SAND2013-5820C

Exceptional service in the national interest

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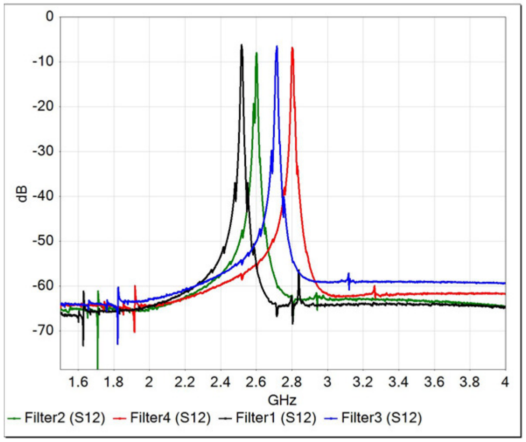
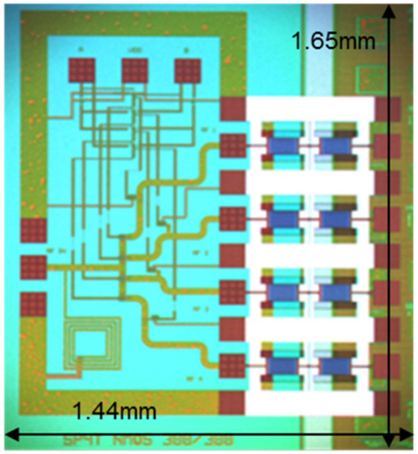
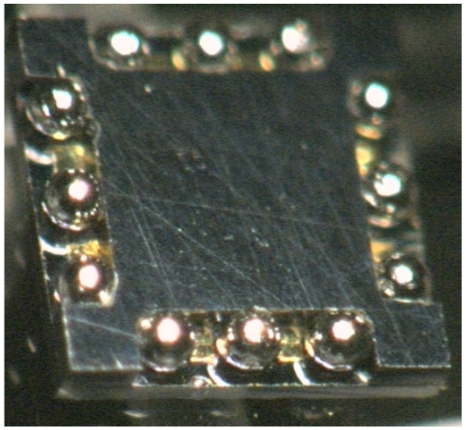






Piezoelectric Microresonators for Advanced RF Devices and Sensors

Roy H. Olsson III, Ken Wojciechowski, Chris Nordquist, Ben Griffin and David Henry

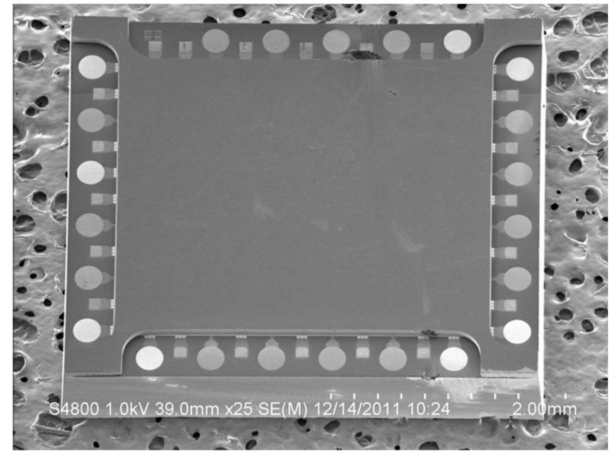
U.S. DEPARTMENT OF ENERGY

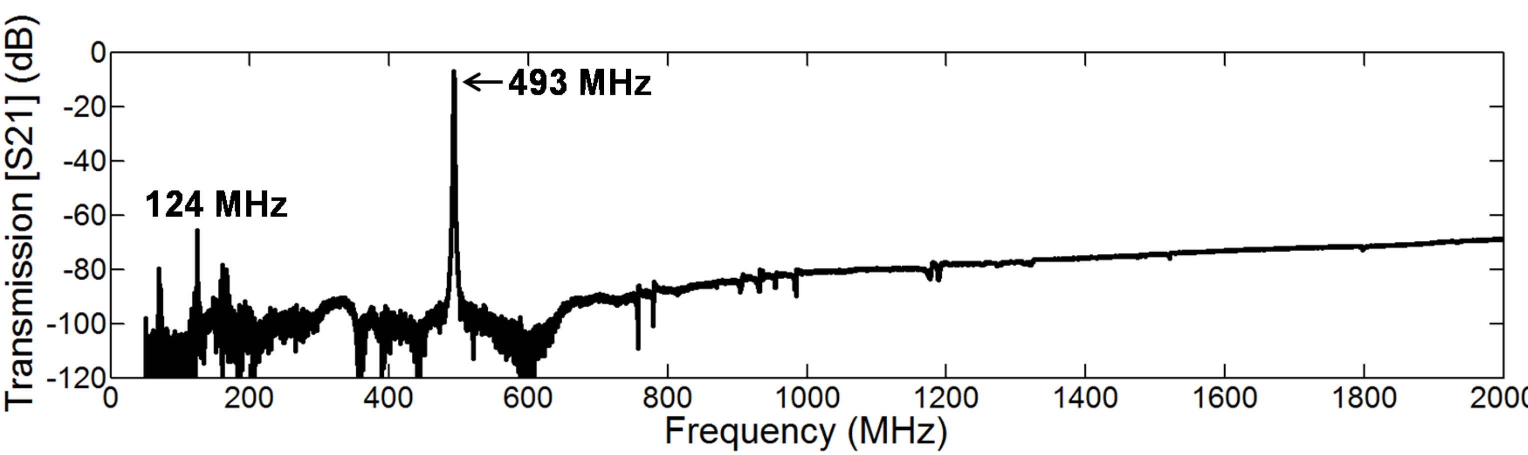
NNSA National Nuclear Security Administration

Outline

- ➢ *Microresonator Filters*
  - Background and Motivation
  - Device Fabrication
  - Device Examples
- ➢ *Microresoantor Oscillators*
  - Device Example
- ➢ *AlN Sensors*
  - Device Example

IF Filter Die Containing 4 Filters



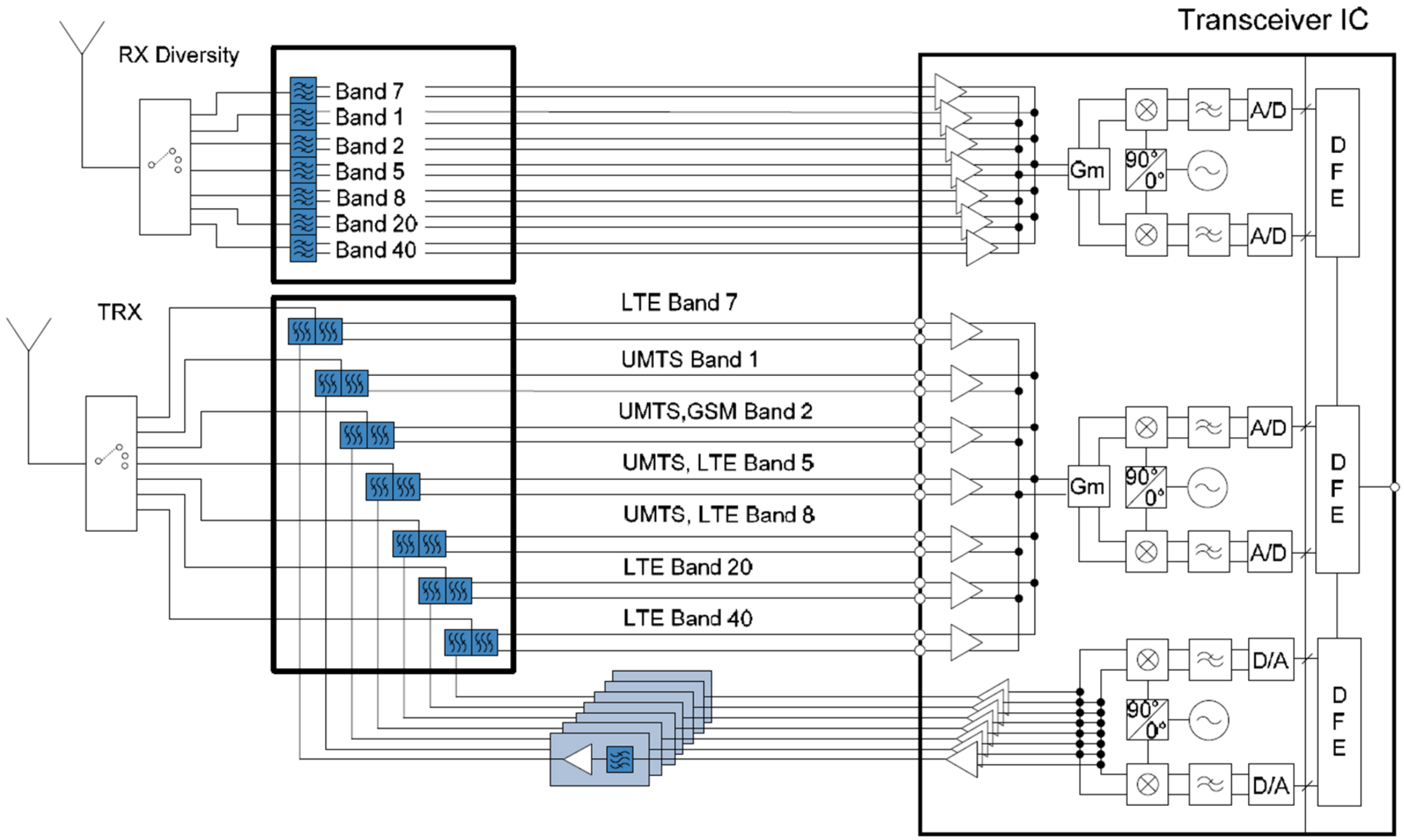


Measurement of an AlN Micromechancial Filter

Filter Arrays for Handsets

- Diagram Contains 28 Filters Operating in ~ 7 Bands
- Microresonator Technology Can Potentially Address Many of These Filters on a Single Chip, Reducing Size and Assembly Costs

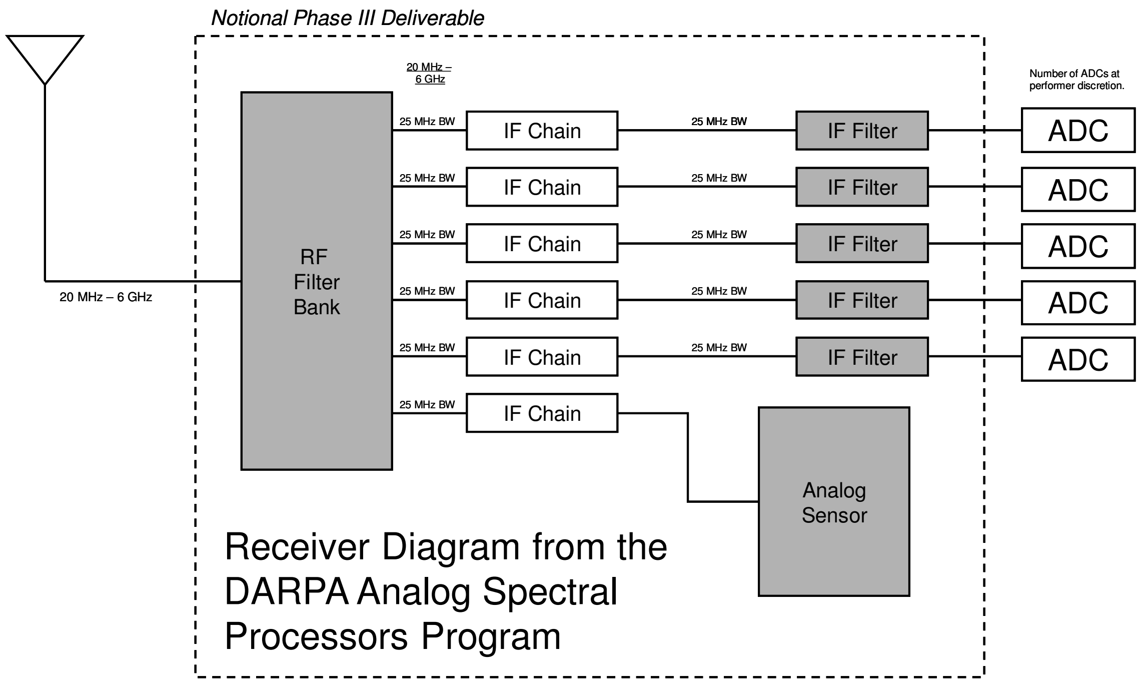
R. Vazny et al. "Front-End Implications to Multi-Standard Cellular Radios: State-of-the-Art and Future Trends", *Proc. Of the 2010 IEEE Ultrasonics Symposium, pp. 95 – 98, Oct. 2010*



RF Front-End of a Modern Cellular Radio

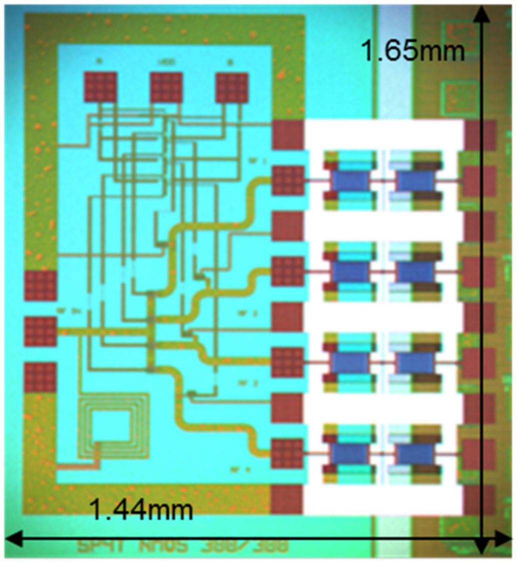
Filters in Military Radios

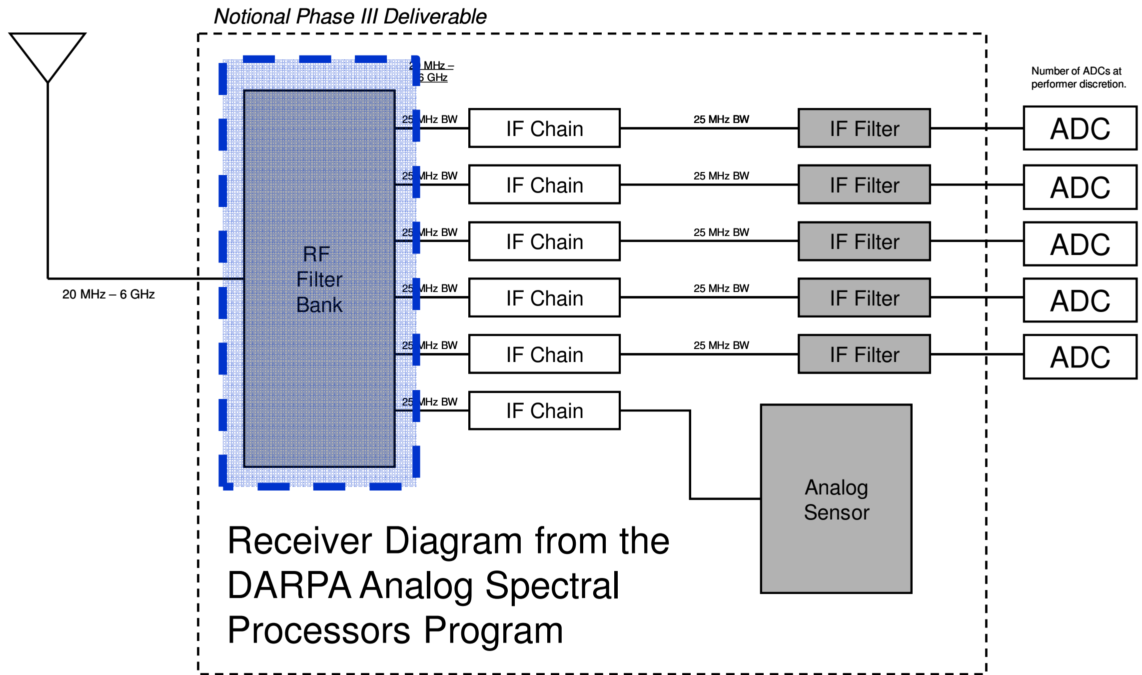
- Current Military Radios Are Mandated to be Backwards Compatible
  - *Legacy and Updated Frequencies and Waveforms*
    - *Many RF Frequencies and Bandwidths Required*
- Future Military Radios Will Require Spectral Knowledge and Real Time Adaptability to Mitigate Both Co-Site and Adversary Jamming

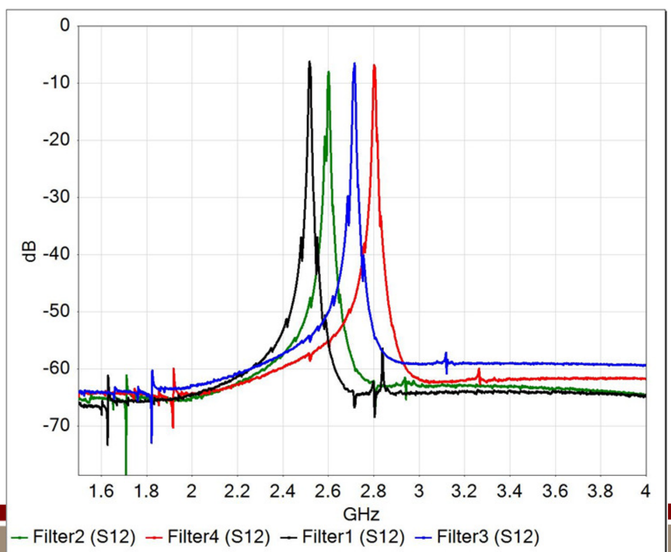


Receiver Diagram from the DARPA Analog Spectral Processors Program

Frequency Adaptability on the RF Front-End



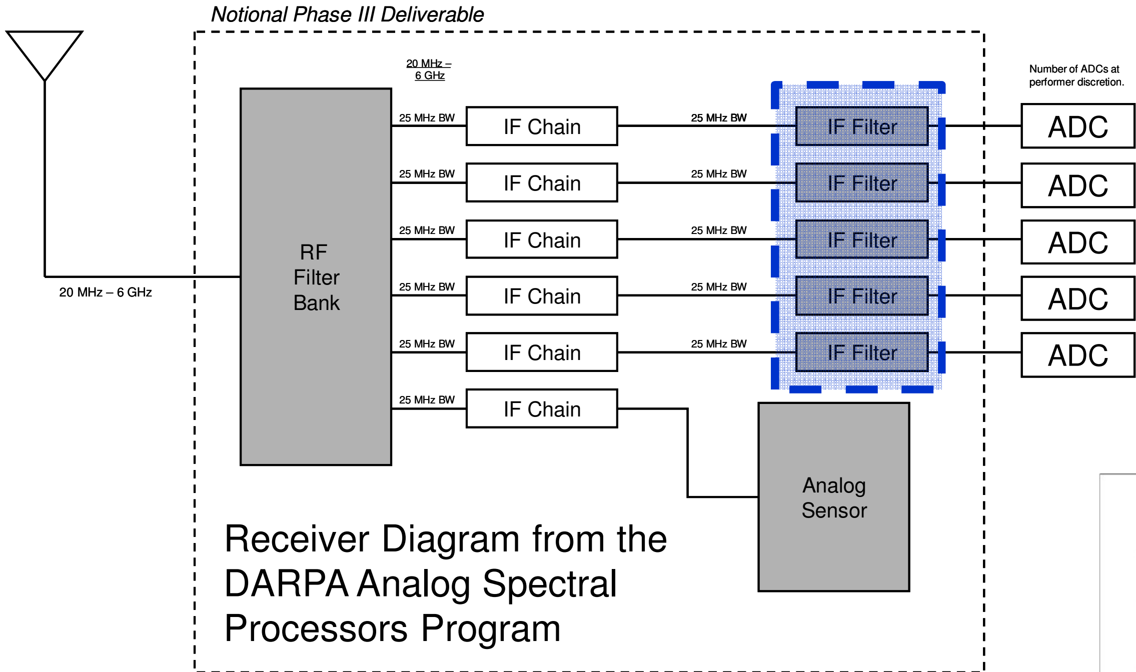




S-Band Switched Filter Array on CMOS for RF Center Frequency Adaptability

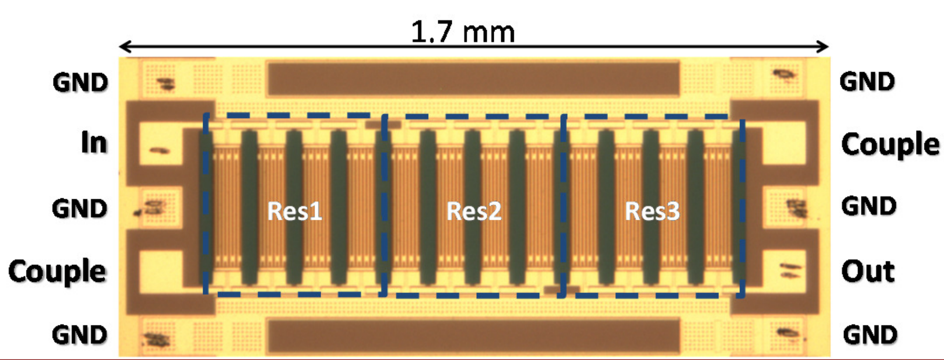
E. R. Crespin, R. H. Olsson III, K. E. Wojciechowski, D. W. Branch, P. Clews, R. Hurley and J. Gutierrez, "Fully Integrated Switchable Filter Banks," *IEEE International Microwave Symposium,* pp. 1-3, June 2012.

Waveform and Bandwidth Adaptability IF Filtering

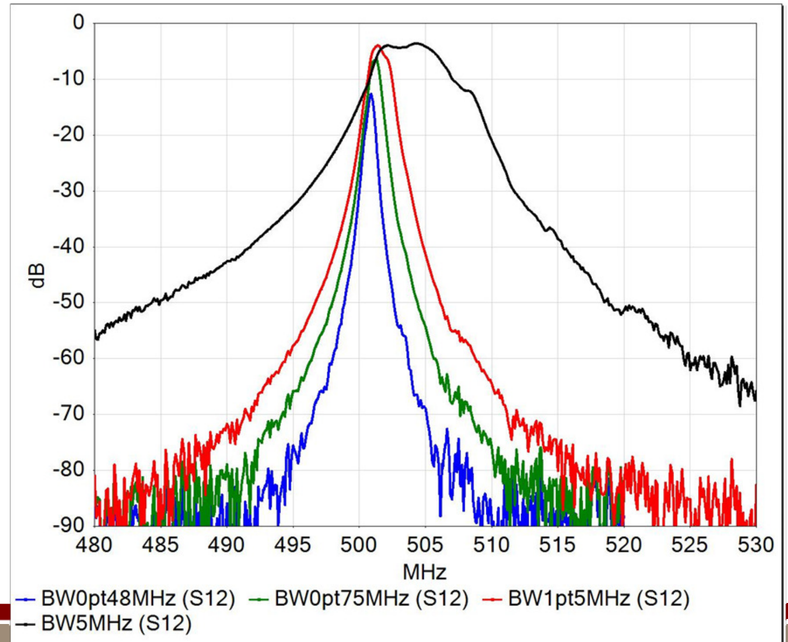


Receiver Diagram from the DARPA Analog Spectral Processors Program

R. H. Olsson III, J. Nguyen and T. Pluym, “A Programmable Bandwidth Aluminum Nitride Microresonator Filter,” *Govt. Microcircuit App. and Critical Tech. Conf.*, March 2013.



IF Filter with Programmable Bandwidth from 5.1 MHz to 0.48 MHz



RF Spectral Awareness

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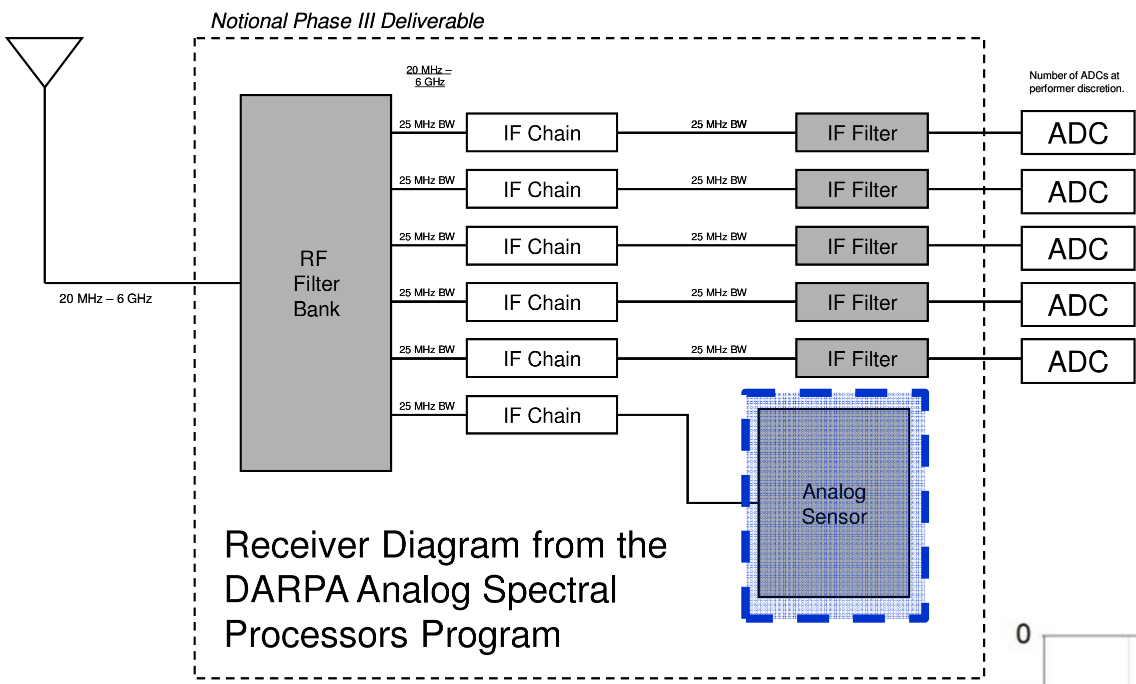
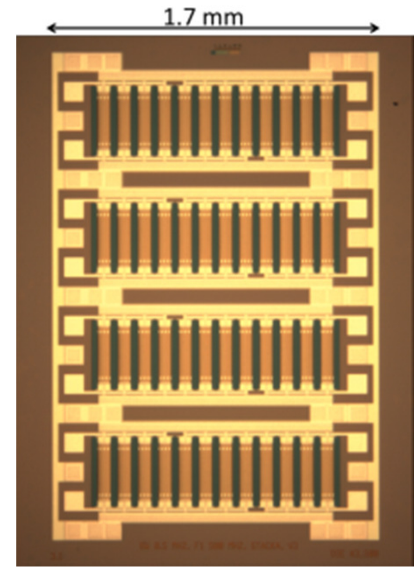
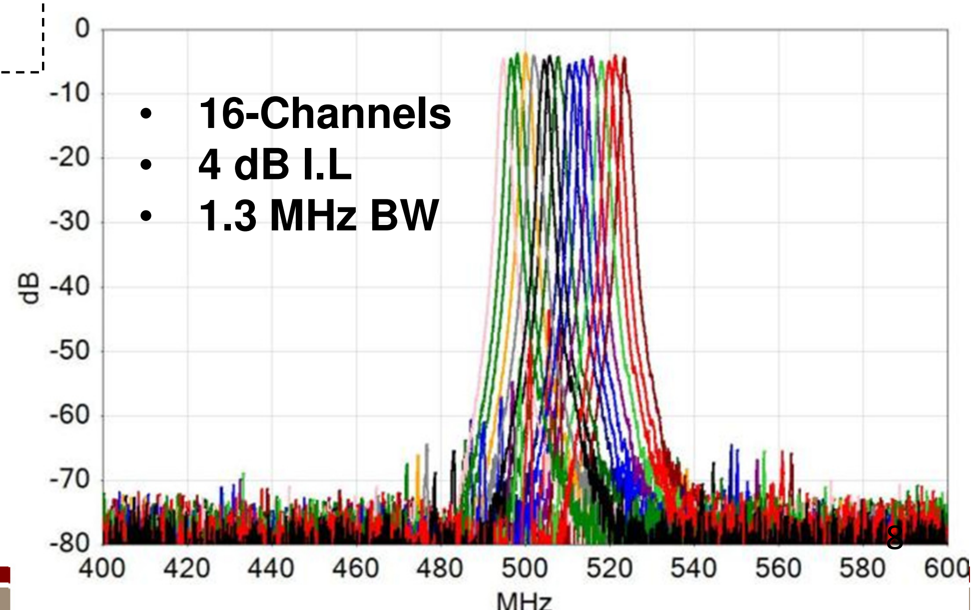


Receiver Diagram from the DARPA Analog Spectral Processors Program



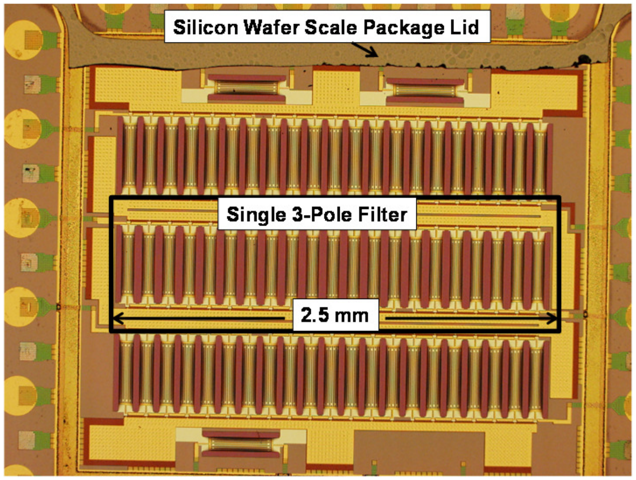


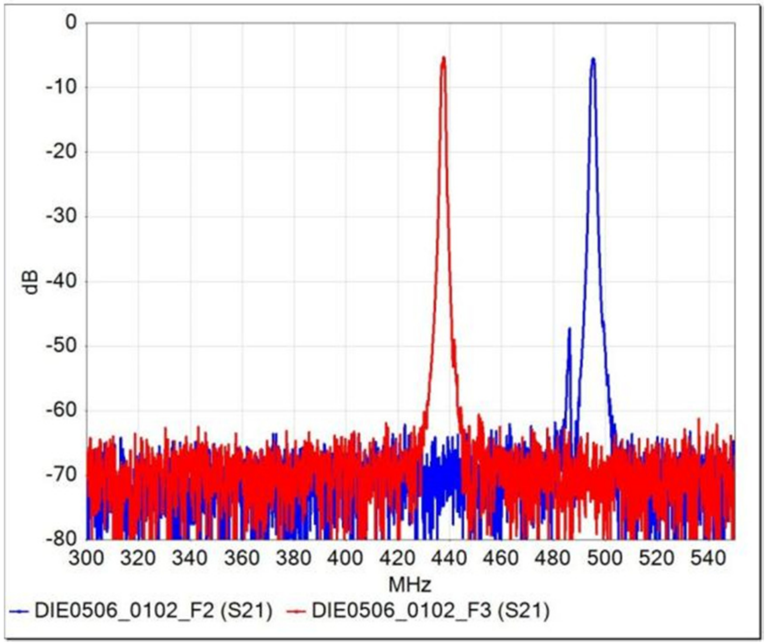
16-Channel Filter Array for RF Spectral Sensing

Microresonator Technology

Microresonators are miniature, high quality factor acoustic resonators that:

- *Are mass produced using CMOS IC fabrication techniques*
- *Are lithographically defined, allowing any resonant frequency between 32 kHz and 14 GHz on a single chip*
- *Are an enabling filter technology for multi-band and cognitive radios*
- *Can be integrated with CMOS transistors for configurability and added signal processing*
- *Can be Engineered with High Thermal Isolation for Low Power Ovenization*

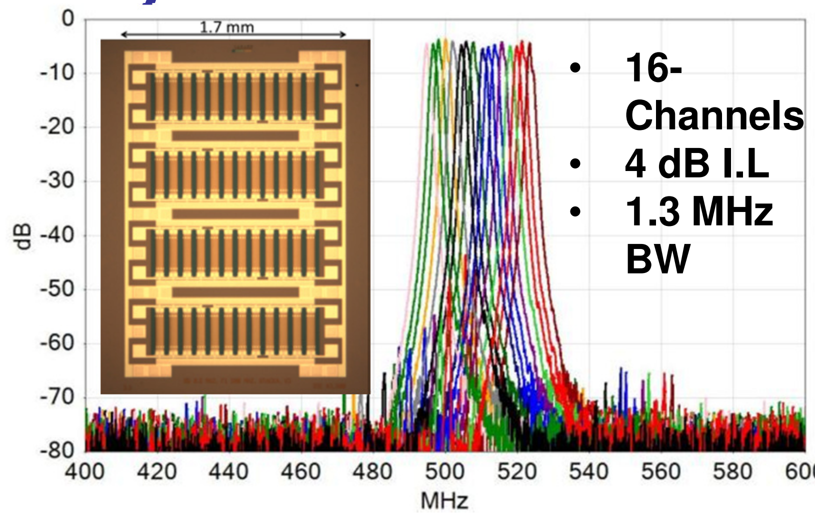


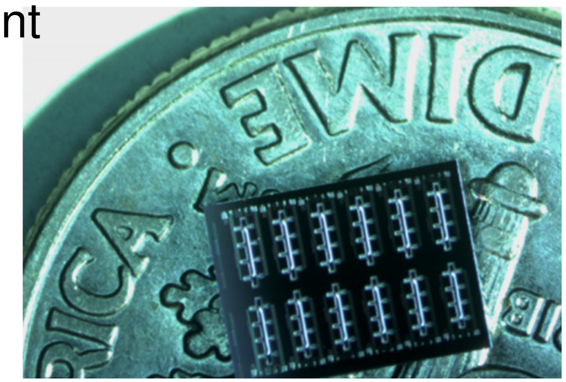


1.7 MHz 3 dB Bandwidth AlN Filters in a Wafer Level Package

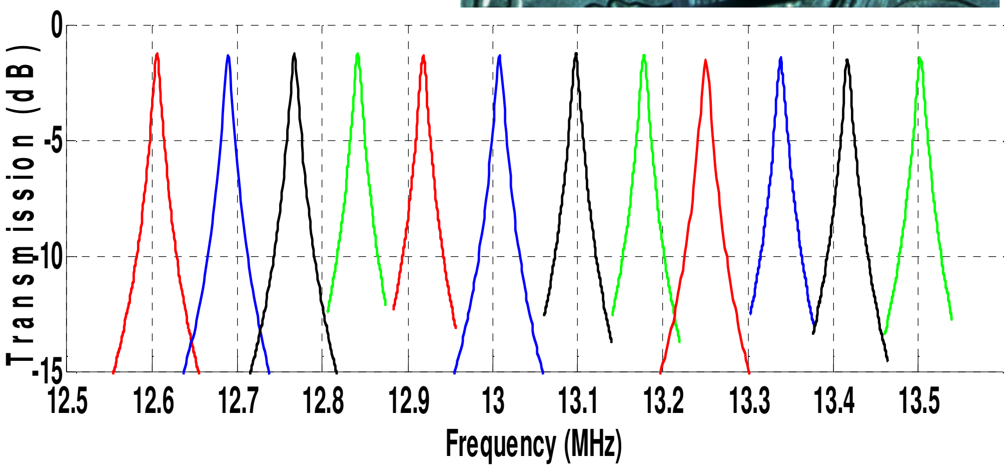
Microresonator Filter Arrays

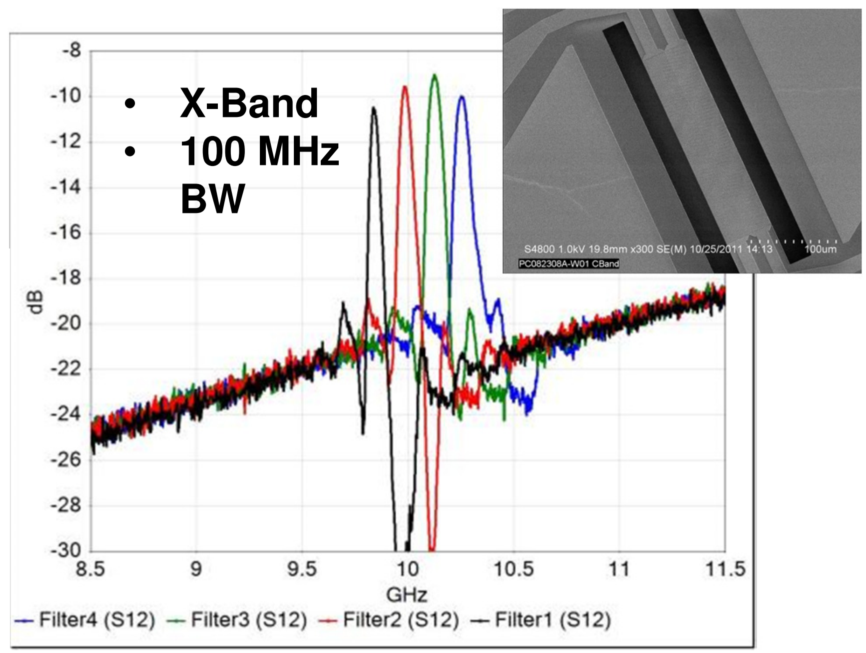
- Filter Banks for Cognitive and Multi-Band Radios
- Anti-Jam and Secure Adaptive RF Front-Ends
- Filter Arrays for Fast Spectrum Analysis
- Ultra Small Footprint
- HF to X Band!





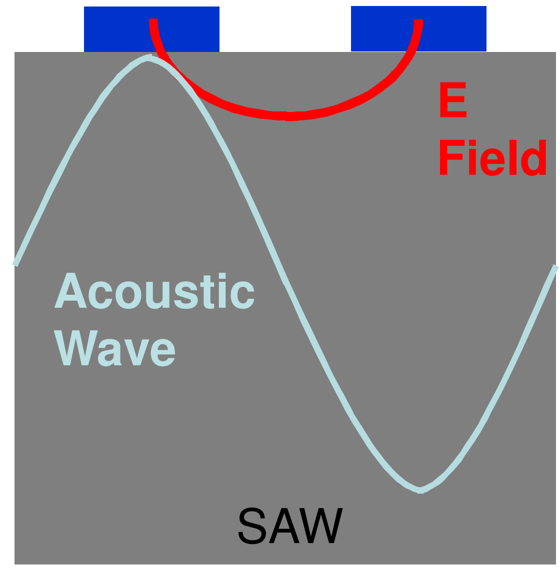
- **HF-Band**
- **25 kHz BW**
- **12-Channels**

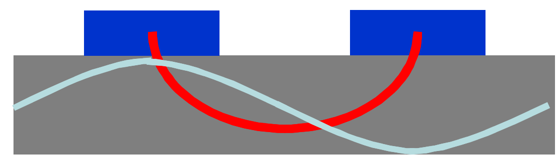


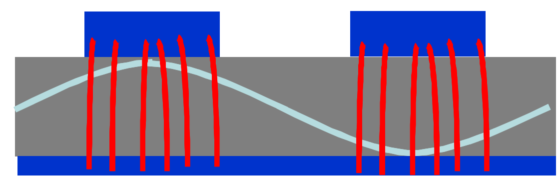


Why Micromachining for Acoustic Resonators

- Acoustic isolation from the substrate via undercut and etched sidewalls
  - ❑ ***Many frequencies on a single chip***
  - ❑ ***Higher Q-factor***
  - ❑ ***Lower loss***
  - ❑ ***Vastly Smaller size***
  - ❑ ***Closely packed filters***
  - ❑ ***Thermal isolation for ovenization***
- Increased interaction of the acoustic wave and electric field
  - ❑ ***Higher coupling coefficient***
  - ❑ ***Lower loss***
  - ❑ ***Wider bandwidth***
  - ❑ ***Higher tuning range***
- Decouple acoustic wavelength and transduction gap
  - ❑ ***Vastly Smaller Size***
  - ❑ ***Increased Transduction***




Microresonator


Microresonator

Piezoelectric Resonator Transduction

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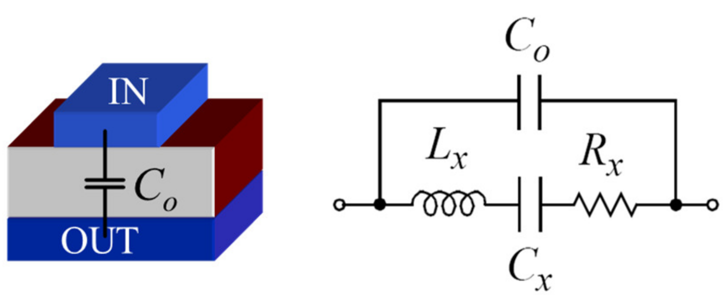
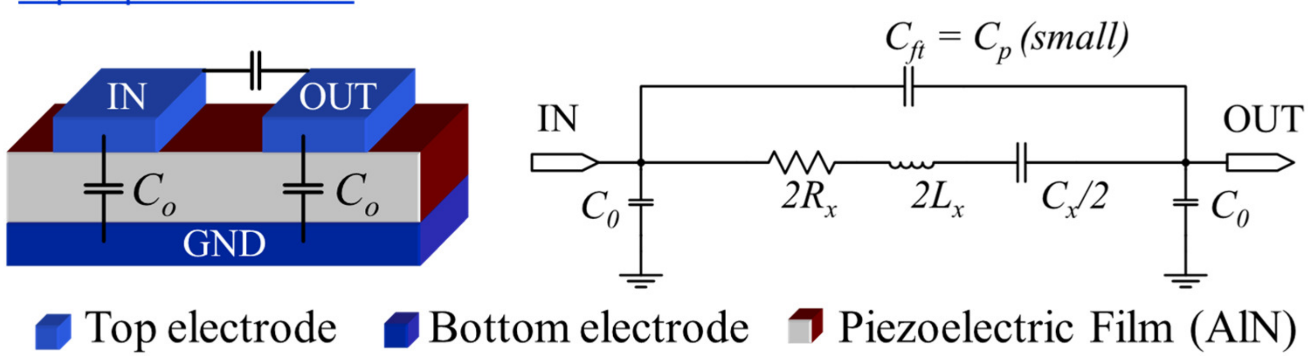
- ***Filter Loss***
  - Proportional to FOM
- ***Filter Bandwidth***
  - Minimum Practical Filter Bandwidth is Determined by Q
  - Maximum Practical Filter Bandwidth is Determined by k_t^2
- ***Maximum Tuning Range ~ k_t^2***

Top-Bottom Transduction



Top-Top Transduction



$$C_x = 0.8 k_t^2 C_0$$

$$L_x = \frac{1}{0.8\omega^2 k_t^2 C_0}$$

$$R_x = \frac{1}{0.8\omega C_0 k_t^2 Q}$$

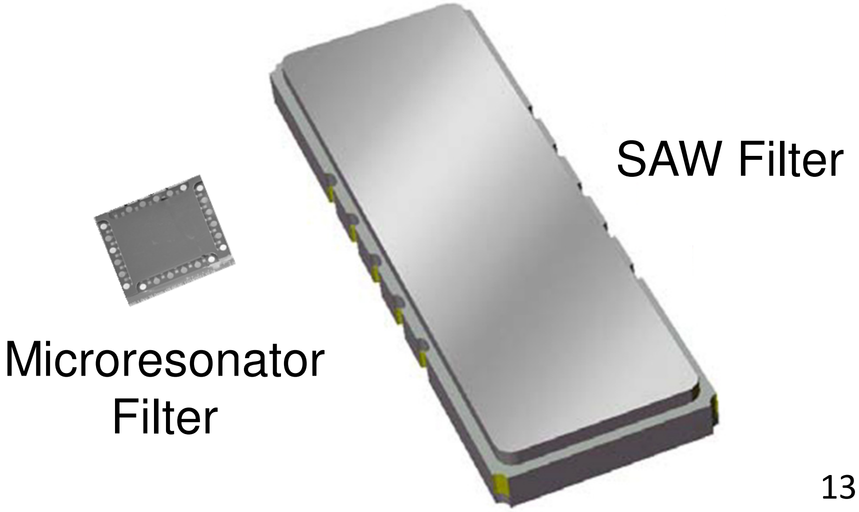
$$k_t^2 = \frac{d_{31}^2 E}{\varepsilon}$$

$$FOM = k_t^2 Q$$

Types of Acoustic Resonators (Thermally Stable For Narrow Band Filters)

Technology/ Metric	k_t^2 theory	k_t^2 experiment	Q @ ~ 1 GHz	~FOM Measured	Multiple Frequencies on a Substrate	TCF (ppm/ C)	CMOS Integration
Quartz SAW	0.16%	0.16%	10000	16	Yes	<0.1	No
Temperature Compensated AlN Microresonator	**1.3%**	**1.3%**	**2000**	**26**	**Yes**	**<0.5**	**Yes**

- *Aluminum Nitride Microresonator Has Higher Figure of Merit for Lower Loss*
- *Aluminum Nitride Microresonator Has Massively Reduced Size*
- *Aluminum Nitride Microresonator Can be Integrated With CMOS*



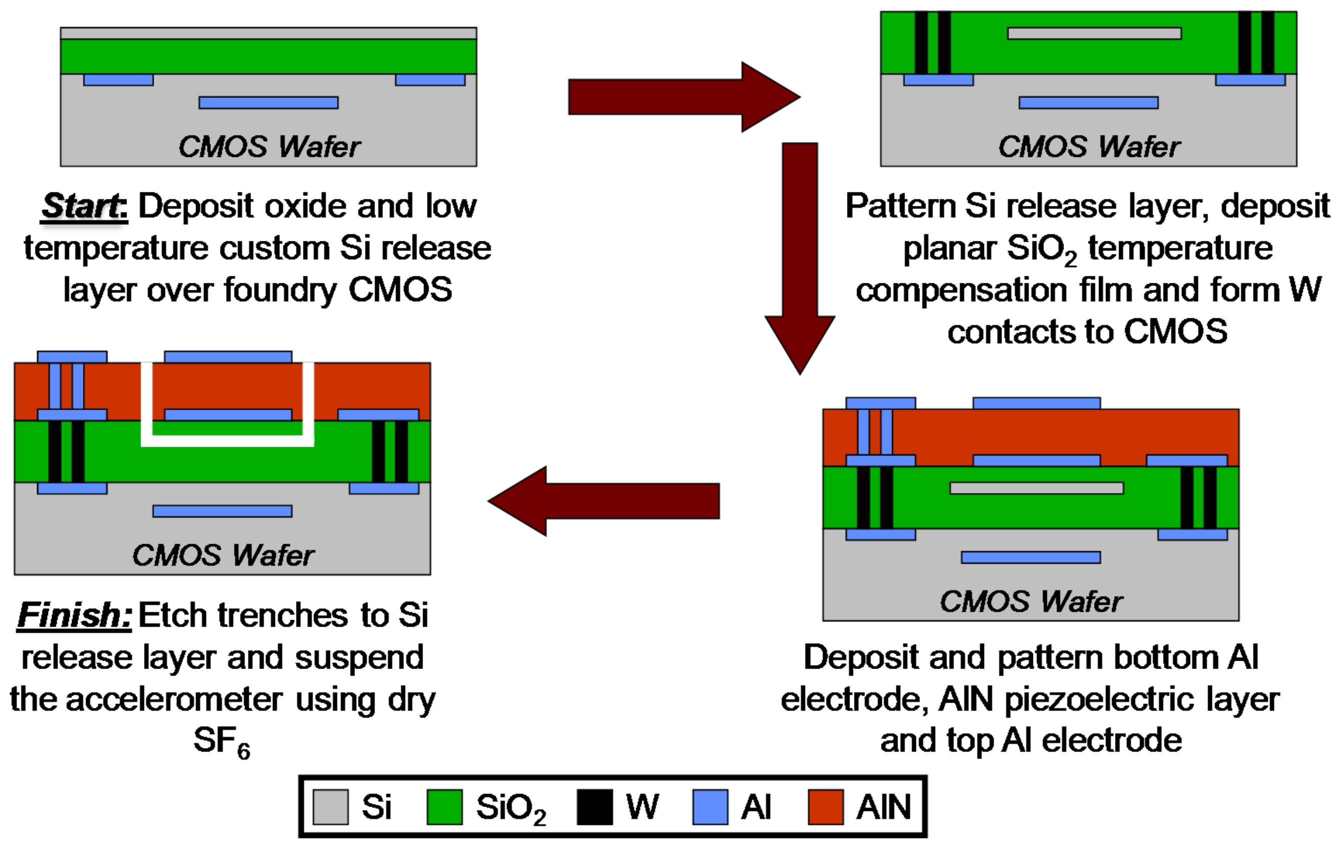
Types of Acoustic Resonators (Wideband and Low Loss RF Filters)

Technology/ Metric	k_t^2 theory	k_t^2 experiment	Q @ ~ 1 GHz	~FOM Measured	Multiple Frequencies on a Substrate	TCF (ppm/ C)	CMOS Integration
AlN BAW/FBAR	6.5%	7%	3000	200	High Cost	-30	Yes
Standard $LiNbO_3$ SAW	6.5%	6.5%	1000	65	Yes	-70	No
AlN Microresonator	**2%**	**2%**	**2000**	**40**	**Yes**	**-30**	**Yes**

- *AlN Microresonator Has Higher Lower Figure of Merit Than SAW or BAW*
- *AlN Microresonator Only For Applications*
  - **Arrays**
  - **CMOS Integration**
  - **Size**
  - **Low Frequency**

Post-CMOS AlN MEMS Fabrication

- *6-Masks*
- *Replace Poly Release Layer with 400C a-Si*
- *a-Si Thickness Limit is 600 nm*
- *CMOS Metals for RF Routing and Passives*



K. E. Wojciechowski, R. H. Olsson, T. A. Hill, M. R. Tuck and E. Roherty-Osmun, "Single-Chip Precision Oscillators Based on Multi-Frequency, High-Q Aluminum Nitride MEMS Resonators," *IEEE International Solid-State Sensors, Actuators and Microsystems Conference,* pp. 2126-2130, June, 2009.

Temperature Compensation

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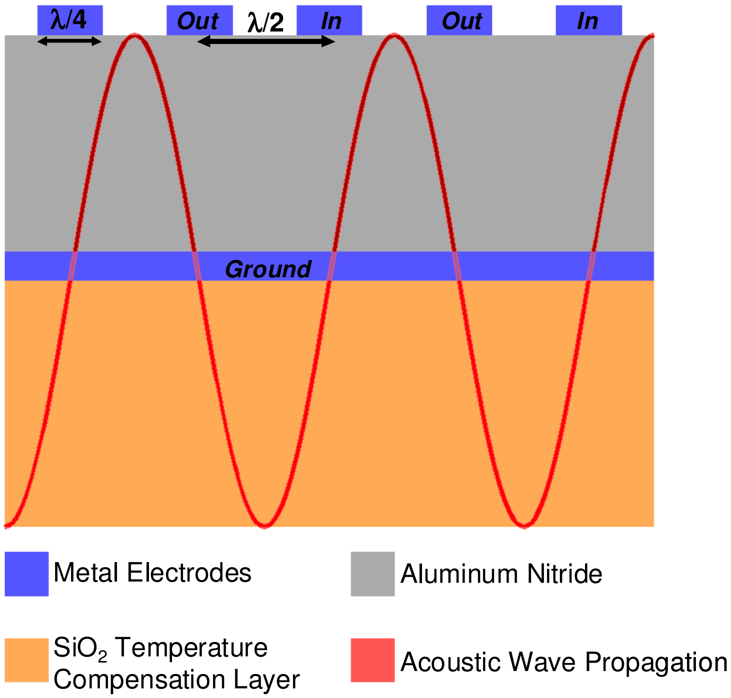
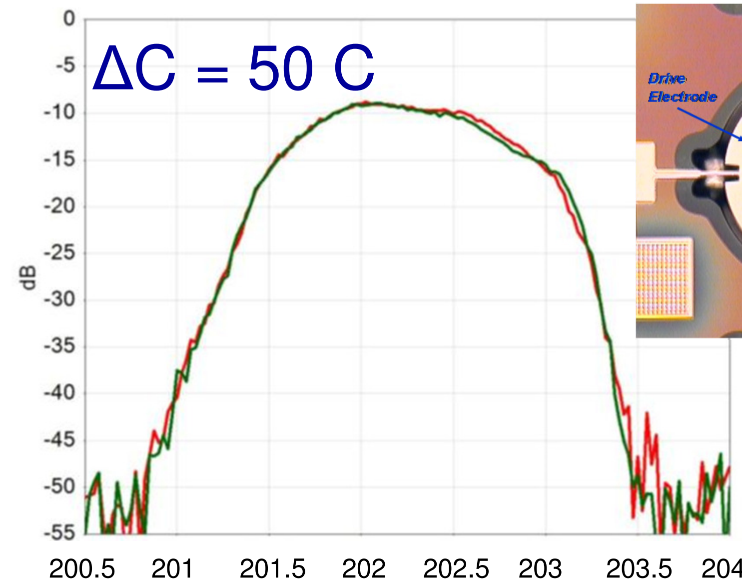
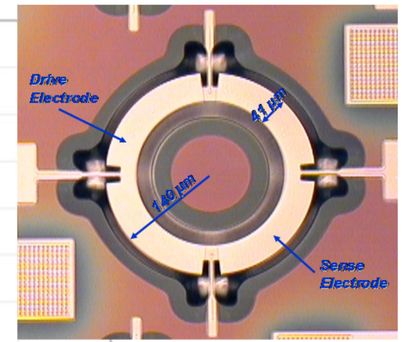


Resonator Cross-Section

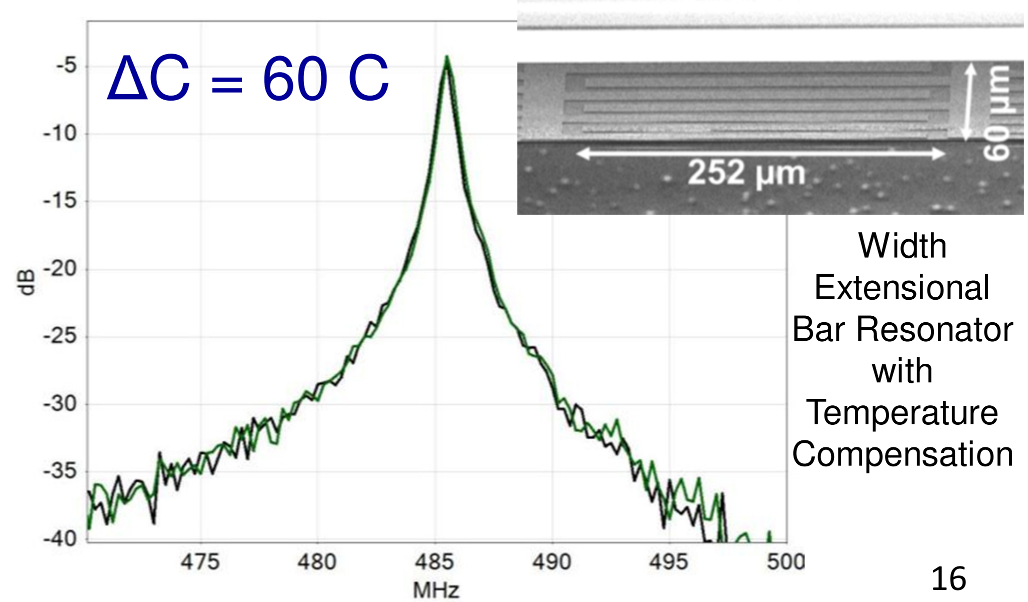
$$TCF_{AlN} \approx -33\,ppm/C$$

$$TCF_{oxide} \approx +93\,ppm/C$$





Ring Resonator Filter with Temperature Compensation



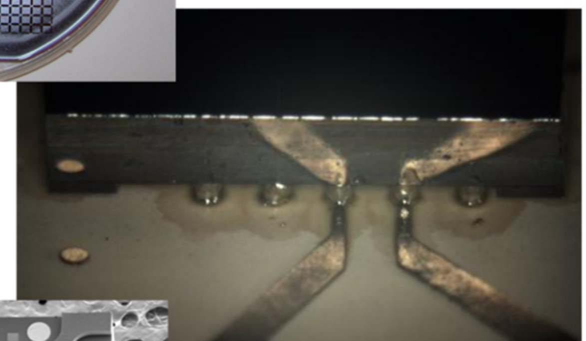
Width Extensional Bar Resonator with Temperature Compensation

R. H. Olsson III, C. M. Washburn, J. E. Stevens, M. R. Tuck and C. D. Nordquist, "VHF and UHF Mechanically Coupled Aluminum Nitride MEMS Filters," *IEEE Frequency Control Symposium*, pp. 634-639, June 2008.

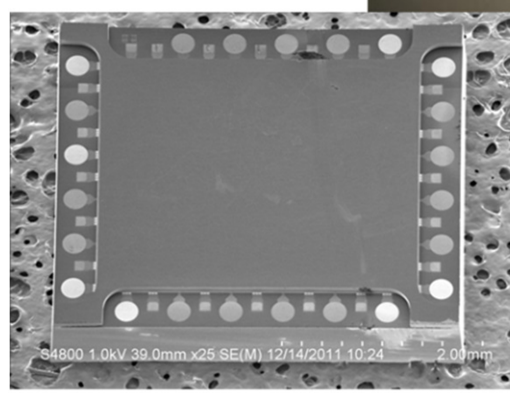
Wafer Level Packaging

- *Maintains Small Footprint*
- *Surface Mount or Chip and Wire Assembly*
- *Enables Wafer Level Release*
- *Protects MEMS During Dicing*
- *Wafer Level Auto-Probe For Part Down Select*
- *Package Pressure = 10 Torr, Lower with Getters*

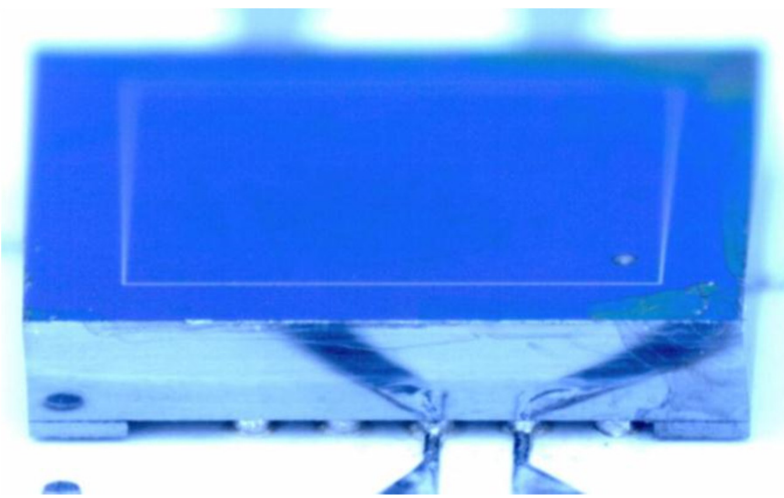
Wafer of Packaged AlN MEMS Devices



Packaged Surface Mount AlN Filter on a PCB



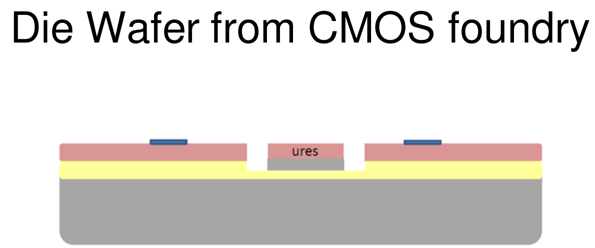
Chip and Wire AlN MEMS Die

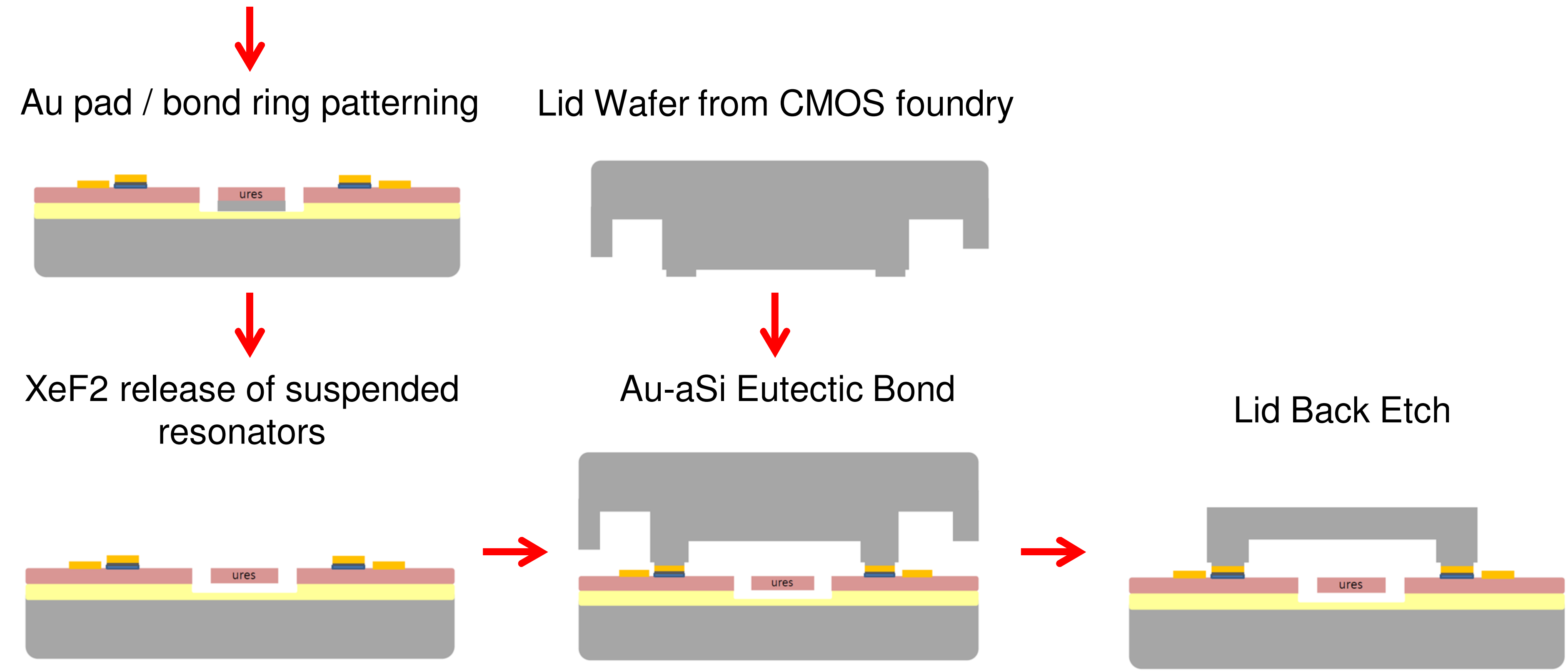


M. D. Henry, K. D. Greth, J. Nguyen, C. D. Nordquist, R. Shul, M. Wiwi, T. A. Plut and R. H. Olsson III, "Hermetic Wafer-Level Packaging for RF MEMs: Effects on Resonator Performance," *IEEE Electronic Components and Technology Conf.*, pp. 362-369, May 2012.

WLP Integration

Advantage of WLP : Release of resonators on a wafer scale, hermetic encapsulation on a wafer scale, inexpensive lid technology (silicon) .

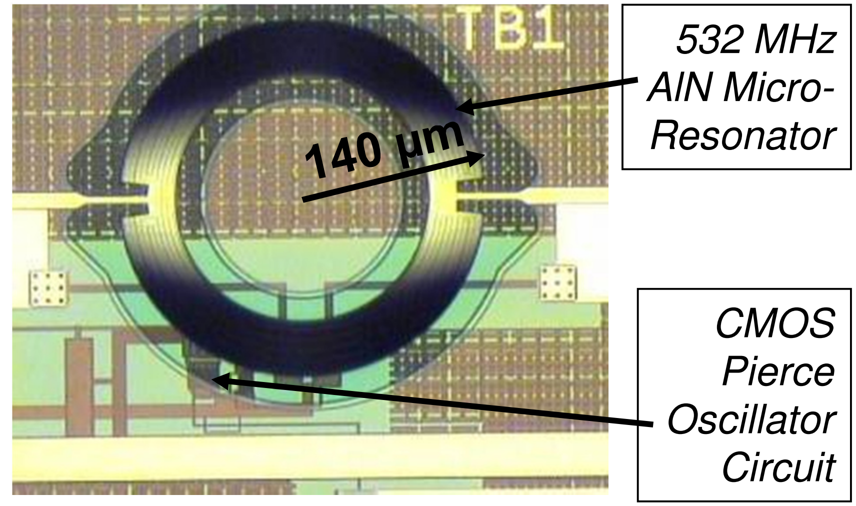




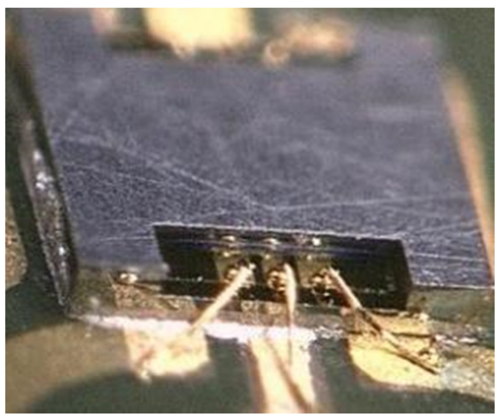
Microresonator Wafer-Level-Packaging Process Flow

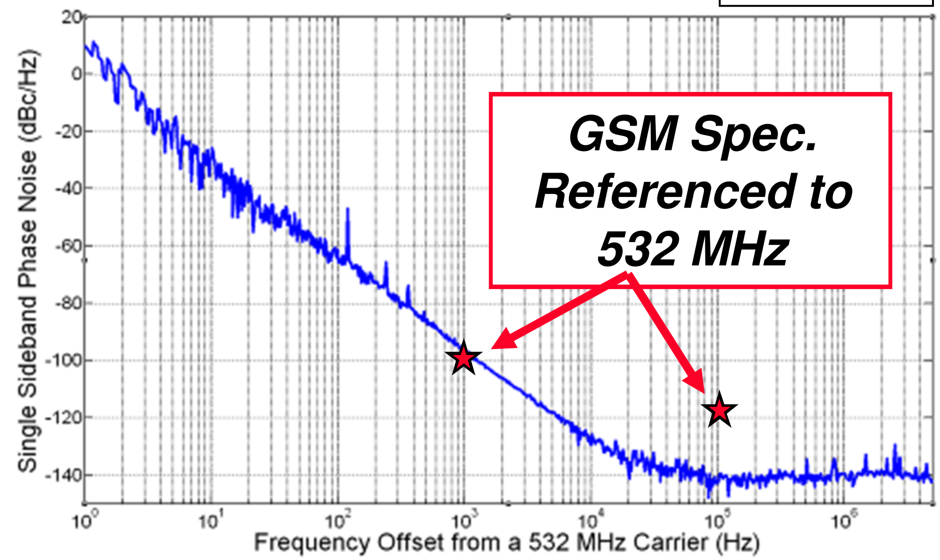
AlN MEMS Oscillators

- ➢ Overcome Thickness Limitations of Quartz Crystals
- ➢ Oscillator Synthesis Directly at RF for Reduced Power (No PLL) and Size
- ➢ Communications Grade Phase Noise Performance
- ➢ Ovenization at Ultra Low Power Levels



1.3 x 1.3 x 0.2 mm Microresonator Packaging





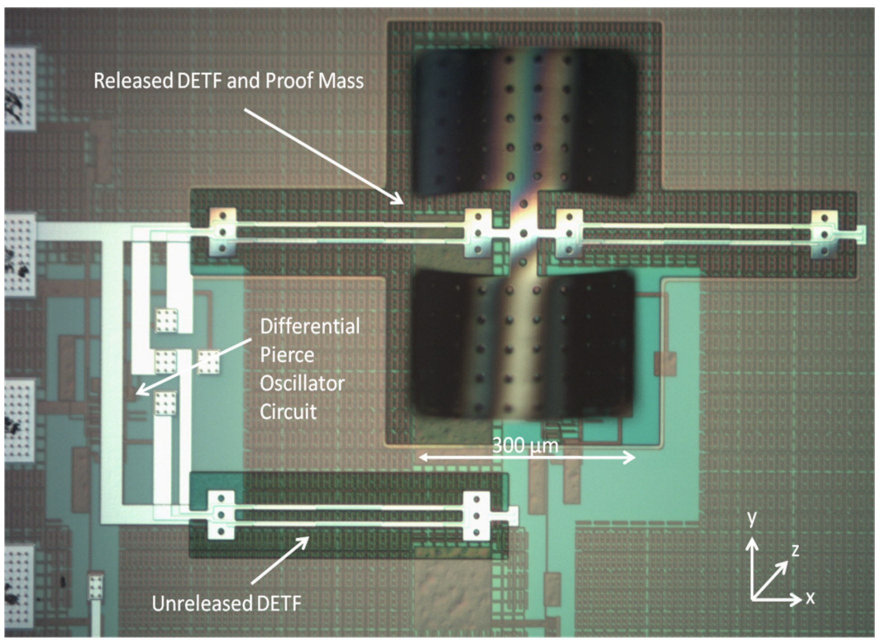
Picture and Phase Noise of a 532 MHz AlN Oscillator Integrated Directly Over CMOS

R. H. Olsson III, K. E. Wojciechowski, M. R. Tuck, J. E. Stevens and C. D. Nordquist, "Multi-Frequency Aluminum Nitride Micro-Filters for Advanced RF Communications," *Govt. Microcircuit App. and Critical Tech. Conf.*, pp. 257-260, March 2010.

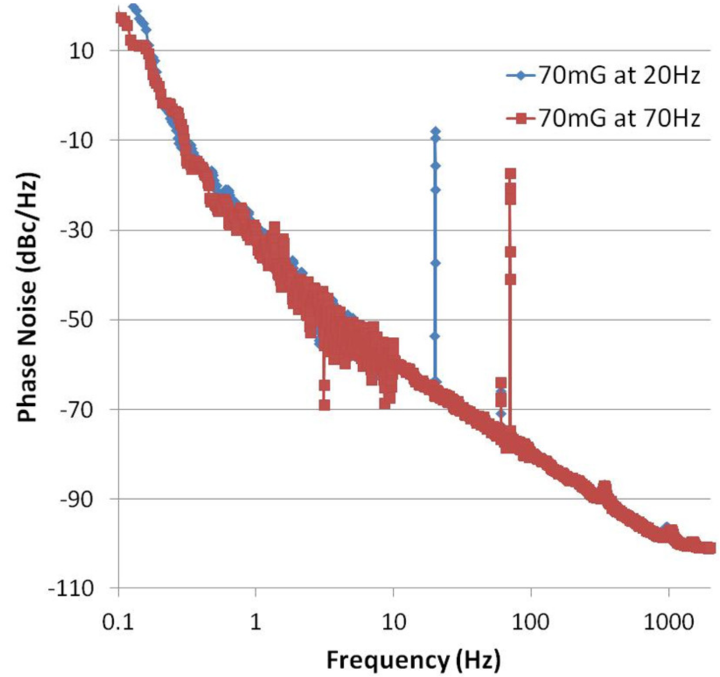
AlN MEMS Accelerometers

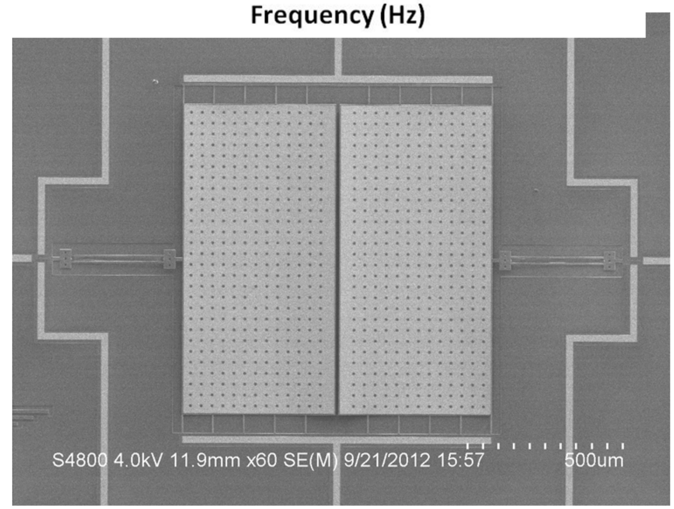
Sandia National Laboratories

- **Resolution = 70 μG/√Hz**
- **Mobile Phone Level Performance**
- **Integration with CMOS**
- **Wafer Level and Thin Packaging**



AlN Accelerometer on CMOS7 Photo



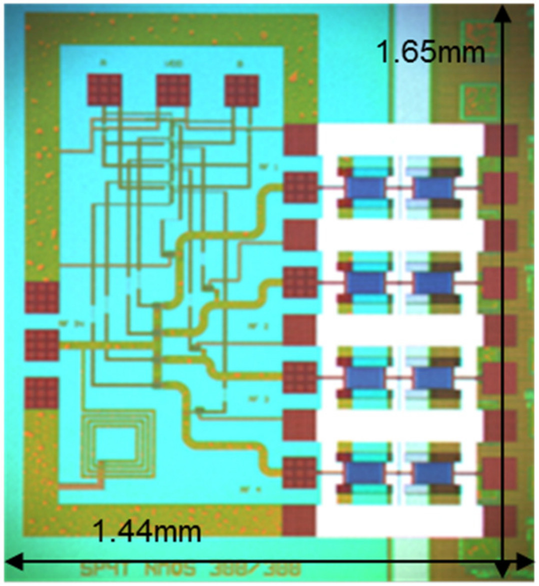


Inertial Sensor Die Photo and Measurement

Conclusions

- ***Aluminum Nitride MEMS Devices Offer Advantages Over Incumbent Technologies***
  - Contour Mode AlN Filters
    - Frequency/Bandwidth Diversity, Size
  - AlN MEMS Oscillators
    - Power, Thermal Stability, Thickness
  - AlN Inertial Sensors
    - Power, Size, Resolution

- ***In the Future***
  - Reconfigurable and Tunable Filters
  - Higher FOM Materials for Lower Loss, Wider Bandwidth and Tuning



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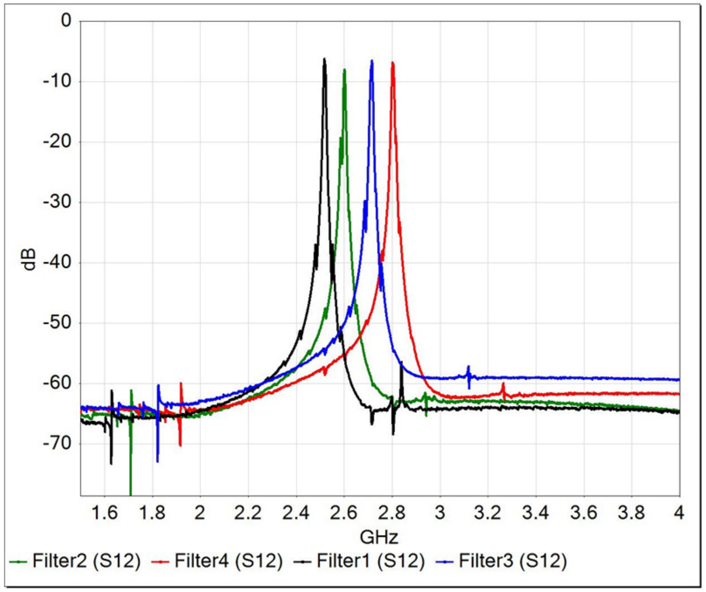
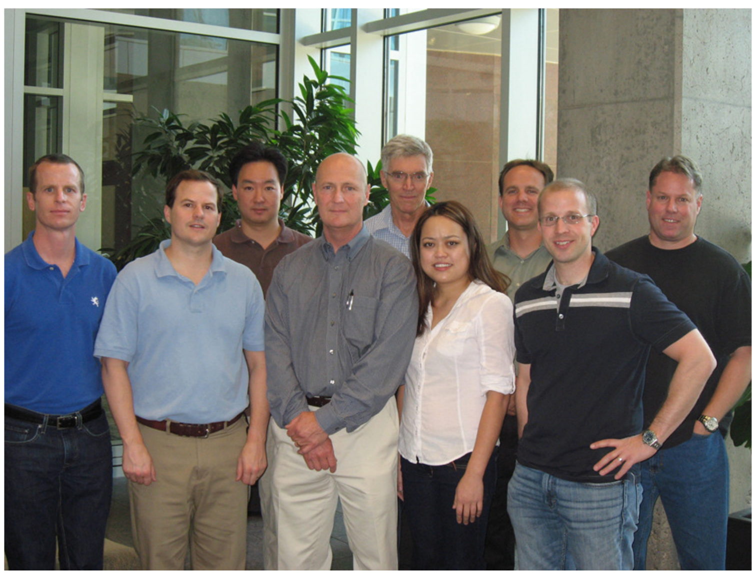
S-Band Switched Filter Array



Acknowledgments

Sandia wins R&D Magazine's 2011 R&D100 Award: "Microresonator Filters and Frequency References"



Funding Sources

Sandia National Laboratories LDRD Program, DARPA ASP, CSSA and RFFPGA Programs, Many Others

Acknowledgement

Microelectronics Development Laboratory Staff at Sandia National Laboratories

Key Contributors

Mike Baker, Bongsang Kim, Peggy Clews, Tammy Pluym, Emily Crespin, Jim Stevens, Janet Nguyen, Travis Young, Brian W., Vic Yarberry, Eric Langlois, Heidi Harvey, Andy Gross, Chris Ford, Todd Bauer, Anathea Ortega, Sasha Summers, Tom Hill, Steve Volk, Tony Farino, Keith Yoneshige, Bob Timon, Darren Branch, Camille Padilla, Stephanie Johnson, Kathy Myers, Tina Dallo, Henry Dallo, Colleen Wakefield, Ramona Macleod, Sean Scott, and more….