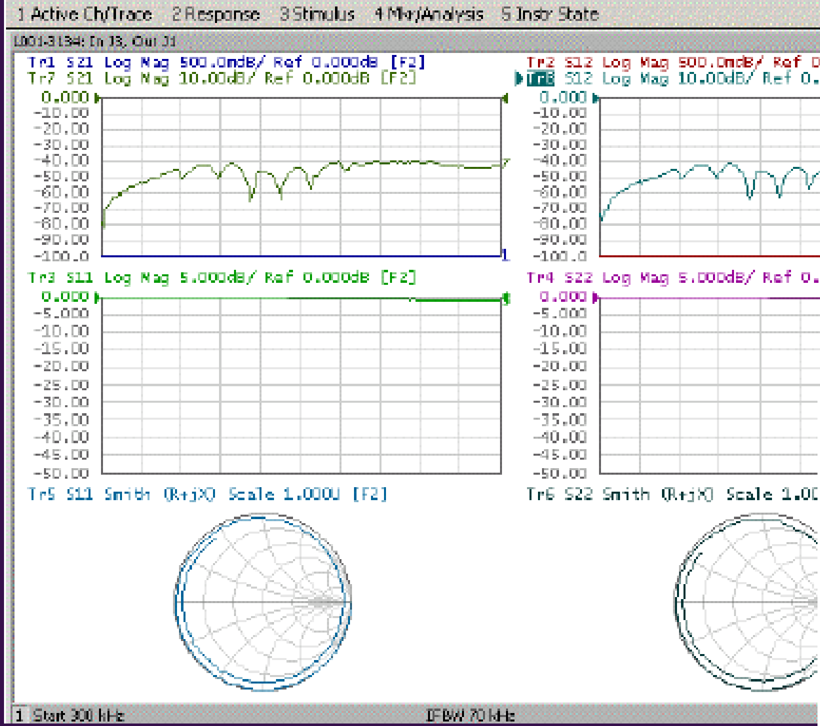


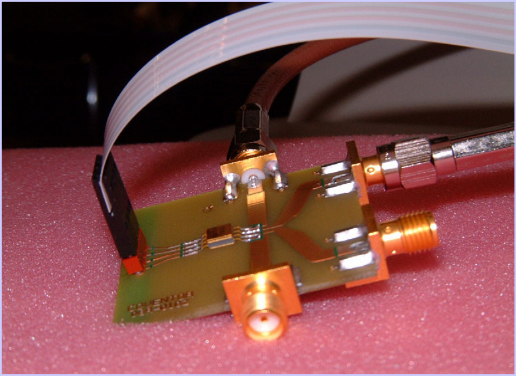
Typical Switch Die S-parameters

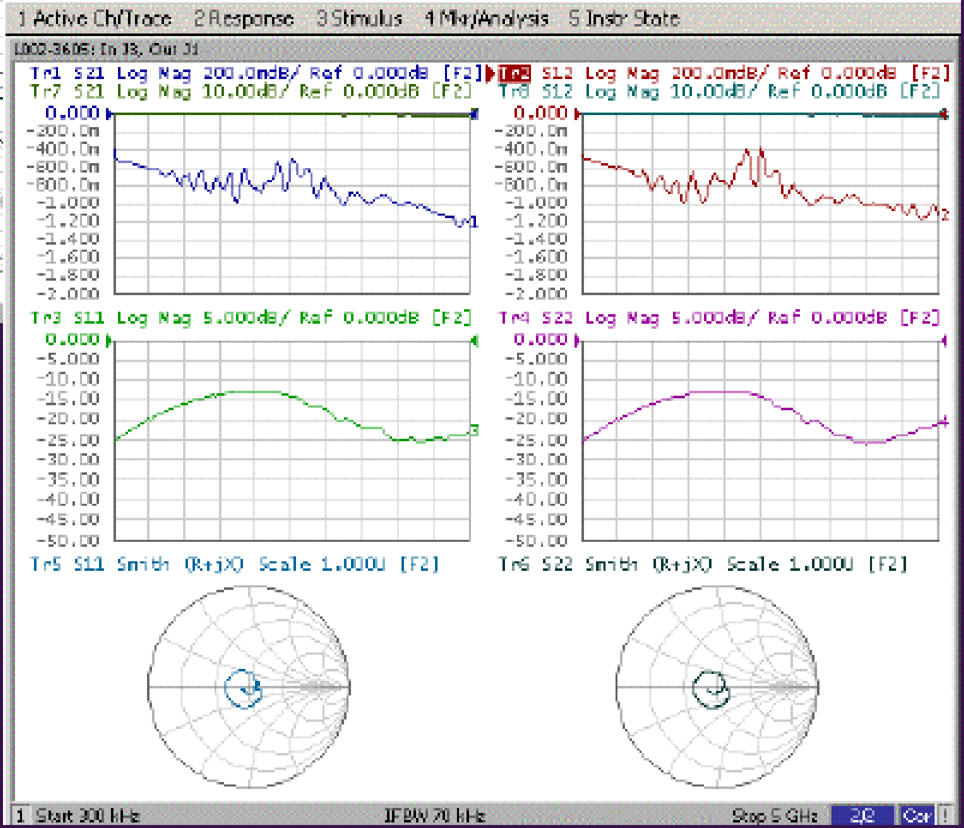


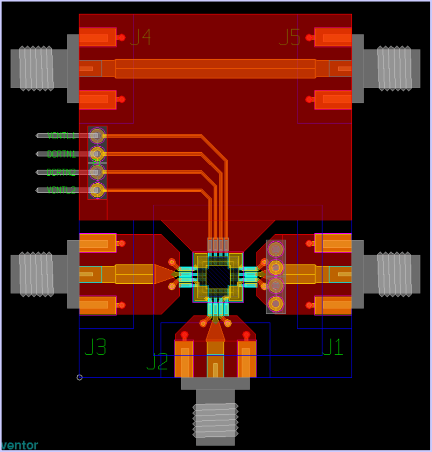
Non-deembedded results on low resistivity silicon!

Packaged S-parameters – Customer Tests









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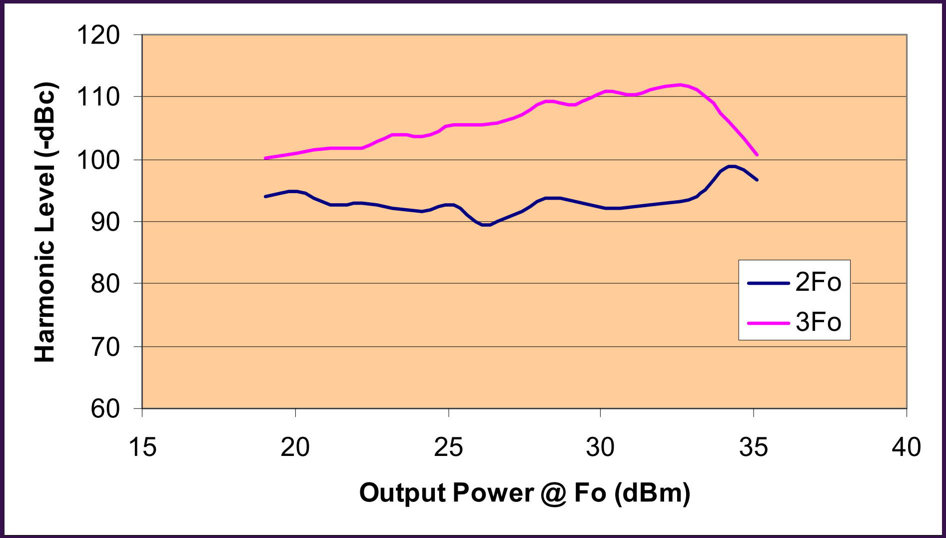
Large-Signal Switch Measurements

- Negligible harmonics to 4 watts



- Clean ACLR at 1 watt

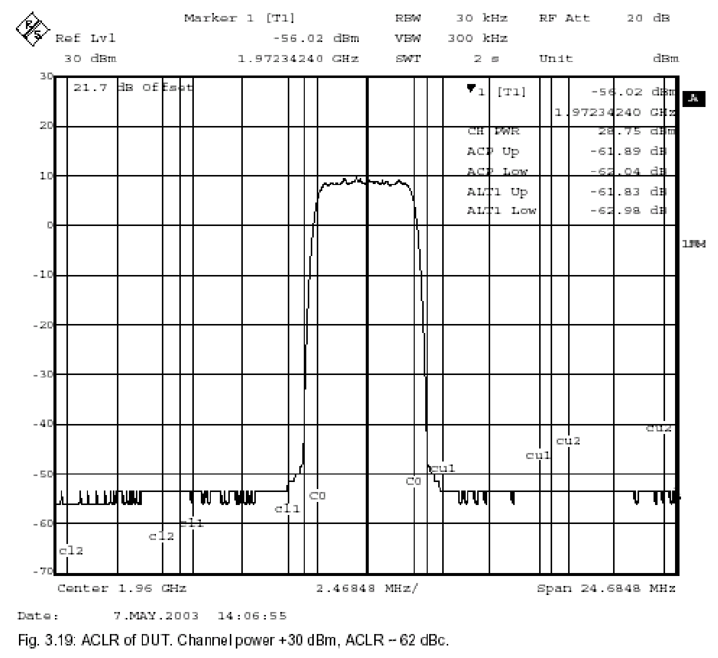
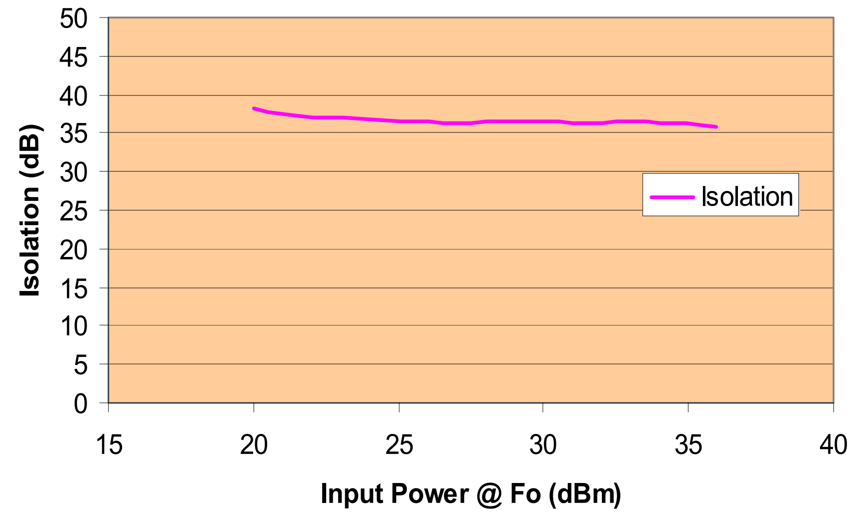


Fig. 3.19: ACLR of DUT. Channel power +30 dBm, ACLR ~ 62 dBc.

- Negligible RF actuation to 4 watts



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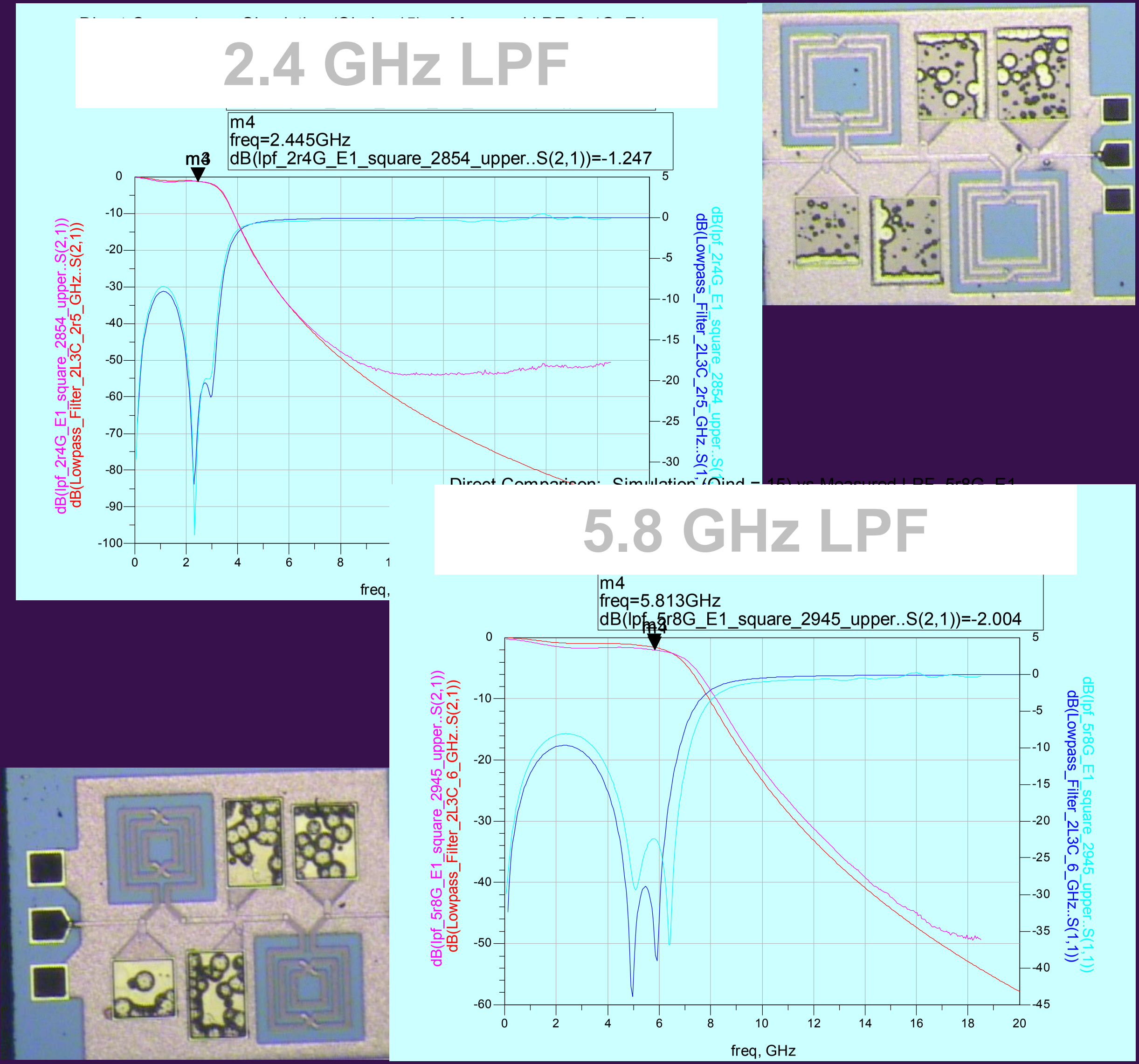
First-Pass Filter Performance

- Lowpass filters from same wafers as switches
- Sub-component of switchplexer
- Modeled design and measured data agree
- Insertion loss high
  - low resistivity substrate
  - Q =~ 15 @ 2.4 GHz
  - Q =~ 12 @ 5.8 GHz

- Expect Q > 50 with improved design
  - Meet specs in next run



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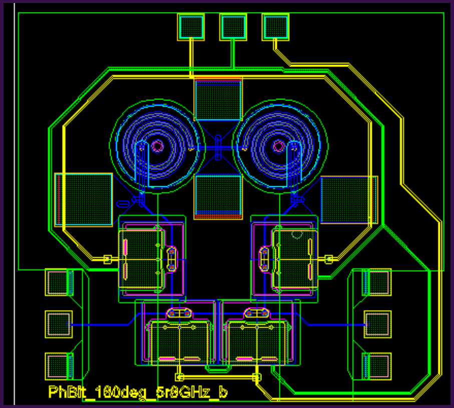
(Red and blue = simulation; pink and lt.blue = measurement)

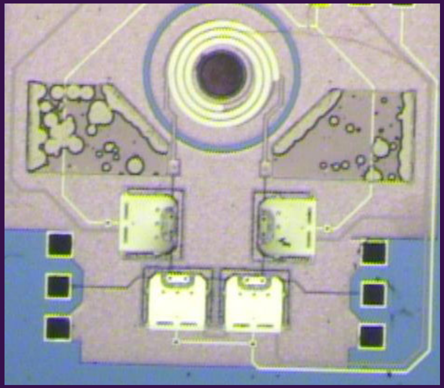
Phase Shifter

- "Smart" Antenna Applications

- Single Chip, Chip-Scale Packaged
  - ~ 2 mm^2
- Through loss < 0.2 dB per bit
- Integrated Low Loss Delay Lines
  - Transmission Lines at High Frequencies
  - Compact LC Delay Line at Low Frequencies (800MHz – 6 GHz)



5.8 GHz



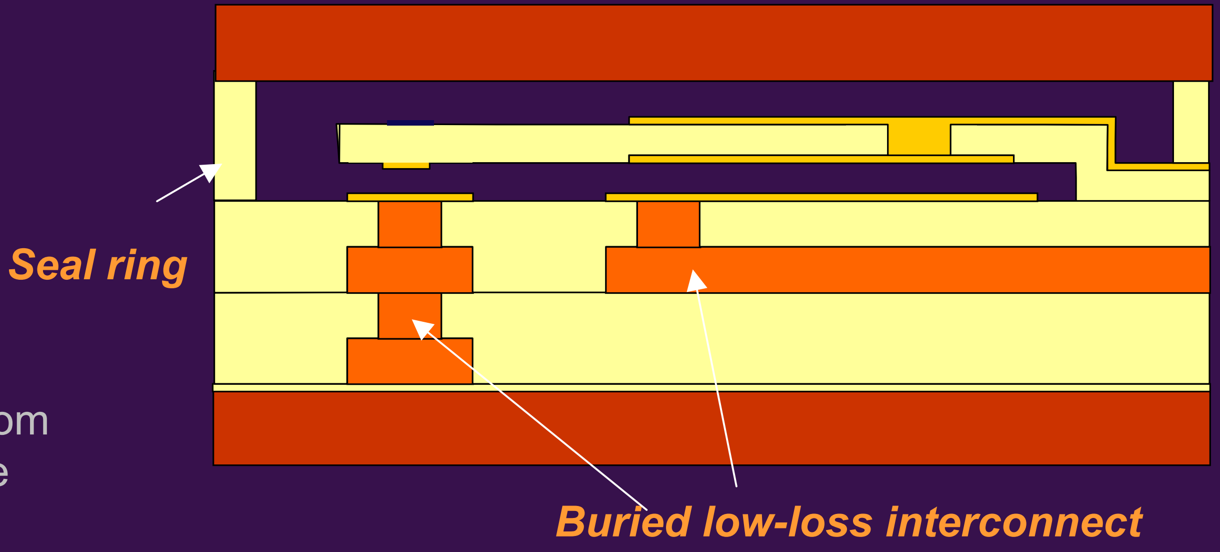
2.4 GHz

Key Challenges and Solutions

- Why are RF-MEMS not already in the mainstream?
  - MEMS dominate accelerometer and projection display markets
- Cost
  - Hermetic sealing and packaging
  - Size of overall solution
  - Integration barriers
  - Insufficient foundry volumes
- Reliability
  - Design/process specific issues
  - Reliability has been unproven
- Control
  - High voltages or currents have been required
  - Switching time slower than solid-state

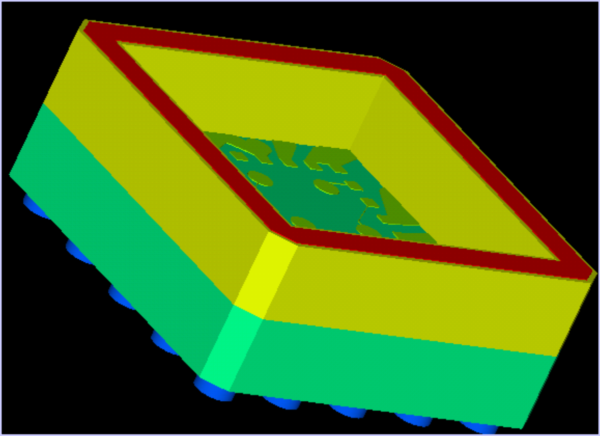
Wafer-Level Encapsulation

- Lower Cost
  - Cavity packaging expensive
  - Higher yield
  - Lower labor costs
- Easier Integration
  - MCM
  - Flip-chip
  - Monolithic
- Longer Life
  - Sealed in fab clean room
  - Controlled atmosphere
- Higher Performance
  - Controlled Impedance
  - Chip-on-board, etc.
  - Reduced contamination

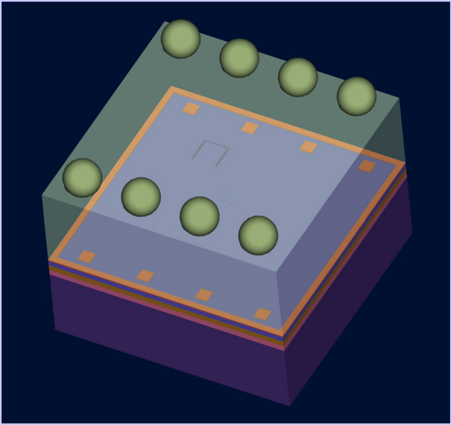


Packaging Approaches

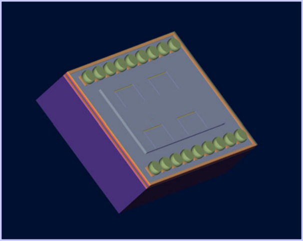
- Protos and PCB Mounting (DRS1)
    - 2 x 2 x 1.2mm package
    - 400um Pitch; 200um Balls
    - 25 Balls on 5 x 5 Grid
- Module Mounting (ERS1)
    - 1.5 x 1.5 x 0.5mm WLCSP
    - 200 um Pitch; 75um studs
    - 36 pins on 6x6 grid
    - Solder Ball on Plated Via
    - Wafer-Level Bond
- Next-gen Module Mounting (LRS1)
    - 1.0 x 1.0 x 0.3 mm WLCSP
    - 150 um Pitch; 50um studs
    - 32 pins; Quad Configuration
    - Thin-Film Cap



In Development →



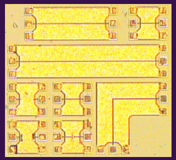
In Research →

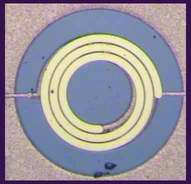


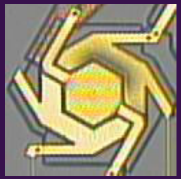
Integration within a single process

Extensive Reuse of Proven Components

- <u>Basic Component Set</u>
  - Switches
  - Transmission Lines
  - Multi-layer Capacitors
  - Inductors
  - Transformers
  - Variable Capacitors
  - Variable Inductors
- <u>Post-processing of Actives</u>
  - Charge Pump Circuit
  - RF-CMOS







- <u>Unique RF-MEMS Process</u>
  - Low k & tanδ glass
  - Thick Copper and Gold
    - No Polysilicon
  - Low Thermal Budget
  - Wafer-Level (Chip-Scale) Packaging
  - Stand-Alone or Post-Process Any IC Wafer
    - High performance on low or high resistivity silicon
  - Available in Multiple Foundries

+ + =

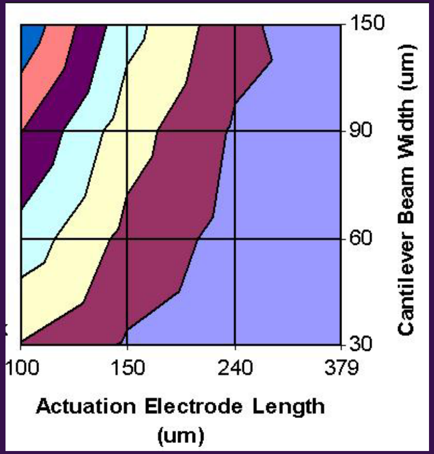
Complete Solution

wiSpry

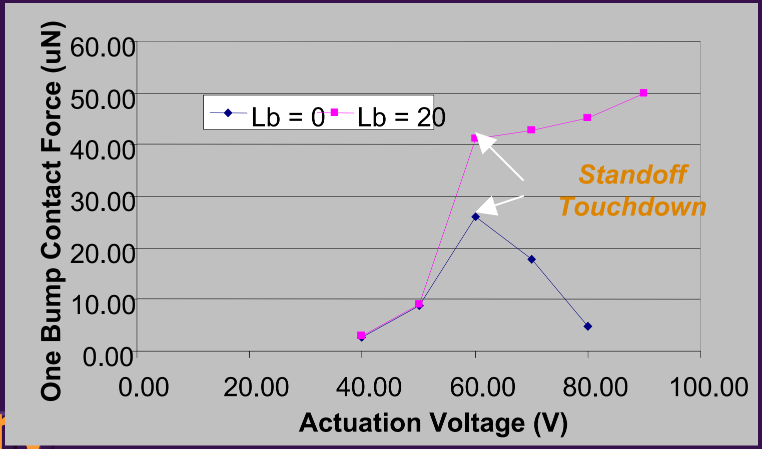
Thorough Design for Reliability

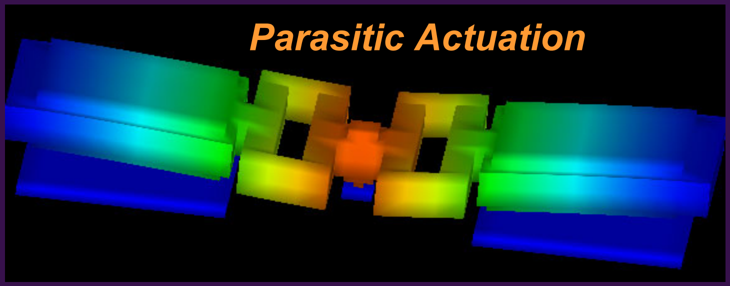
- Device Operation
  - Contact and Release Forces
  - Contact Materials
  - Electric Fields and Charging
  - Mechanical Materials
  - Mech. Stress Concentrations
  - Defect Analysis
  - Current Handling
  - Thermal Stability
  - Vibration
- Extremes
  - Overvoltaging
  - ESD
  - RF Pull-in
  - Pulsed Current
  - Shock
- Packaging
  - Sealing
  - Atmosphere
  - Gettering
  - Stresses

Release Force



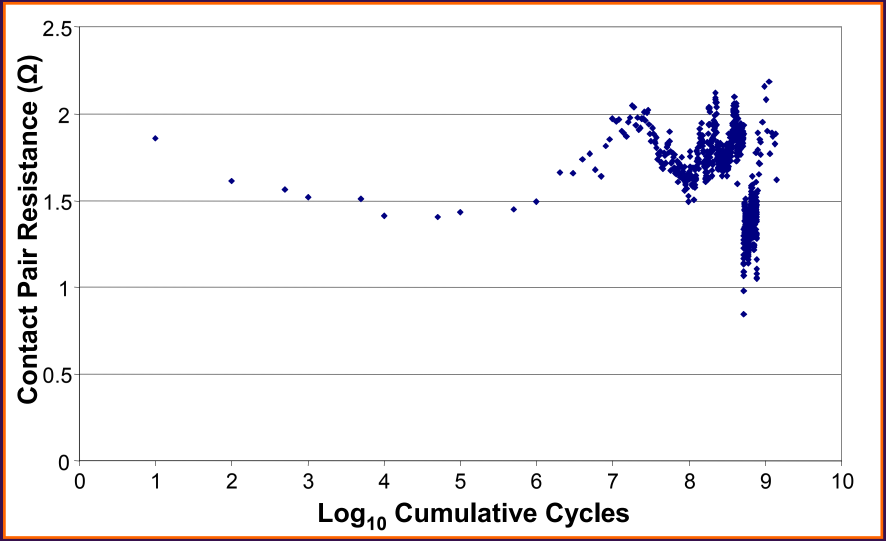
Standoff Position

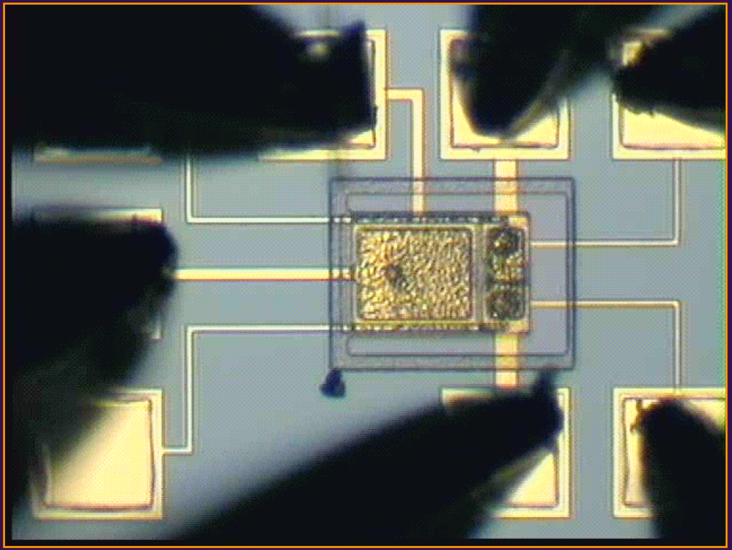



Parasitic Actuation

Switch Life Cycling

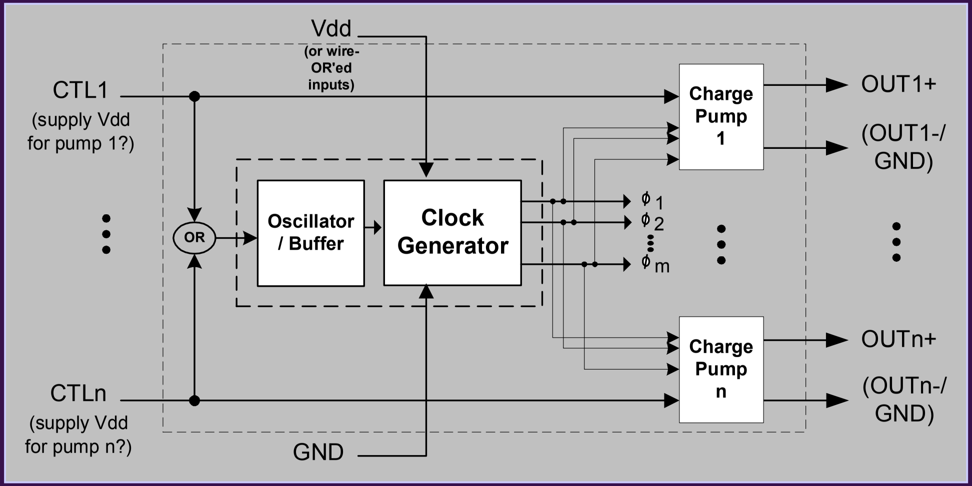
- Operate to billions of cycles without failure unpackaged
- Contact stable with <1 mΩ increase per million cycles
- Numerous switches tested using automated equipment
- Reliability testing of fully packaged parts is continuing
    - Acceleration method search underway

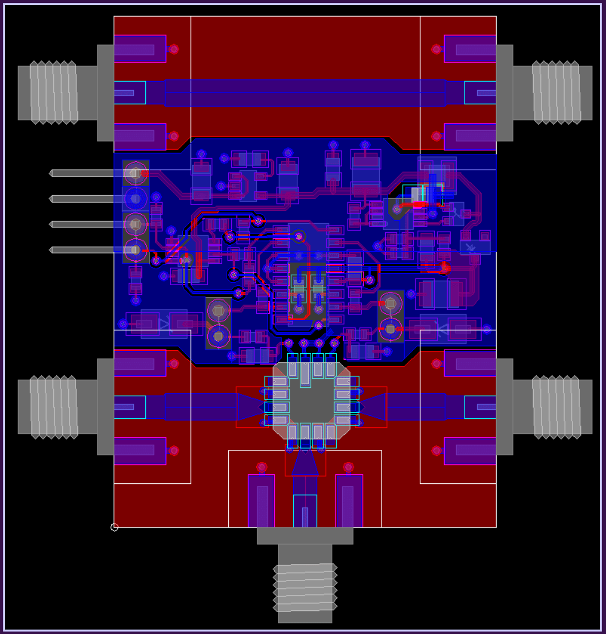




Charge Pump

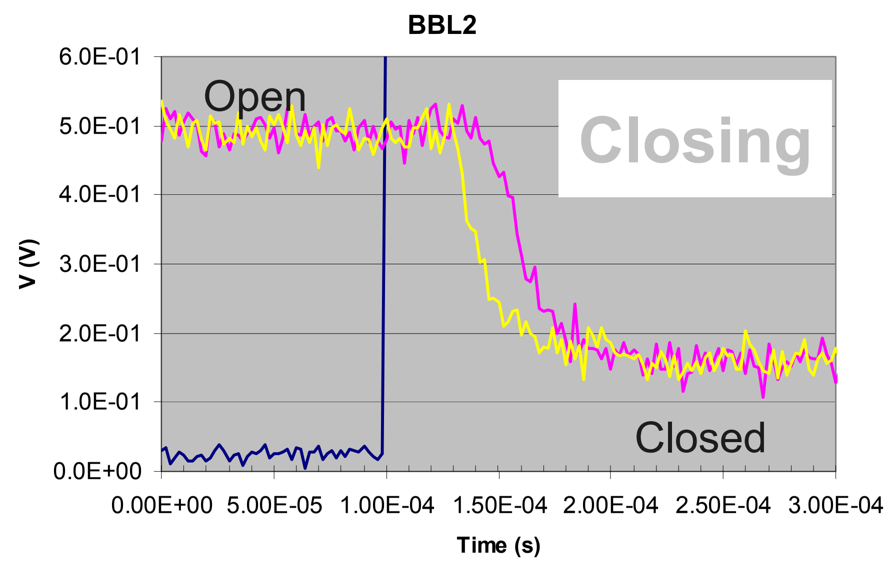
- 2.7V supply
- Regulated +/- 15V Control
- Includes
  - Voltage converter
  - Switch drivers
  - CMOS/TTL Interfaces
- 35uA available per switch for worst case of continuous switching operation
- Shutdown During Stand-By
- Power Up/Down <100usec
- Discrete version built and tested
- Beginning CMOS Design

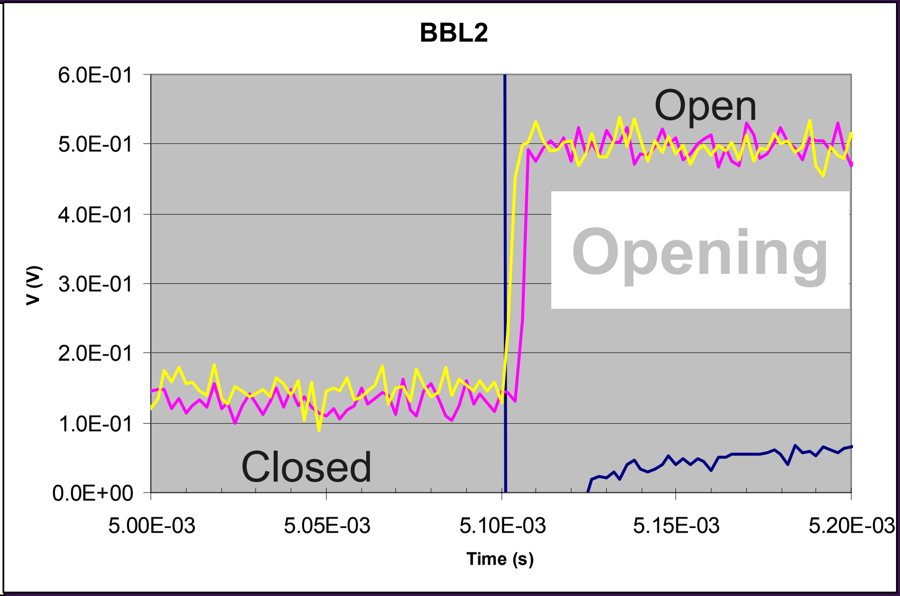




Transient Response

- Closing time: <100 µs to stable resistance
  - <50µs delay, <25µs 10%-90% RF transition
- Opening time: < 10 µs





- Fast enough for many applications, even some T/R
  - Air damping limited, easily lowered by an order of magnitude

Summary

- Low cost overall solution is key
  - Wafer-level chip-scale packaging
  - True relay -> No off-chip components required for DC-RF Isolation
  - Proprietary Unique IC Compatible Process
    - Proven; Silicon Since Late 2000; Ported and Installed in 3 Fabs
    - All Products on Same Process a la Mixed-Signal ICs; Aggregation of Volume
- High reliability achieved
  - DFM Methodology Integrated with RF IC Flow (Cadence)
  - Proven to > 10^9 cycles
  - Acceleration mechanisms under study
- Control issues resolved
  - Actuation Voltages are <±10V with Path to Lower Voltages
  - Less Demanding Charge Pump Design -> Easier direct integration
  - Speed sufficient for most commercial applications
- MEMS are ready for prime-time in RF applications
  - Proliferation of wireless standards increases need
  - Technology is maturing

Questions?

- Email: art.morris@wispry.com