RF MEMS Switches and Tuners: Commercialization trends and business opportunities

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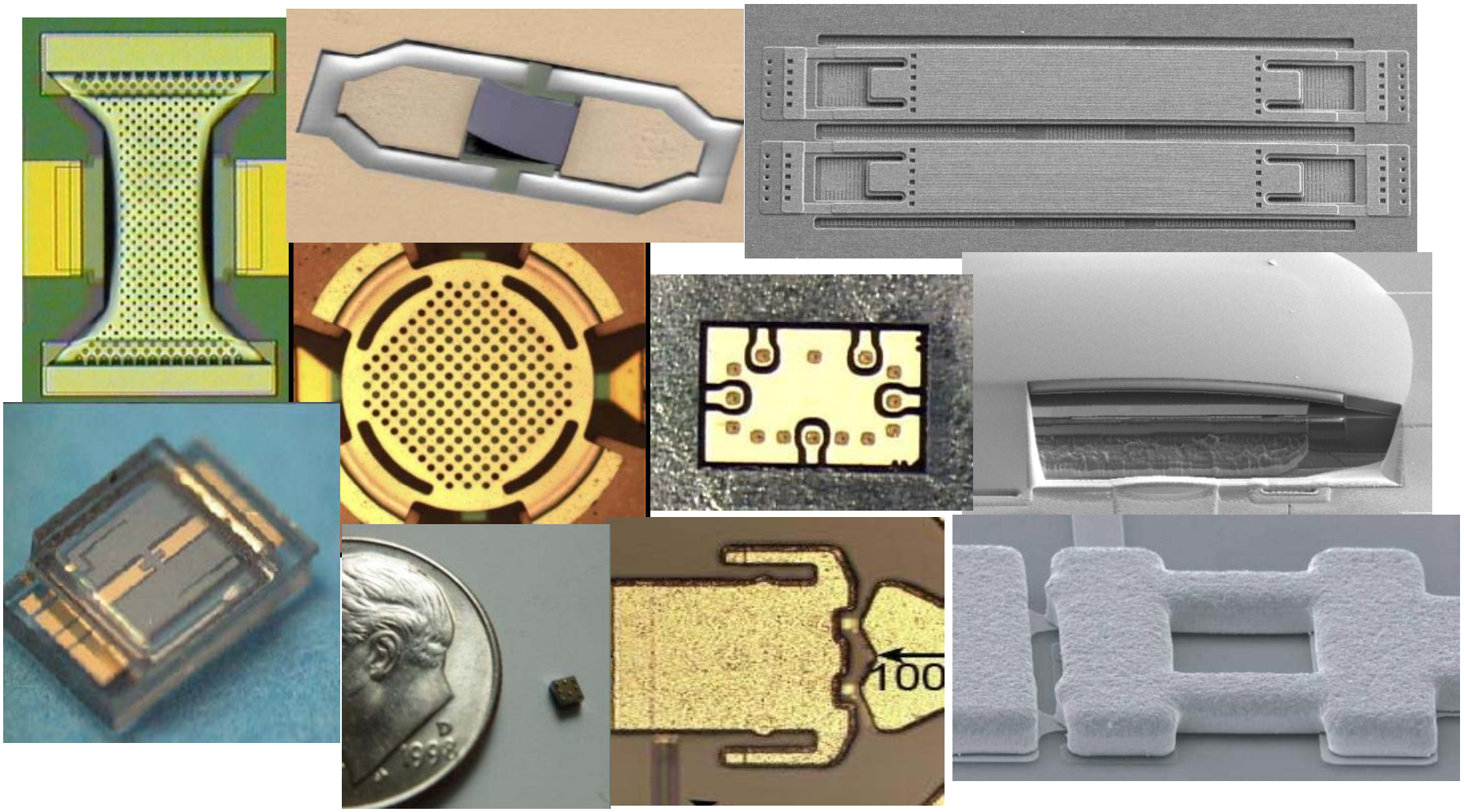
WHAT ARE RF MEMS?

- RF MEMS (Radio Frequency Micro-Electro-Mechanical Systems) are switches and variable capacitors, which are used in the front-end of cell phones, base-stations, etc. to result in lower-loss, higher-performance systems.

- Think of RF MEMS as better switches, better variable capacitors, better tunable antennas, better tunable filters, just better than anything done in solid-state (diodes, CMOS switches, etc.).

- RF MEMS are not transistors and do not provide gain. They only function as switches (metal-contact) or variable capacitors (for tuners).

RF MEMS Activities in the US



A lot of activity but few products (Omron, wiSpry, Cavendish Kinetics).

Why RF MEMS Switches and Varactors?

- Amazingly linear switches and variable capacitors (IIP3 > 75 dBm, IIP2 > 120 dBm, 2nd and 3rd harmonic generation < -90 dBc)
  - *Linearity is essential in cell phones to handle multiple carriers*
- Very low loss (0.1-0.2 dB at DC-60 GHz)
  - *Lower loss means more efficient systems and longer battery life*
- High voltage handling (50-100+V possible)
  - *Needed to handle power levels inside antennas and tuners*
- High Cr (5-50) and high Q (> 200). Excellent for tuning.
  - *Needed for wide frequency tuning. High Q results in low loss.*
- Compatible with 5-100 Ω circuits (power amplifiers, filters).
  - *All circuits inside cell phones operate between 5-100 Ω.*

We are in the 21st century and we still do not have a high performance tuner or a very low loss microwave switch!!

Limitations of RF MEMS (Real and Perceived)

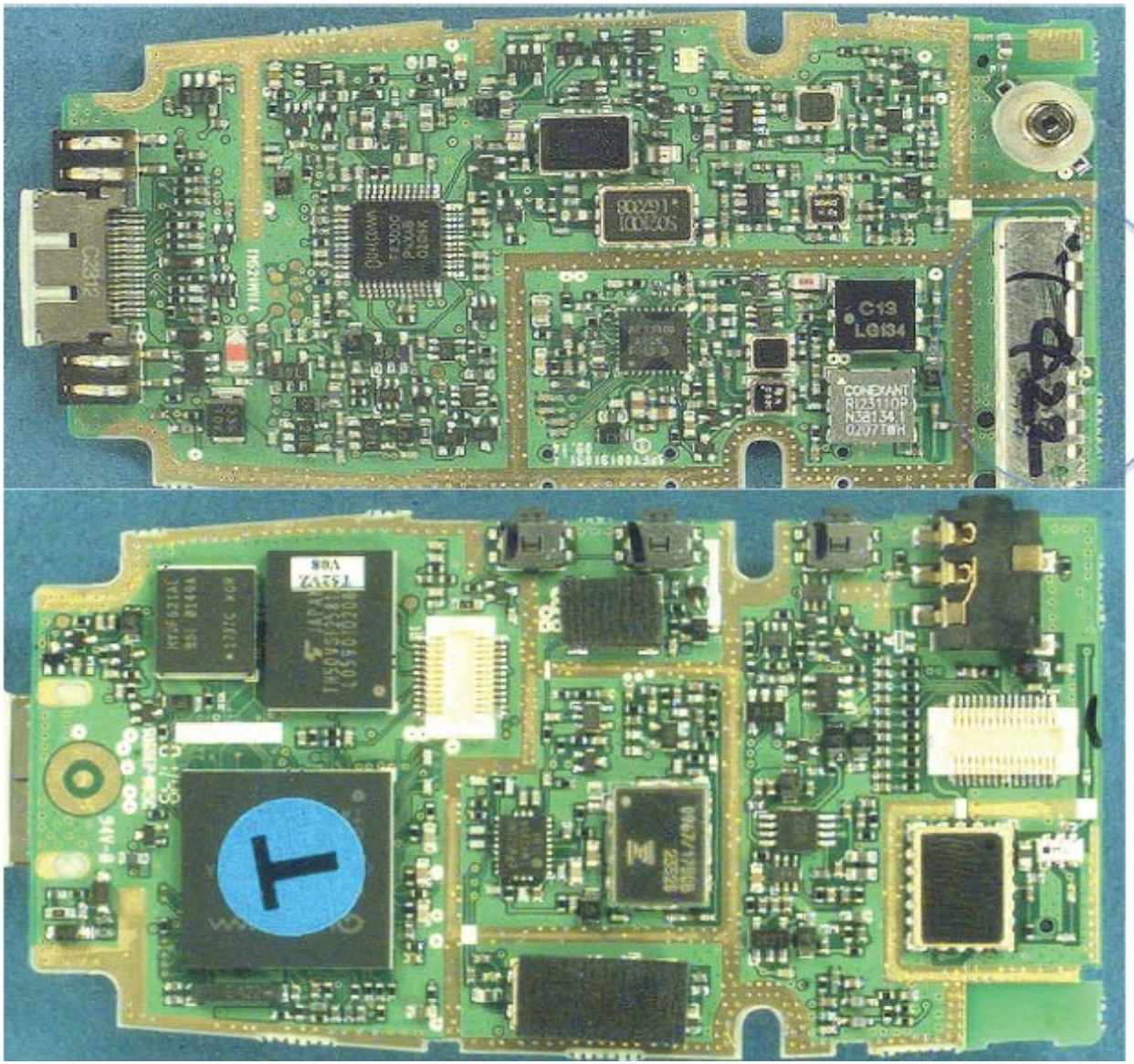
- RF MEMS must be hermetically sealed for reliability.
- RF MEMS, if not well designed, can suffer from dielectric charging and metal contact degradation, affecting reliability.
- RF MEMS, if not well designed, can suffer from metal stress and temperature effects which can warp the movable membrane.
- RF MEMS needs a high voltage (25-90 V) to operate reliability.

- **ALL OF THESE HAVE BEEN SOLVED to result in reliable MEMS!!**
  - *CMOS + MEMS results in hermetic dielectric cap packages*
  - *We know how to design reliable MEMS today which do not suffer from dielectric charging, metal contact degradation, or stress effects.*
  - *Voltage upconverters to 30-90 V are now available cheaply and integrated with RF MEMS and with very low current (< 50 uA).*

History of RF MEMS

- Started in 1995-1996 under DARPA for phased-array programs
- By 1998, it was recognized that RF MEMS can be used for much more than phase shifters: Tunable antennas, tunable filters, tunable front-ends, etc.
- By 2001-2002, RF MEMS had reliability concerns.
- DARPA put a whole new program on RF MEMS reliability (Radant MEMS, Raytheon, Memtronics, etc.) were funded.
- Commercial companies started appearing around this time too.
- Great advances in reliability and cost from 2005-2011.
- Today RF MEMS is basically used for reconfigurable systems (cell phones, future base stations, etc.)

CDMA Dual-band Phone Circa 2001



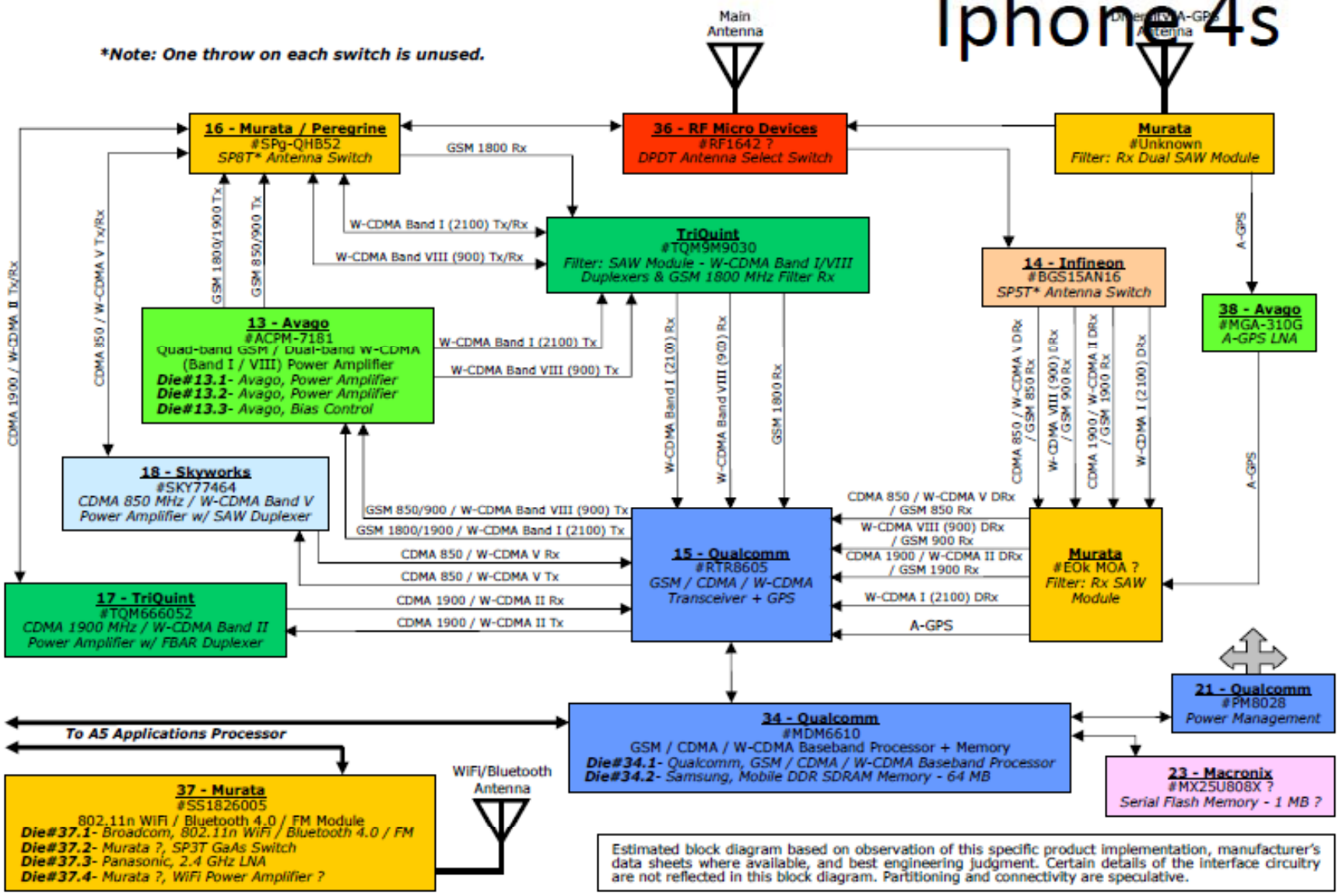
ceramic duplexer

RF Area ~40 cm^2

TECHINSIGHTS

Block Diagram

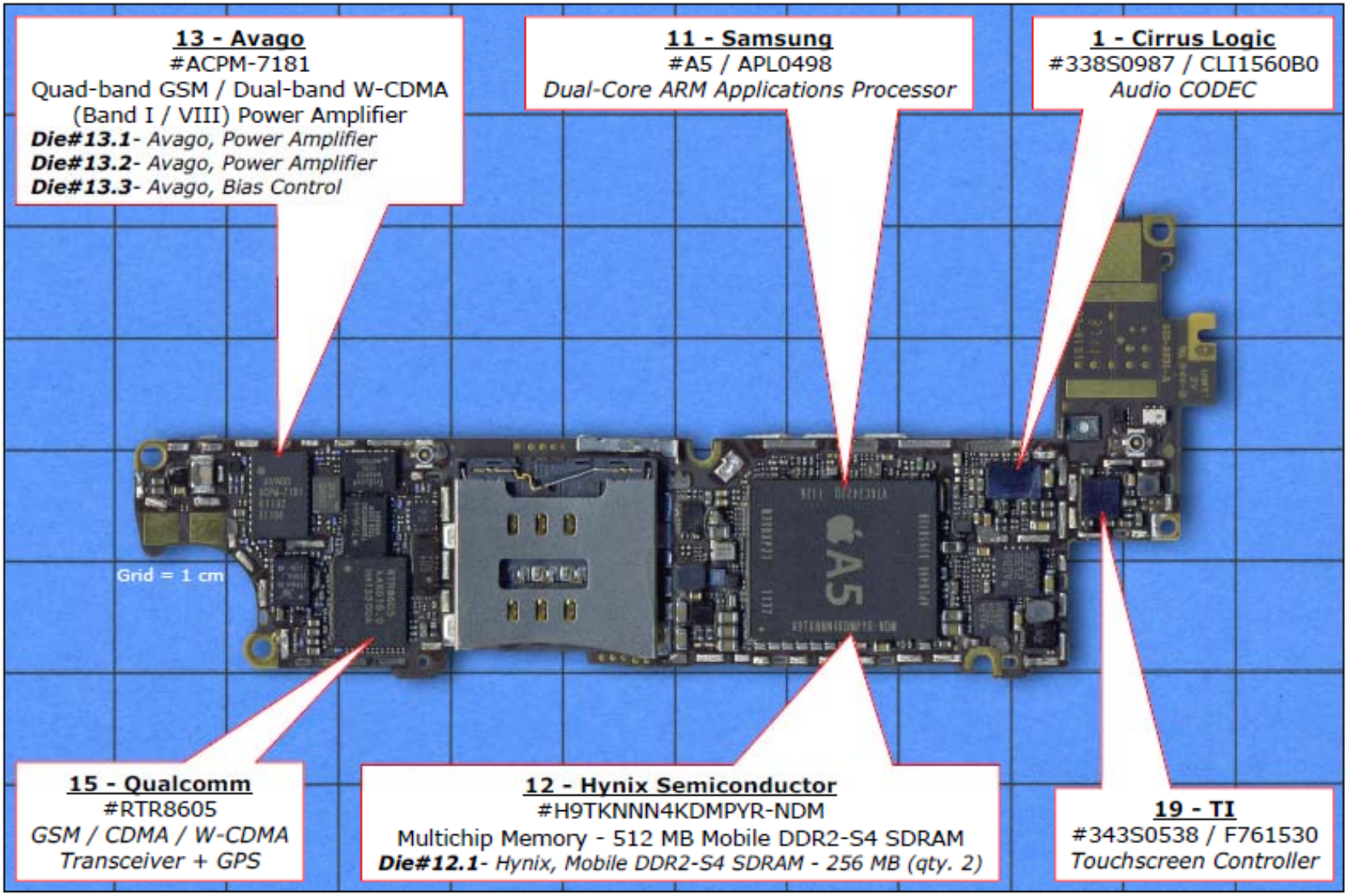
Iphone 4s



Comments?
Email us at feedback@teardown.com

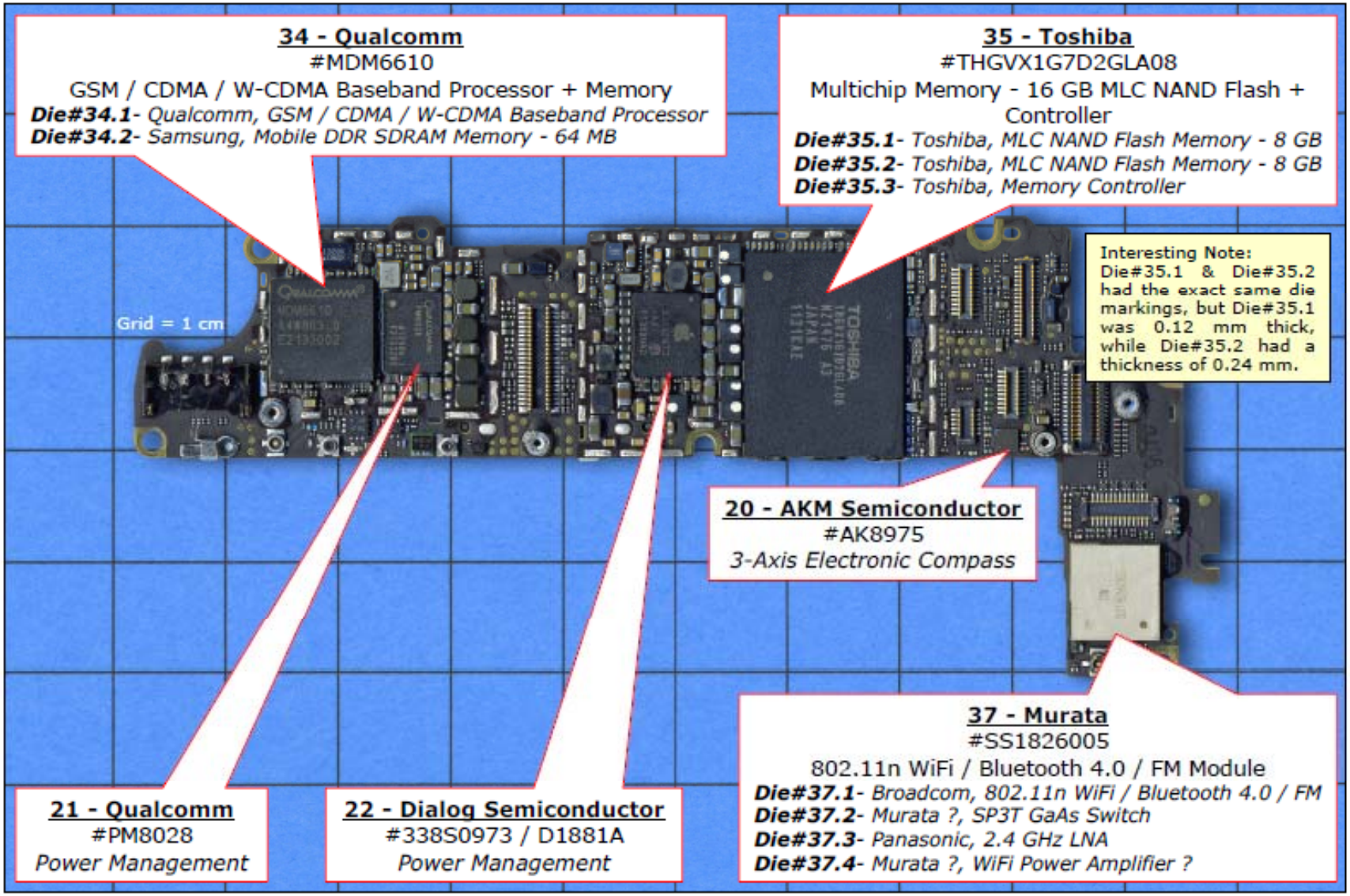
Board layout

TECHINSIGHTS **Main Board** (Side 1 IC Identification)



Board layout side 2

TECHINSIGHTS **Main Board** (Side 2 IC Identification)



Advances in Front-End Integration

- In 10 years, from 2002 to 2012, they (QCOM, Avago, TDK/Epcos, Murata, RFMD, Skyworks, etc.) managed to reduce the RF transceiver area by a factor of 12 (5400mm^2 or 54cm^2 in 2002, to 400mm^2 today), while increasing the radios by a factor of 6-7 (from 2 radios to 12-14 radios).

- This is a factor of 120-140 in 10 years!!! Much better than any DARPA program, or any other commercial program. Even better than microprocessors.

- *Anyone who does not recognize this is doomed to fail in the front-end. Integration is key for the future of front-ends.*

A Vision Since 12+ Years

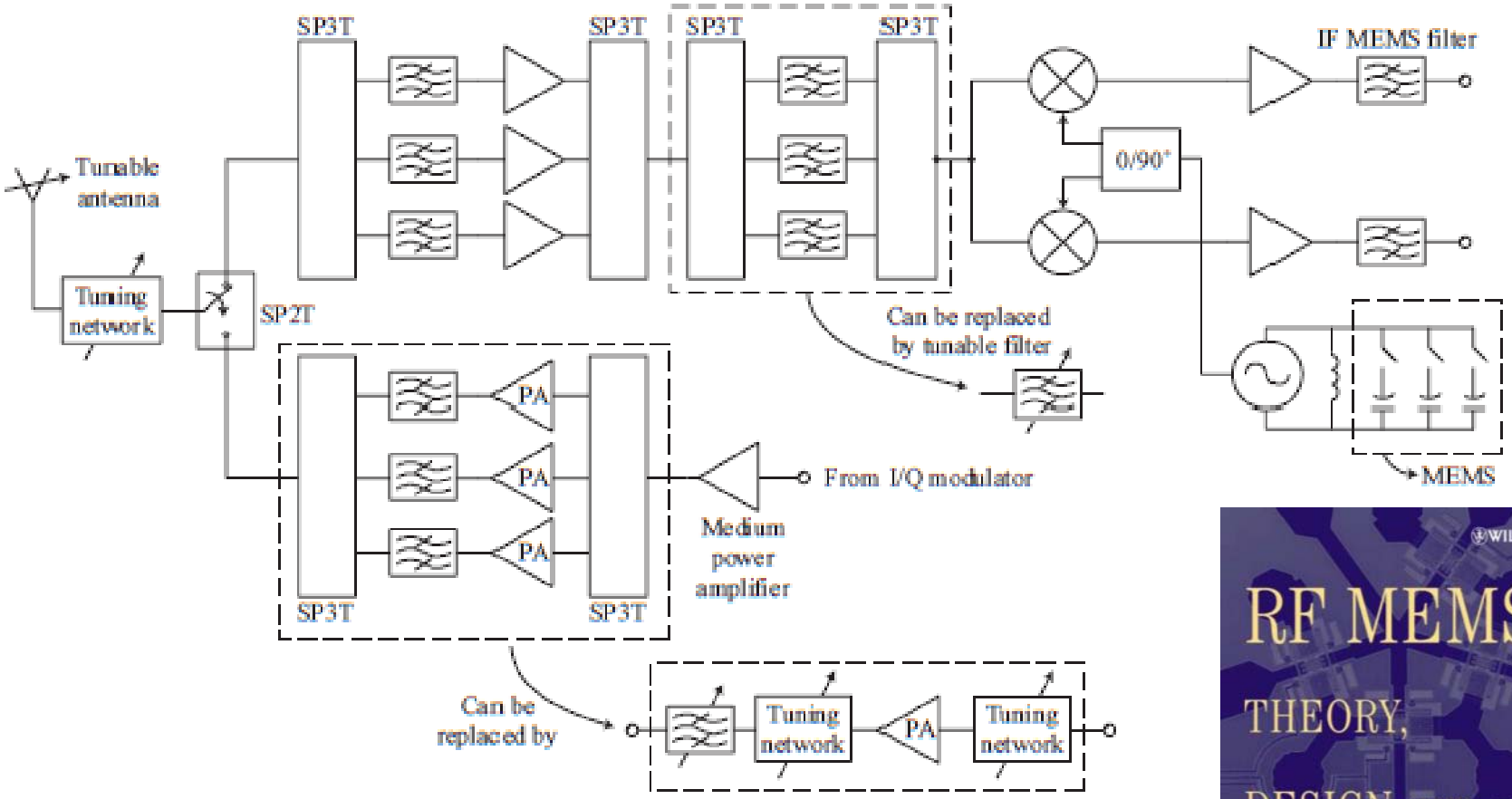
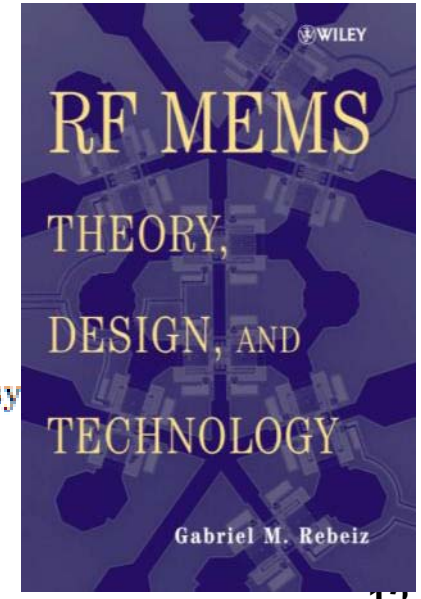
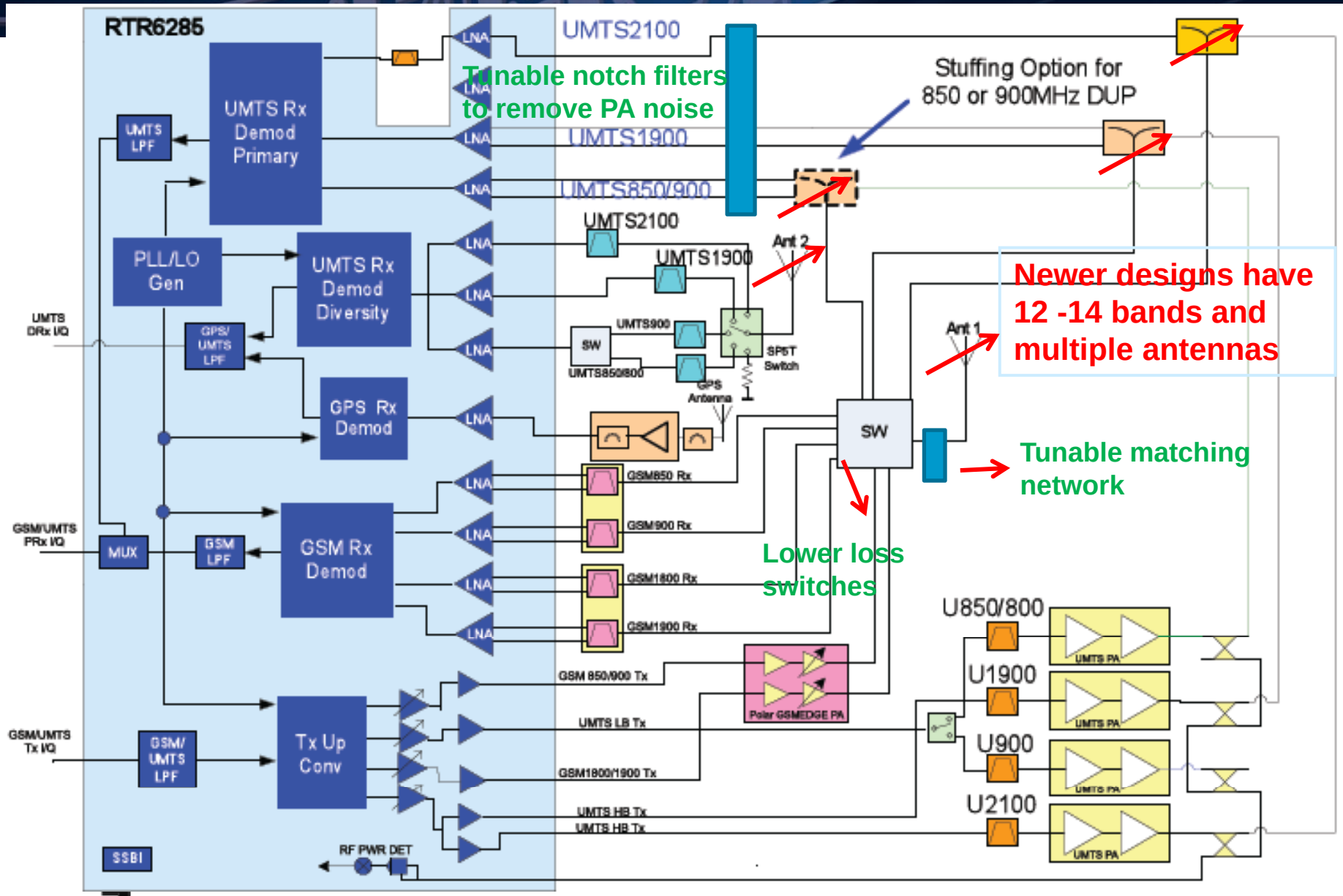


Figure 1.4: Front-end design of a 3-band MEMS wireless telephone sy

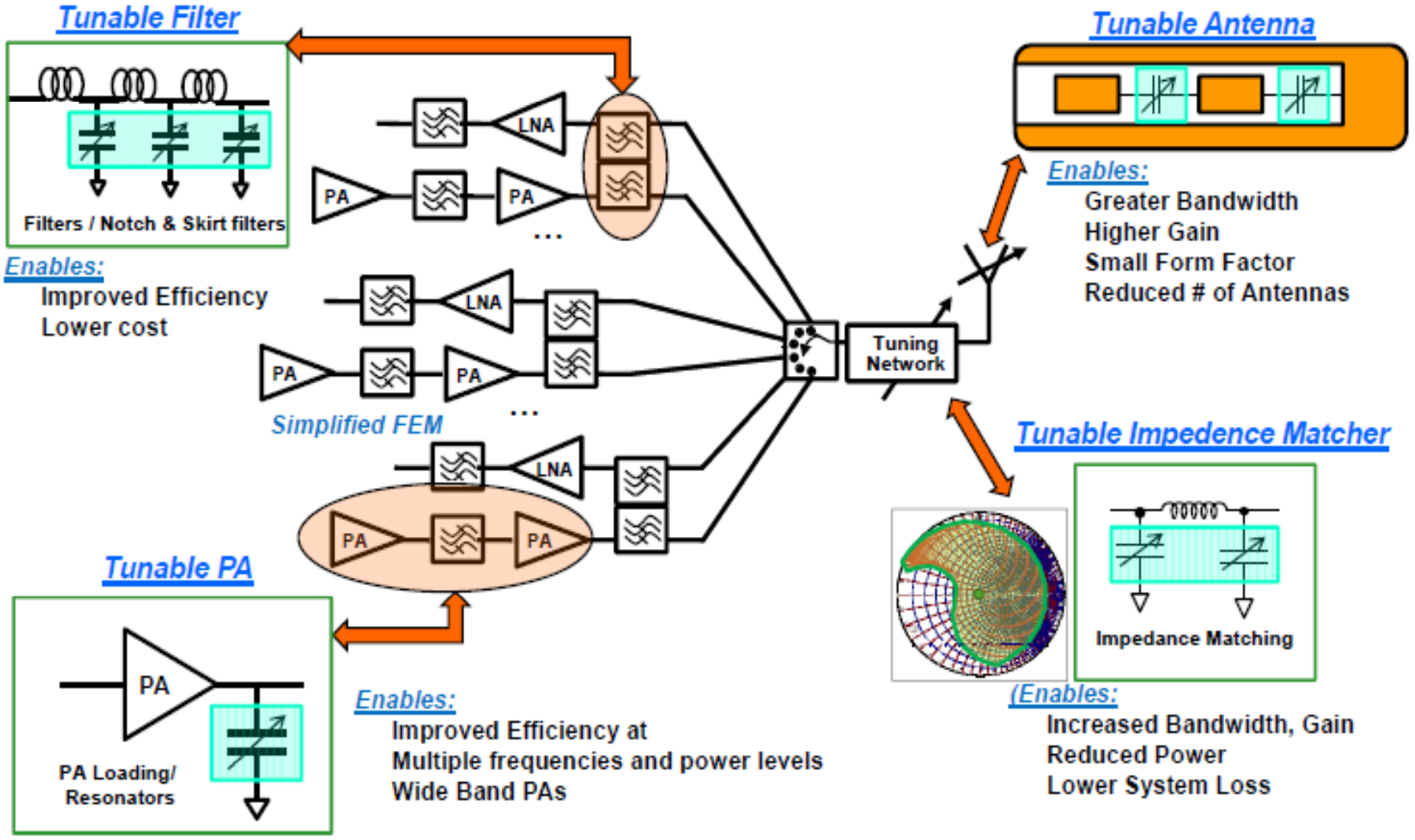


G.M. Rebeiz, RF MEMS: Theory, Design and Technology, Wiley, 2003

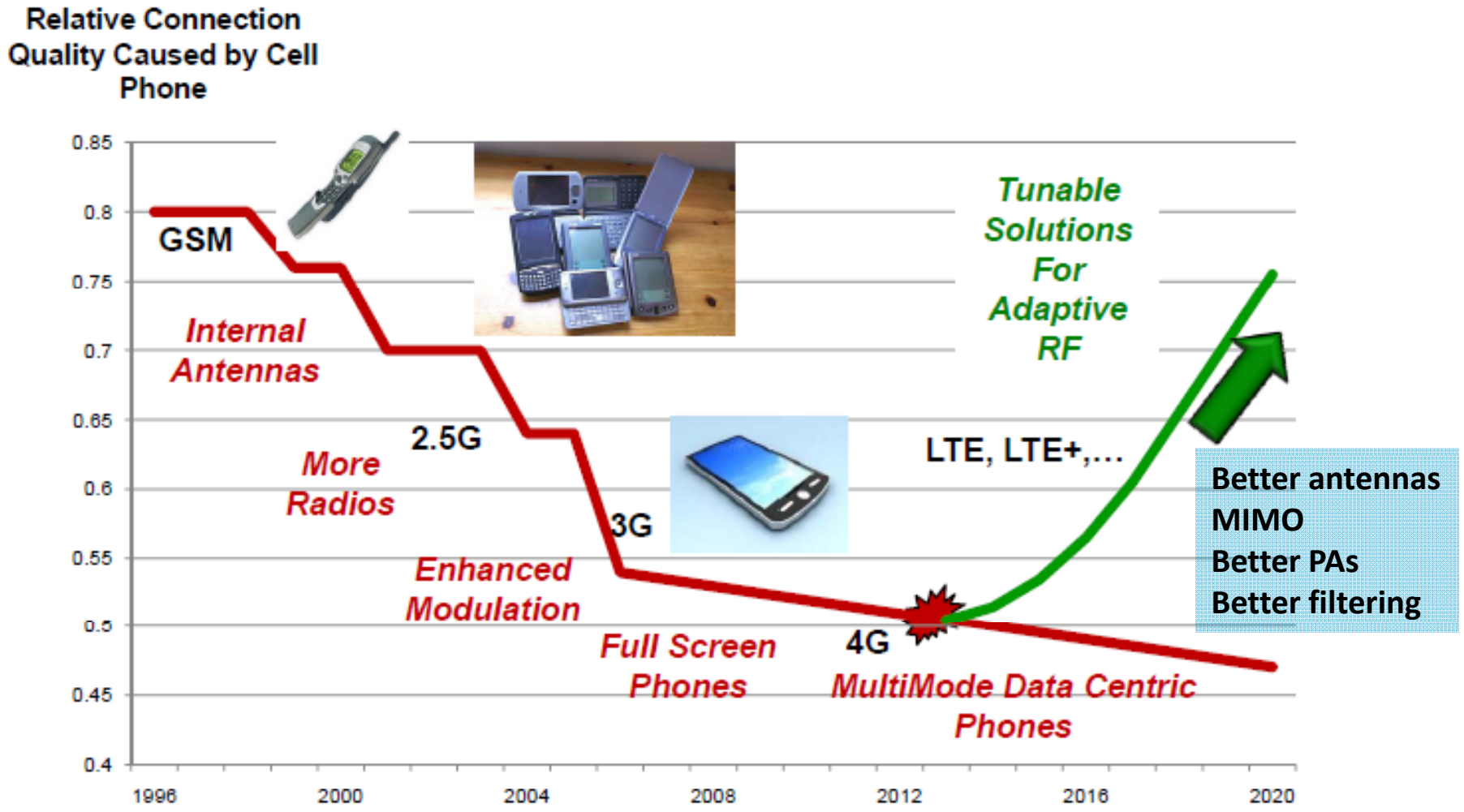
Qualcomm: 4 + 4 + GPS (with RF MEMS)



Tuning in the Mobile Front-End



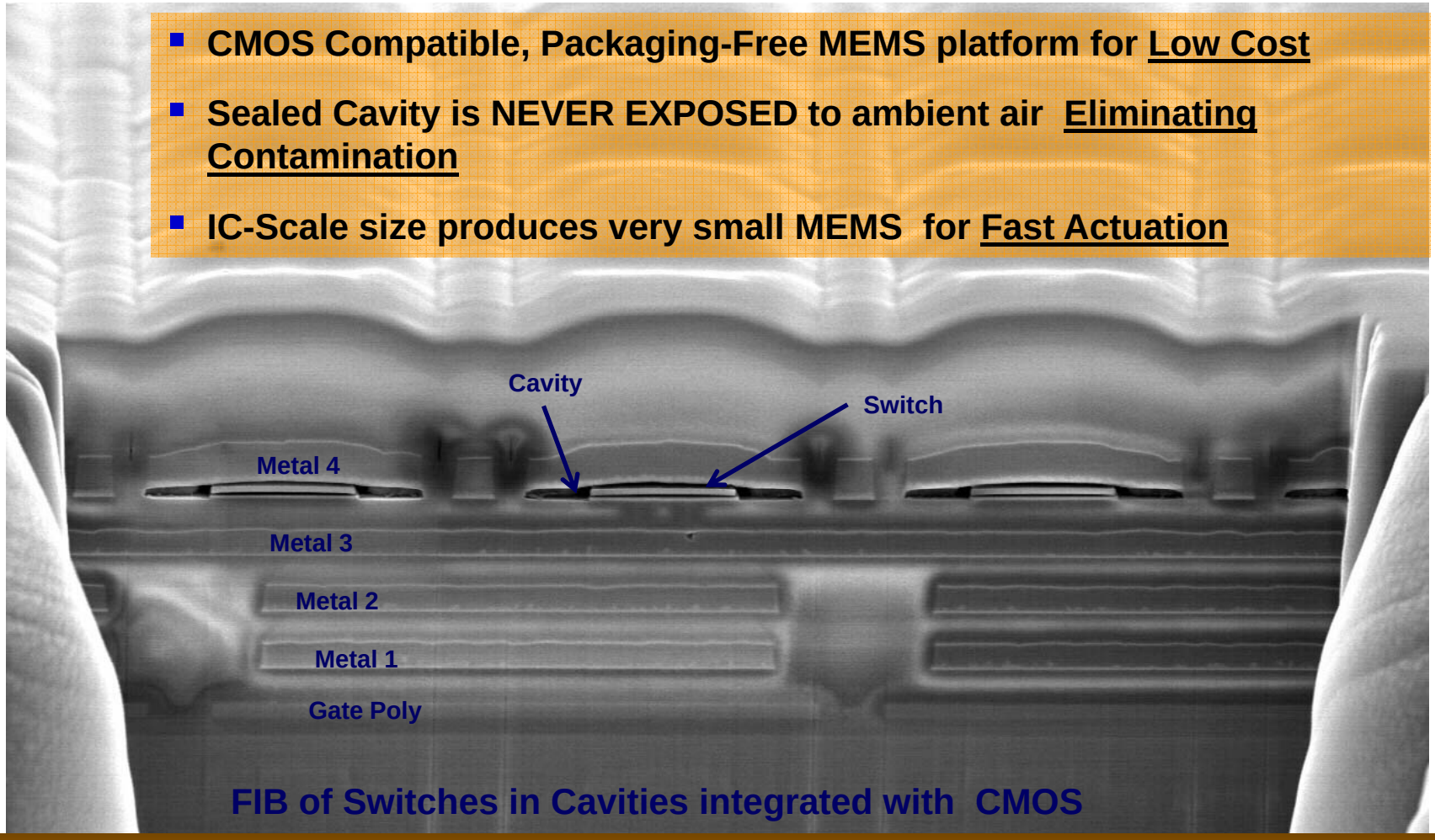
Wireless Industry's Secret
Degrading RF Performance



Industry Needs Technology Break through to Meet Needs of the Consumers

Cavendish Kinetics MEMS Embedded in CMOS Chip
Array of Cavities with RF MEMS Switches

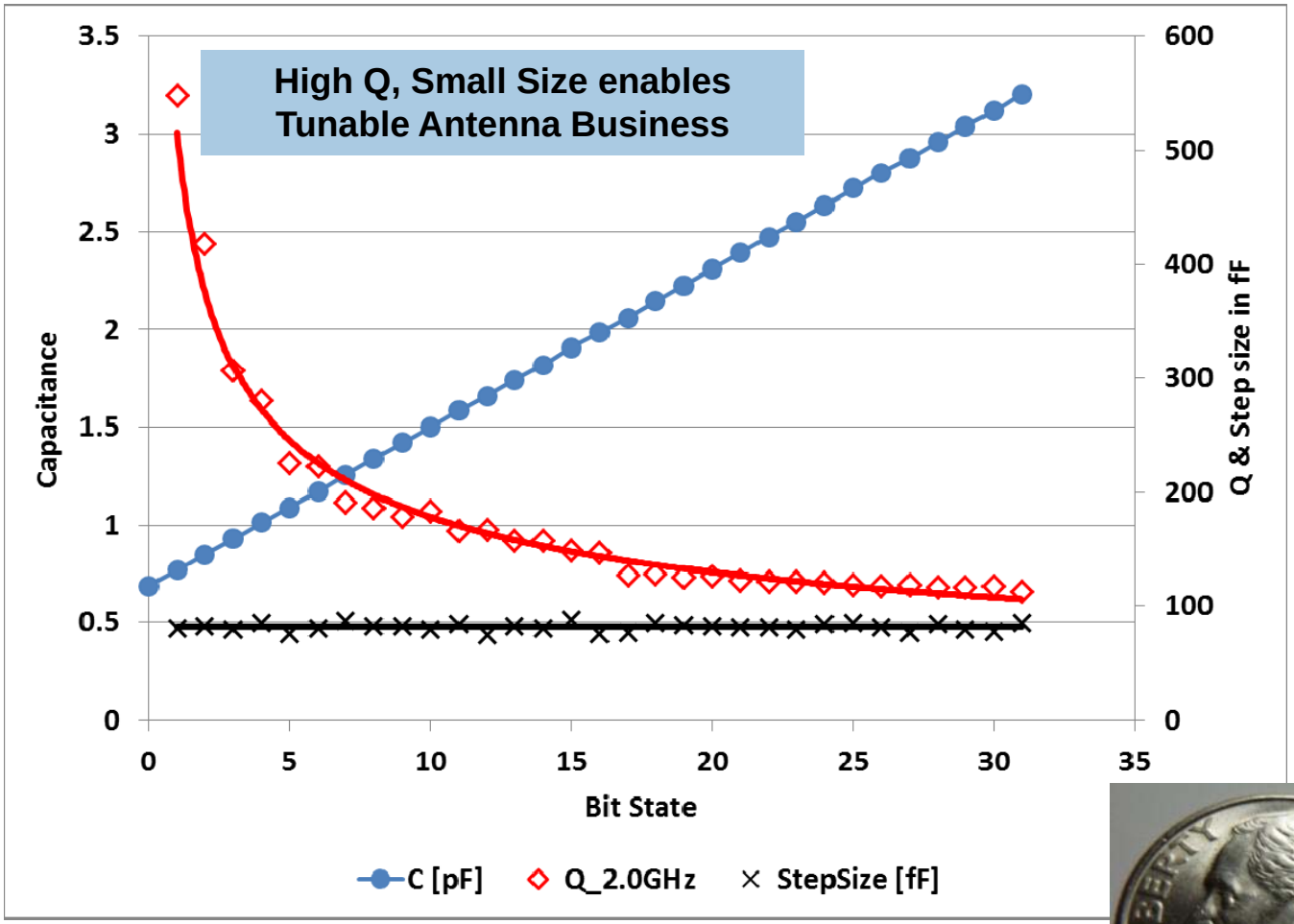
- CMOS Compatible, Packaging-Free MEMS platform for Low Cost
- Sealed Cavity is NEVER EXPOSED to ambient air Eliminating Contamination
- IC-Scale size produces very small MEMS for Fast Actuation



FIB of Switches in Cavities integrated with CMOS

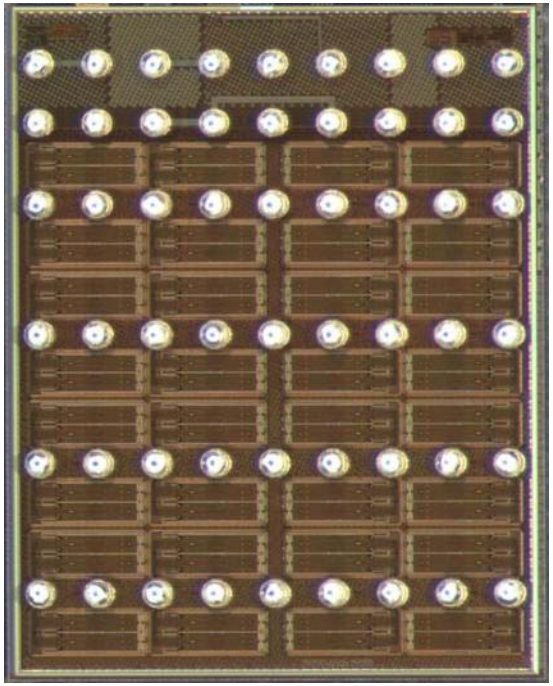
The only way to reduce the cost is by integration with CMOS (SPI, high voltage control, RF, etc.)

Cavendish Kinetics Digital Controlled Capacitor -
Typical Capacitance and Q

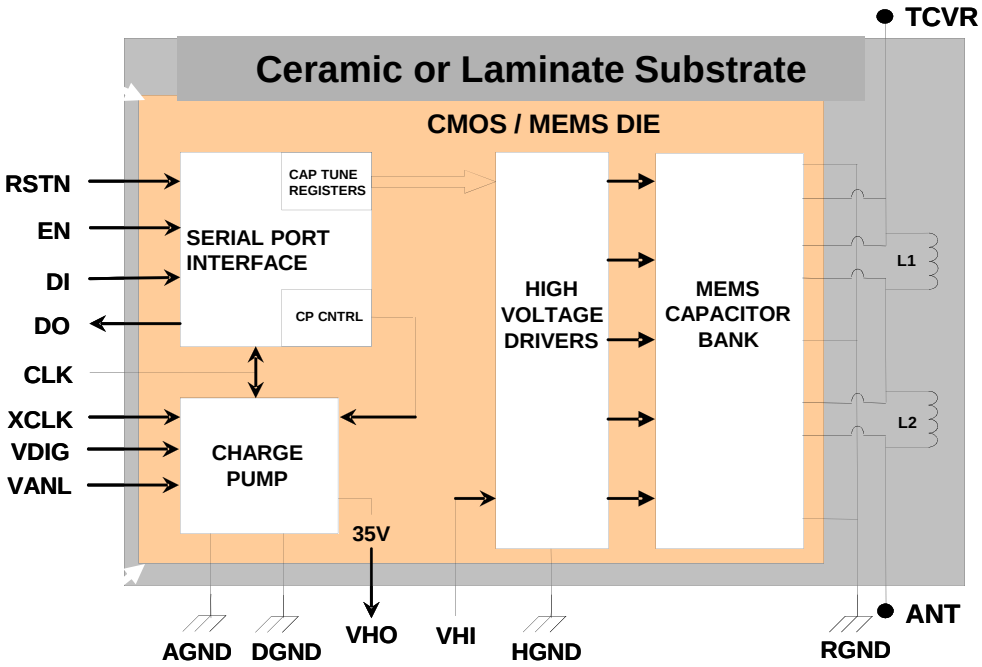


A distributed small MEMS has very high performance and allows higher packing density

wiSpry - Antenna Feed - Tuner Product

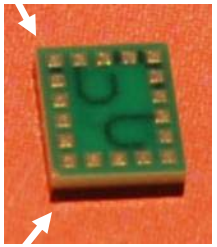


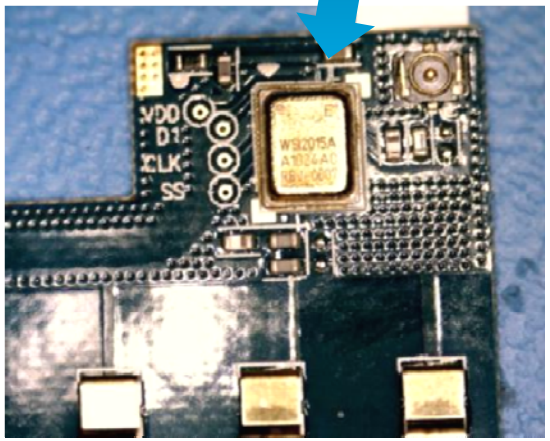
Tuner Flip-Chip Die:
Tunable Caps, Drivers, Serial Port
Wafer Level Lid Seal



Support for several SPI standards and MIPI RFFE

LGA Substrate: Embedded Inductors

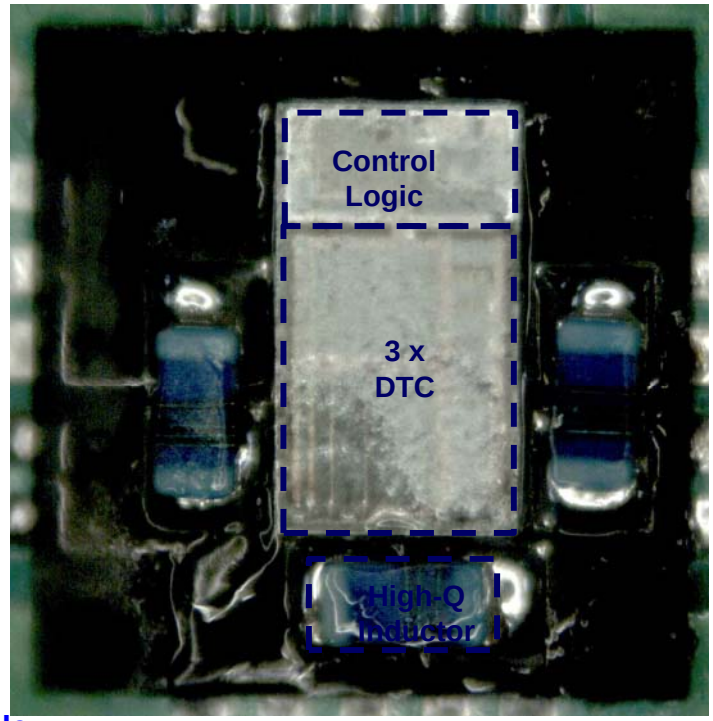


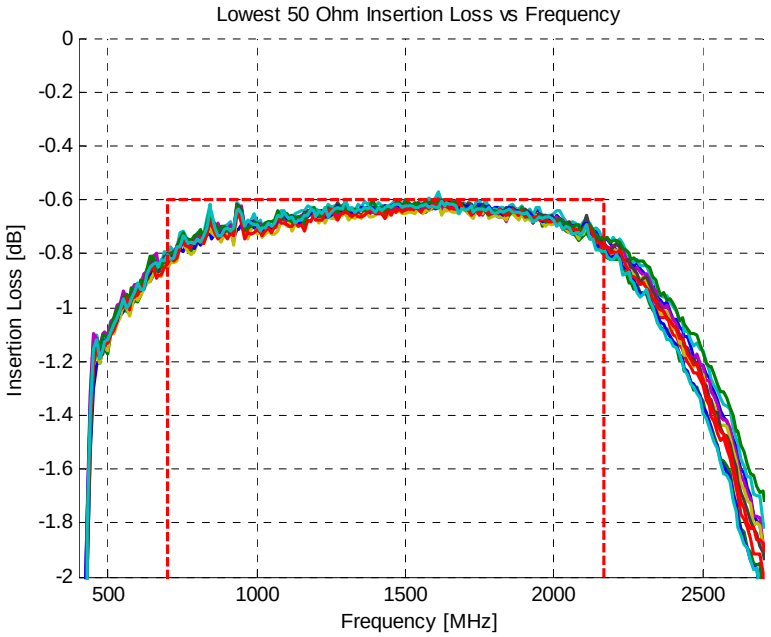


- **Wide Coverage over Multi-band (800-2200 MHz)**
- **Low Loss (Complete Product 0.3 dB)**

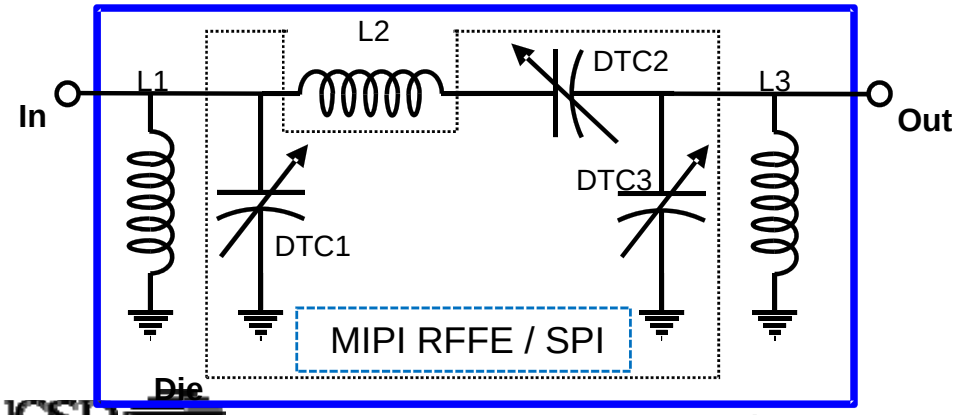
3.5mm x 4.2mm x 1.1mm

Peregrine RFFE Tuner Prototype 4x4 mm SOS/SOI is the competition





Module



Target Specification

Load VSWR	Average Improvement
1:1	-0.6 dB
2.5:1	0 dB
5:1	1.0 dB
8:1	2.0 dB
12:1	3.0 dB

Wireless Factoids & Tuning

- **Verizon Wireless has >110M Subs**
  - Plans in 2012 to require all phones to be LTE-capable
- **LTE is being deployed more rapidly than any previous technology**
- **Strategy Analytics forecasts 67M 4G Phones in 2012**
- **ABI forecasts 148M LTE phones in 2014**
  - LTE antennas require active tuning elements to meet specs
  - Current, non-tuned 4G phones fall short of spec requirements
- **A single Tier-1 OEM placed orders for >10M tuners in 2011**
  - Same OEM forecast demand for tuners is >45Mu in 2012
  - **Will have tuners in "all smart phones" by 2014**

Smart Mobile Platform Market

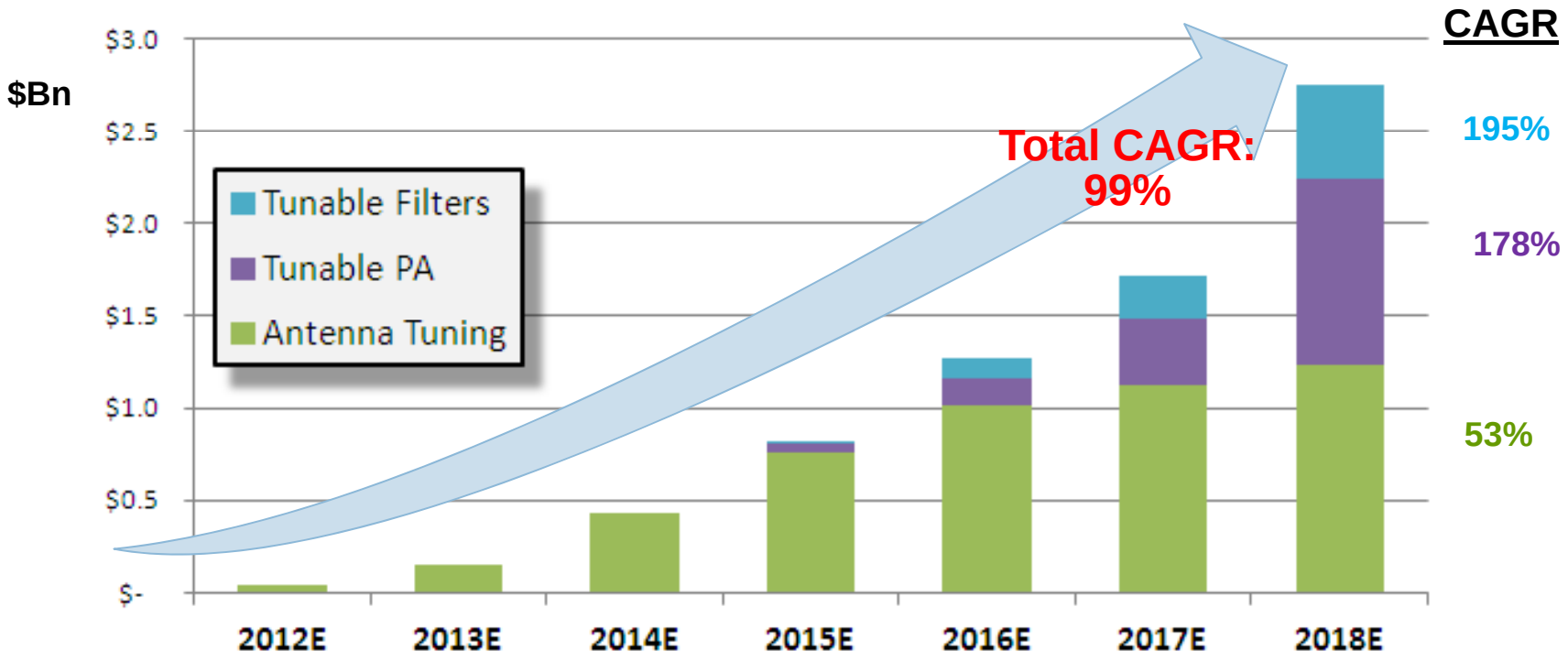
SMP units(M)	2009A	2010A	2011E	2012E	2013E	2014E	2015E	2016E
Apple	*25.1*	*47.5*	*86.4*	*125.0*	*145.0*	*175.0*	*215.0*	*250.0*
Samsung	*6.0*	*24.0*	*67.0*	*95.0*	*115.0*	*150.0*	*205.0*	*230.0*
HTC	*12.0*	*25.0*	*49.7*	*65.0*	*80.0*	*100.0*	*125.0*	*135.0*
Nokia	*68.0*	*100.1*	*74.4*	*75.0*	*78.0*	*85.0*	*95.0*	*100.0*
RIM	*34.5*	*48.8*	*55.7*	*60.0*	*65.0*	*70.0*	*80.0*	*85.0*
LGE	*5.0*	*7.0*	*24.5*	*30.0*	*38.0*	*45.0*	*55.0*	*60.0*
Huawei	*1.0*	*3.2*	*18.7*	*25.0*	*35.0*	*45.0*	*60.0*	*65.0*
ZTE	*1.0*	*3.3*	*14.2*	*22.0*	*30.0*	*40.0*	*55.0*	*65.0*
Sony-Eric'n	*7.0*	*10.0*	*19.5*	*23.0*	*30.0*	*35.0*	*55.0*	*60.0*
Motorola	*8.0*	*14.0*	*20.5*	*24.0*	*28.0*	*32.0*	*40.0*	*45.0*
Others		*12.0*	*31.6*	*18.0*	*10.0*	*8.0*	*7.0*	*5.0*
Total (Mu)	*167.6*	*294.9*	*462.2*	*562*	*654*	***785***	*992*	*1100*

Source: iSupply, Telecom Research, industry conversations

Sandisk: "1Bn by 2014"

- **Ordered by estimated 2014 SMP shipment rankings**
- **Reflects industry transition to SMP platform**
- **Bulk of other handset shipments will be Ultra Low Cost**

RF Tunable Components
Market Opportunity as it Grows

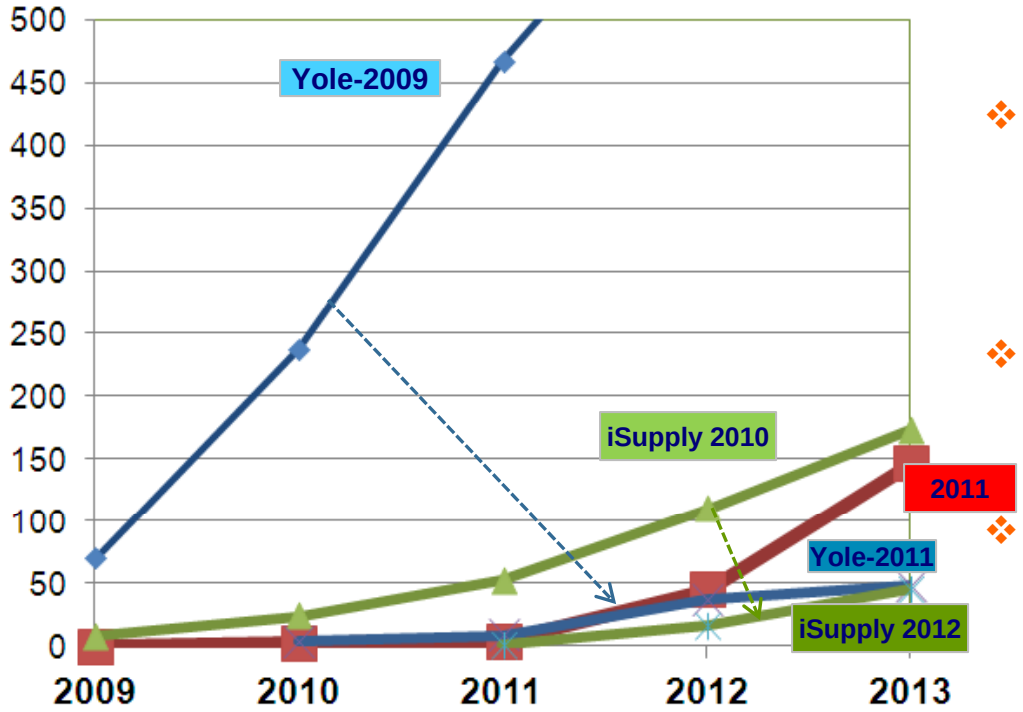


- Total opportunity grows at nearly 100% CAGR over 7 years
- SMP only – excludes tablets, laptops, MTM, 60GHz
- Adoption supply-limited through 2013, then grows quickly

New Market With Explosive Growth Opportunities due to Data demand

After years of forecasting high growth, analysts have become skeptical

Total Tuning Components in Mobile Devices

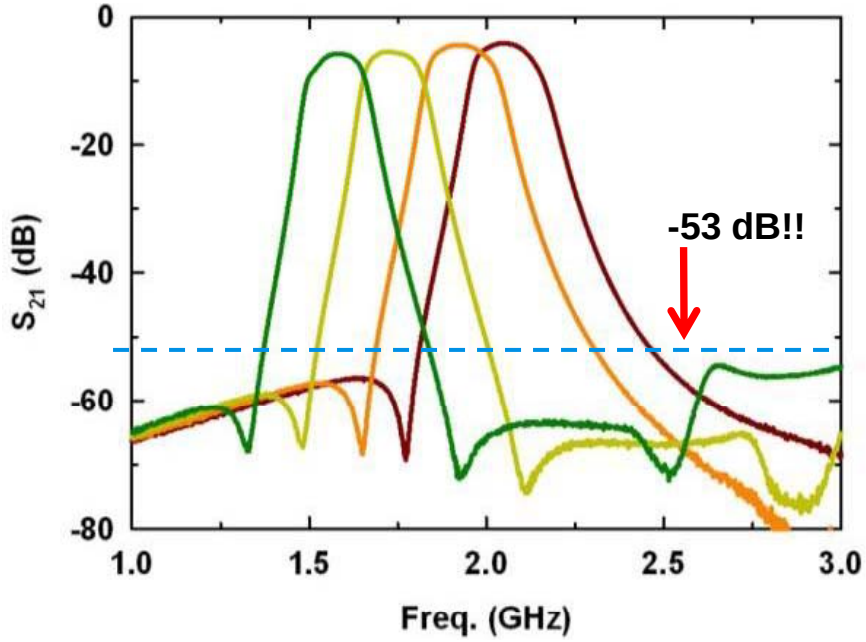


Forecast comparison

- Yole-2011 forecast is below actual shipments in 2011 and orders placed for 2012!!!
- iSupply forecasting slower growth than 4G adoption rate
- **2011 forecast** based on tuning products availability and adoption plans at Tier 1 smart phone makers

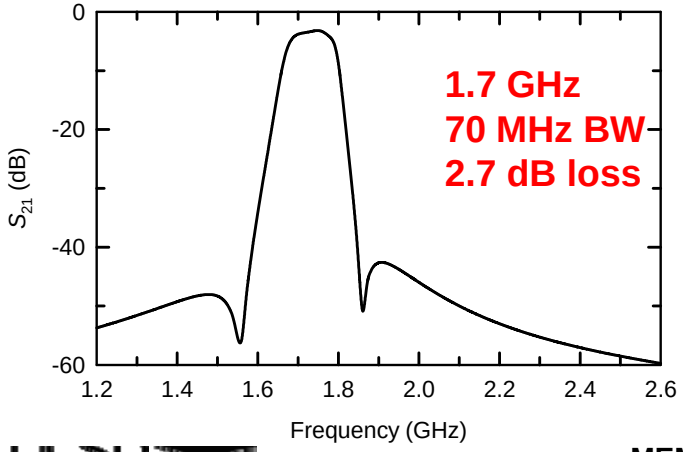
•Analysts have over-corrected after delayed start of RF Tuning. Why?
•Hard to predict because supply is so limited (wiSpry, CK)
•Market WILL TAKE OFF when supply meets demand (2013, 2014)
•In 2014, every smart phone will have tuning!!

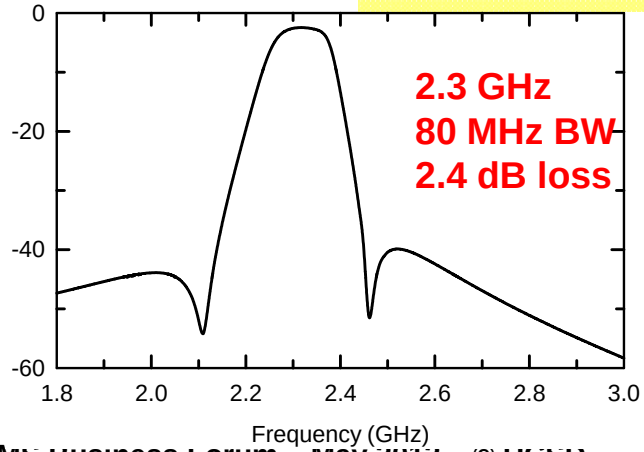
Tunable Filters Using RF MEMS (UCSD)



8x7 mm (for now)
4x5 mm (in the future)

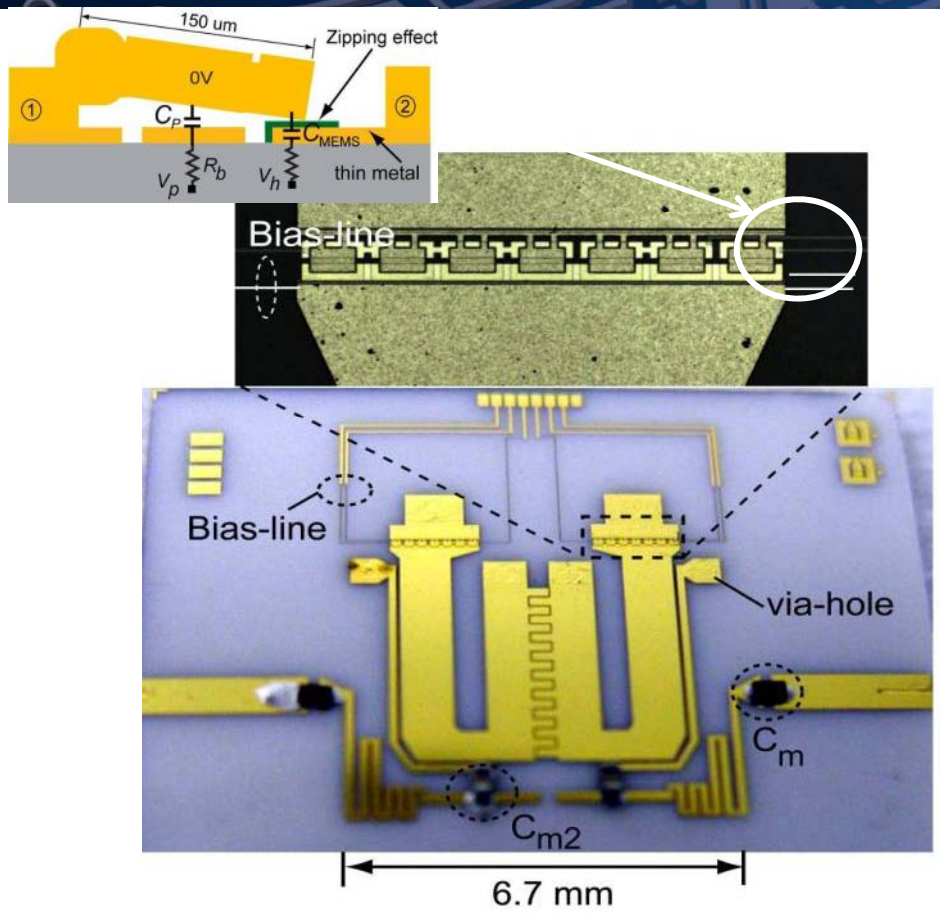
- Tunable frequency and bandwidth
- Two zeroes which track the filter
- Excellent IL and isolation for Q=220

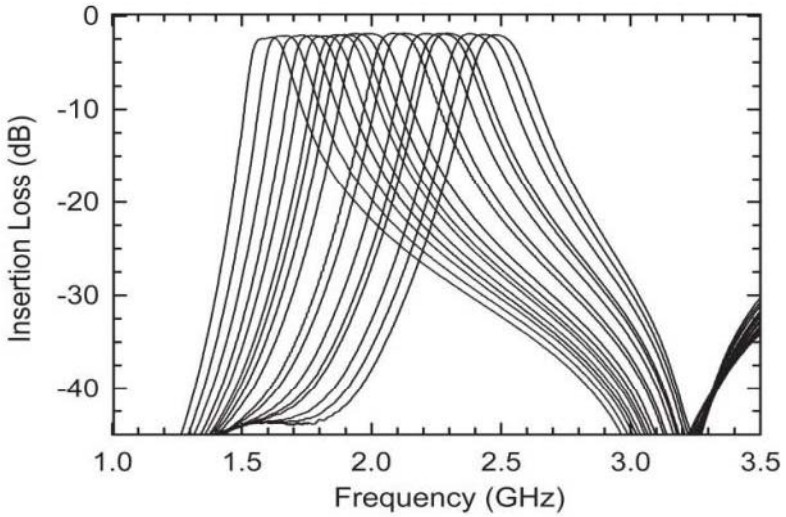


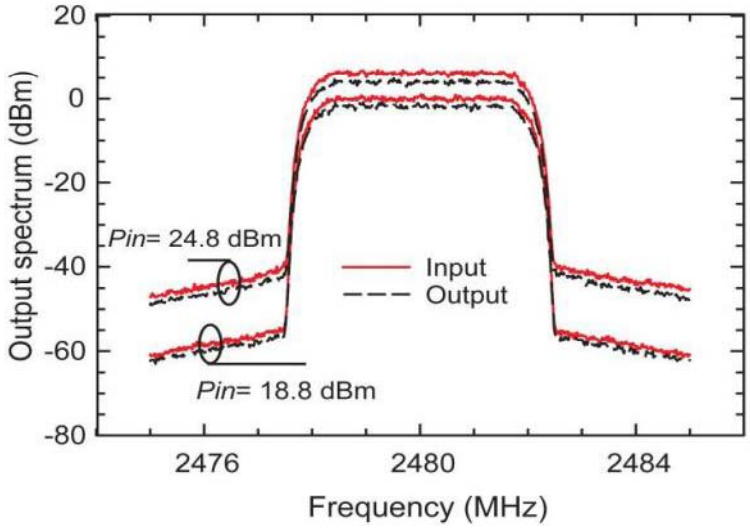


- Flat group delay
- < -45 dB spurious resp.
- < 3 dB IL
- Can be designed to cover 1.5-3 GHz

Reconfigurable RF MEMS Filters







- **1.55-2.51 GHz frequency tuning**
- **115 +/-10 MHz and < 2.2 dB Ins. Loss**
- **No distortion for CDMA signals**

Tunable 1.5 - 2.5 GHz Filter using RF MEMS

RF MEMS In Cell Phones

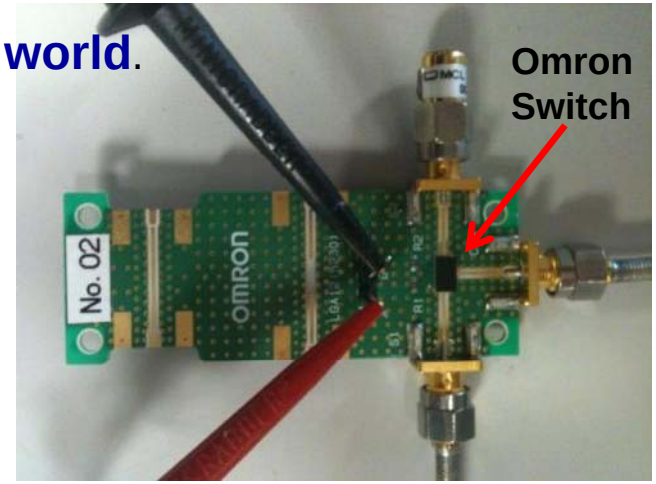
- Cost, cost, cost…cell phones are sensitive to 3-5 cent price differential. Cost must be low: 20-25 cents for a tunable capacitor.
- Size, size, size…size must be very small (for cost and for use inside PA modules and inside antennas).
- INSERTION AREAS:
  - Frequency tunable antennas (MEMS inside the antenna)
  - Matching networks between antennas
  - High efficiency multi-band power amplifiers
  - Tunable notch filters (Q is king, size is king)
  - Tunable bandpass filters (long term..not now).
- I believe that TUNABLE ANTENNAS will dominate in 2013 and 2014, followed by tunable power amplifiers, followed by notch filters, followed by bandpass filters (if any).

Other Application of RF MEMS

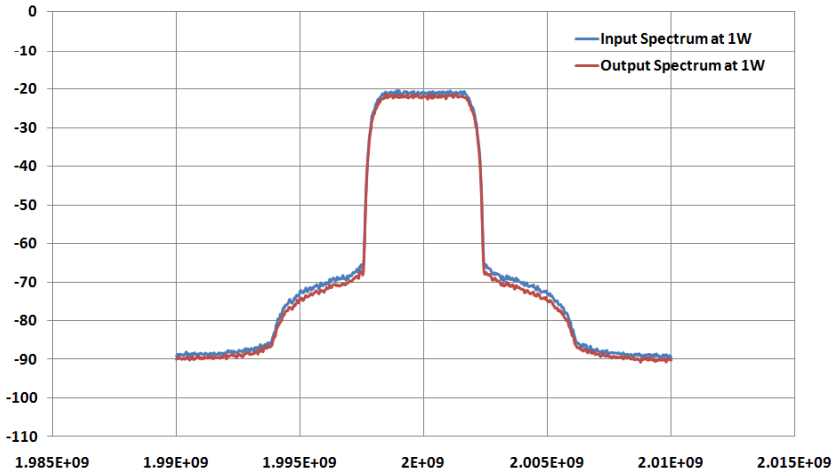
- Cell-Phone BASE STATIONS: We need to increase the data traffic by 1000x in 2020 to handle the 4G cell phone use!!
- This can only be done by multiple-beam antennas and reconfigurable base-stations → *RF MEMS provides the linearity, power handling and low-loss requirements for base-stations.*
- Instrumentation: Hand-held spectrum analyzers, network analyzers, wideband cognitive radios, etc.
- Defense and SATCOM: wideband radios, NxM switch matrices, reconfigurable LNAs and PAs, etc.
- ATE: Automated test equipment, switching matrices, etc.

Characterization of Omron Switches

- **Amazing switch: BEST RF MEMS Switch in the world.**
- **10 W cold switching up to 1+B cycles**
- **300 mW hot switching up to 100+M cycles**
- **10 W continuous power handling for 1+week**
- **IP3>73 dBm. IP2 >120 dBm (limited by test setup)**

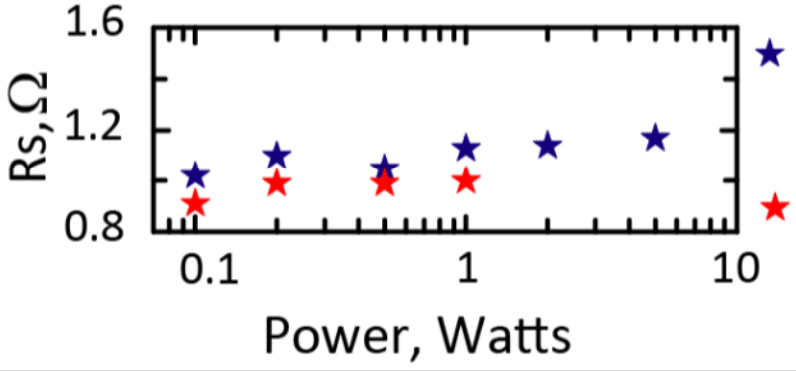


Great for base-station antennas



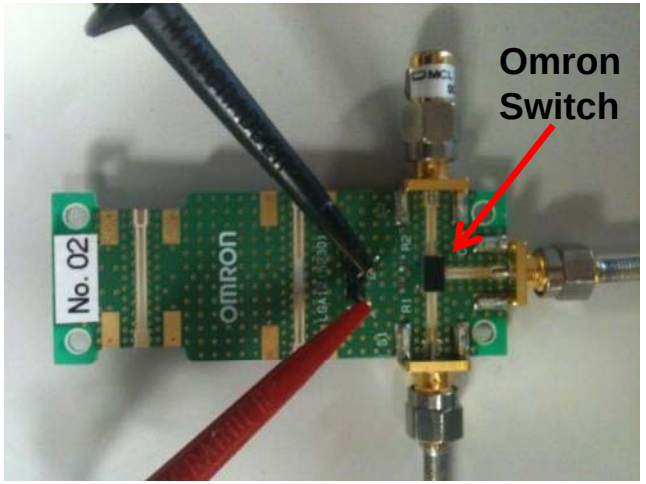
Input and output spectrum under 1 W WCDMA at 2 GHz (peak to average ratio of 4)

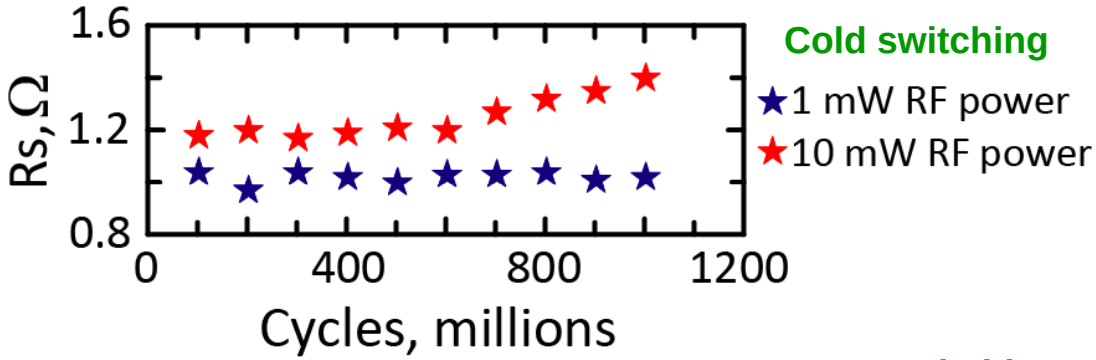
Characterization of Omron Switches

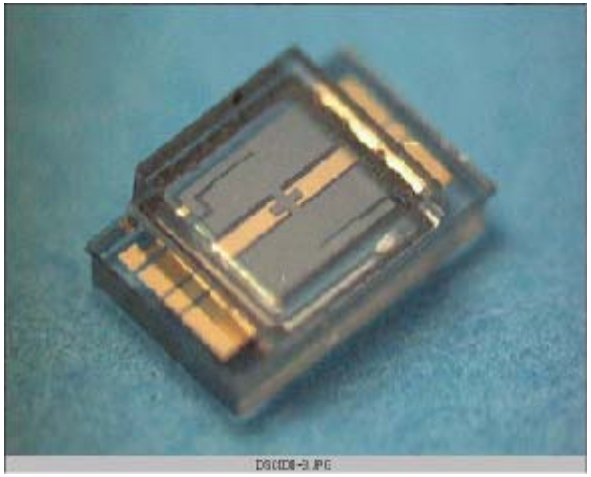


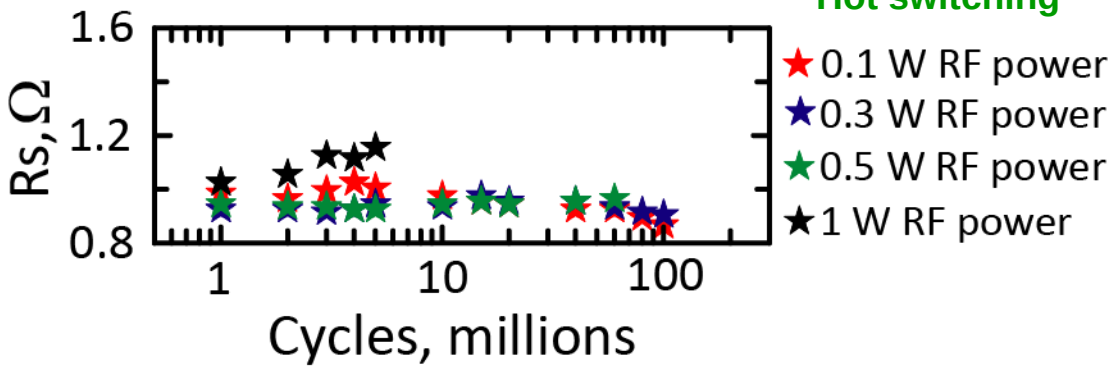
100M cycles cold switched

24 hour hold-down

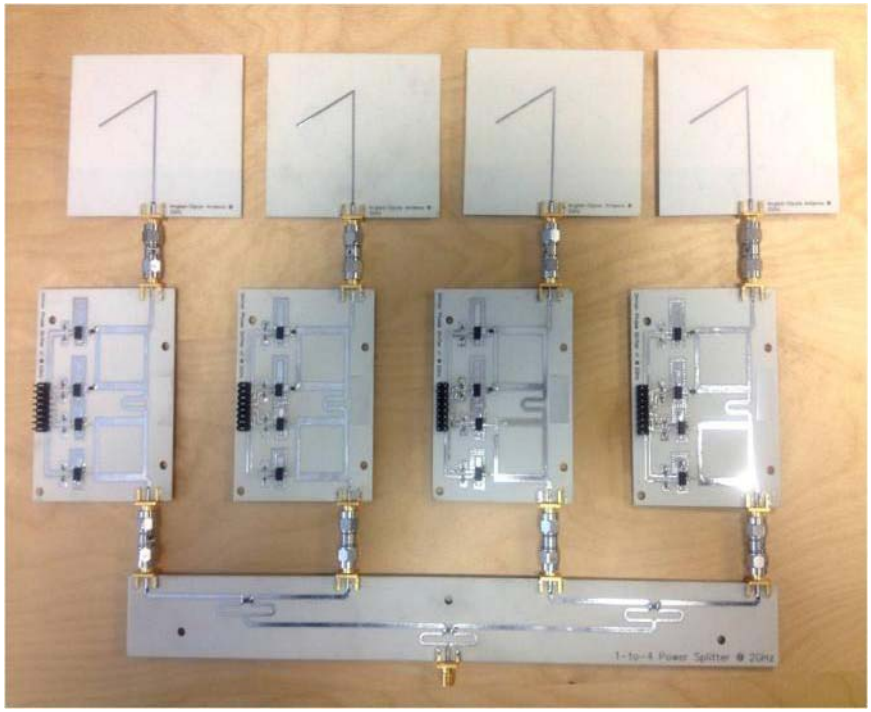




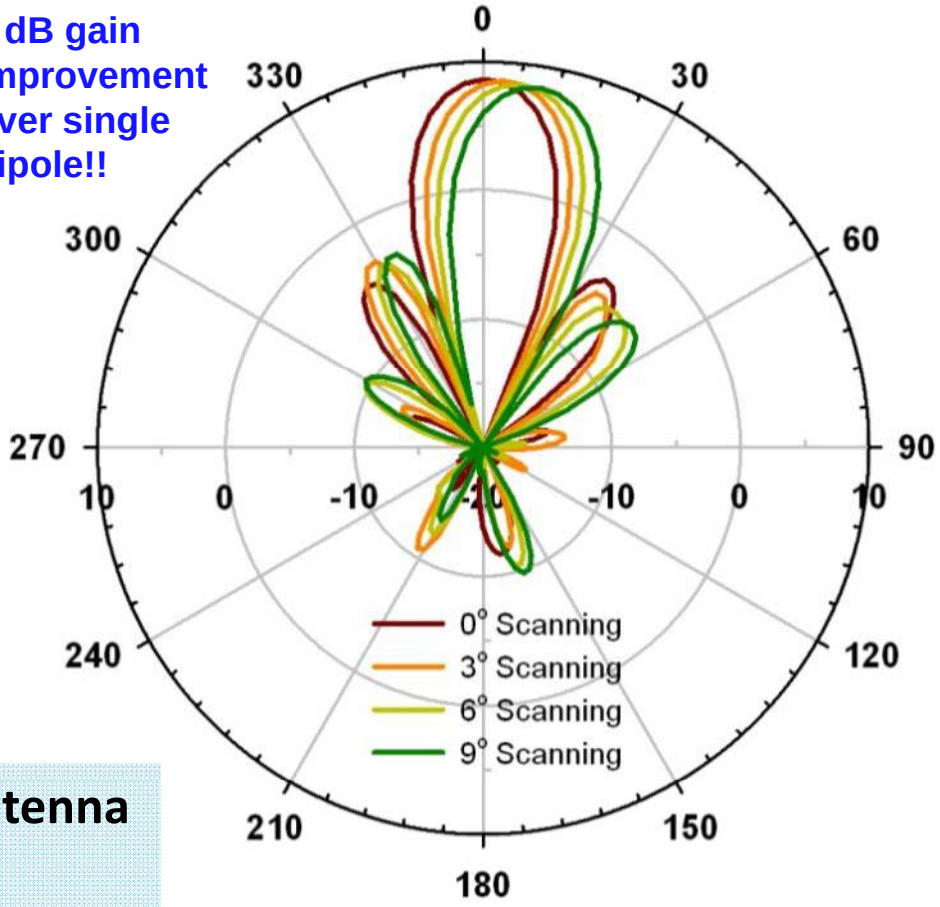




4-Element Phased Array at 1.8-2.1 GHz



5 dB gain improvement over single dipole!!



- First completely passive base-station antenna
- Beam scanning to 12 degrees
- < 1 dB total antenna loss
- Power handling capabilities: 10 W
- Excellent for Micro and Pico LTE Stations

Gain: 8.6- 8.3 dBi over all scan angles

Conclusion

- RF MEMS tunable capacitors can reach the > 500M quantity per year for cell phones, but only if their cost is low, their size is small, and these continue on a down-ward trend. THIS IS POSSIBLE USING CMOS+RF MEMS.
- wiSpry and Cavendish Kinetics lead in the cell phone market.
- Omron leads in the commercial market (ATE, base-stations, etc.)
- Competition is SoS and SOI switches and tuners, but RF MEMS is 5-10x better, and will eventually dominate when the supply meets the demand.
- By 2014, all smart phones will have tuners.