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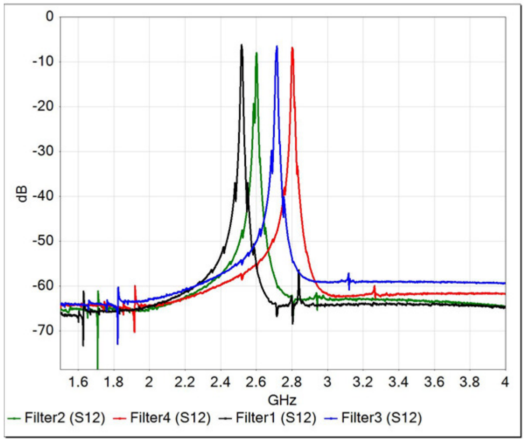

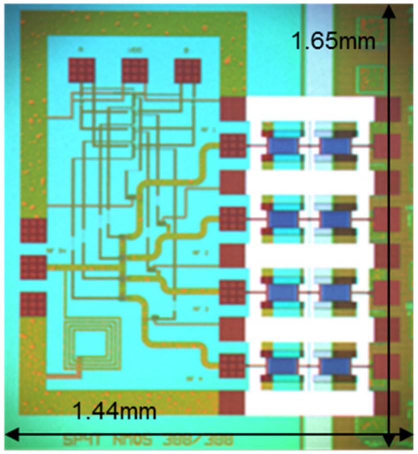

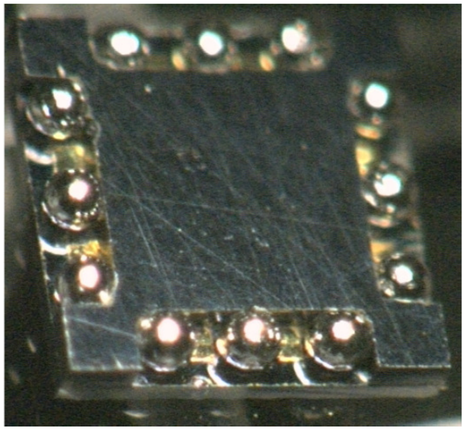

TUNING THE BANDWIDTH AND CENTER FREQUENCY OF MICROMECHANICAL ACOUSTIC FILTERS

Roy H. Olsson III, Bongsang Kim, Janet Nguyen, Peggy Clews, Tammy Pluym and Kenneth E. Wojciechowski

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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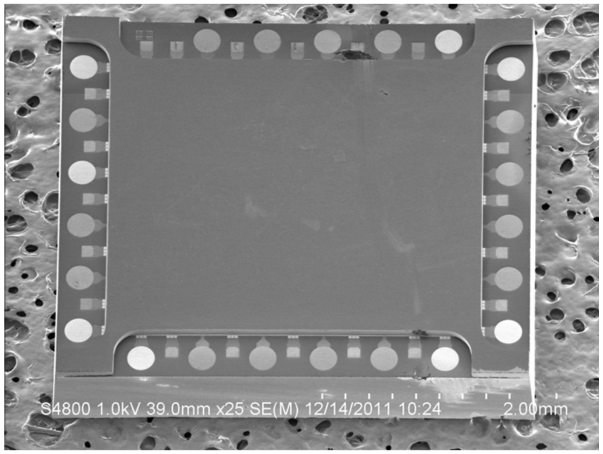
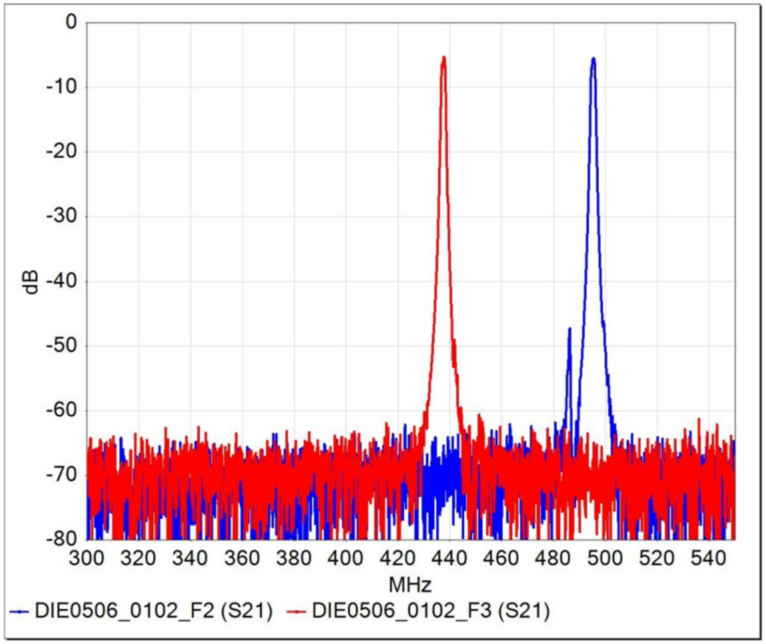
Acoustic Micro-Scale Resonators

Outline

- *Motivation*
- *Fundamentals*
  - k_t^2-Q FOM
  - Material Based Tuning Limitations
- *Tuning of Acoustic Resonators*
  - Tuning Range
  - Tunable Filters
  - Active Tuning
- *New Materials and Impact on Performance*
  - Comparing Acoustic Resonators
  - High k_t^2 Microresonators
  - Impact on Tuning

IF Filter Die Containing 3 Filters

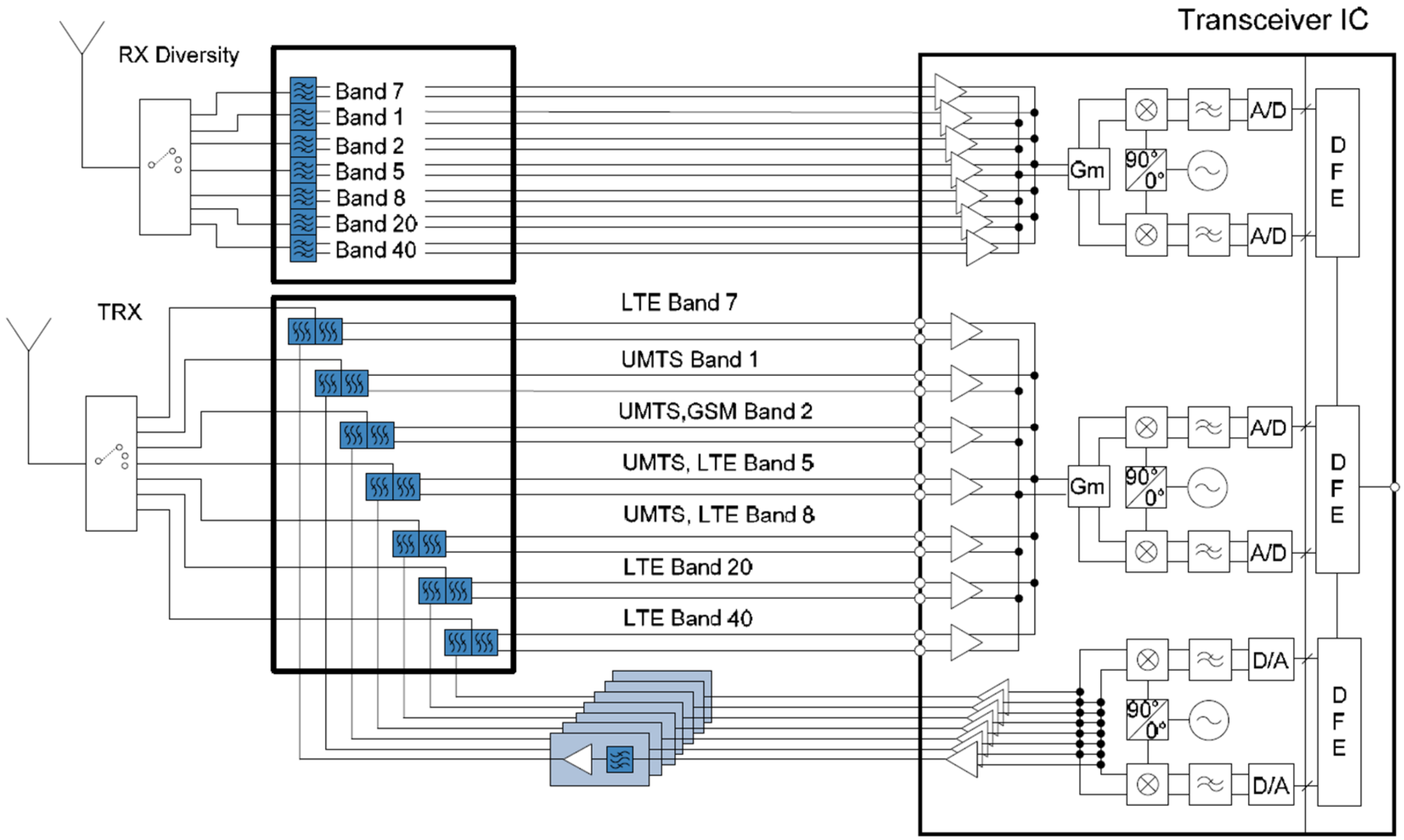




Filter Arrays for Handsets

- 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

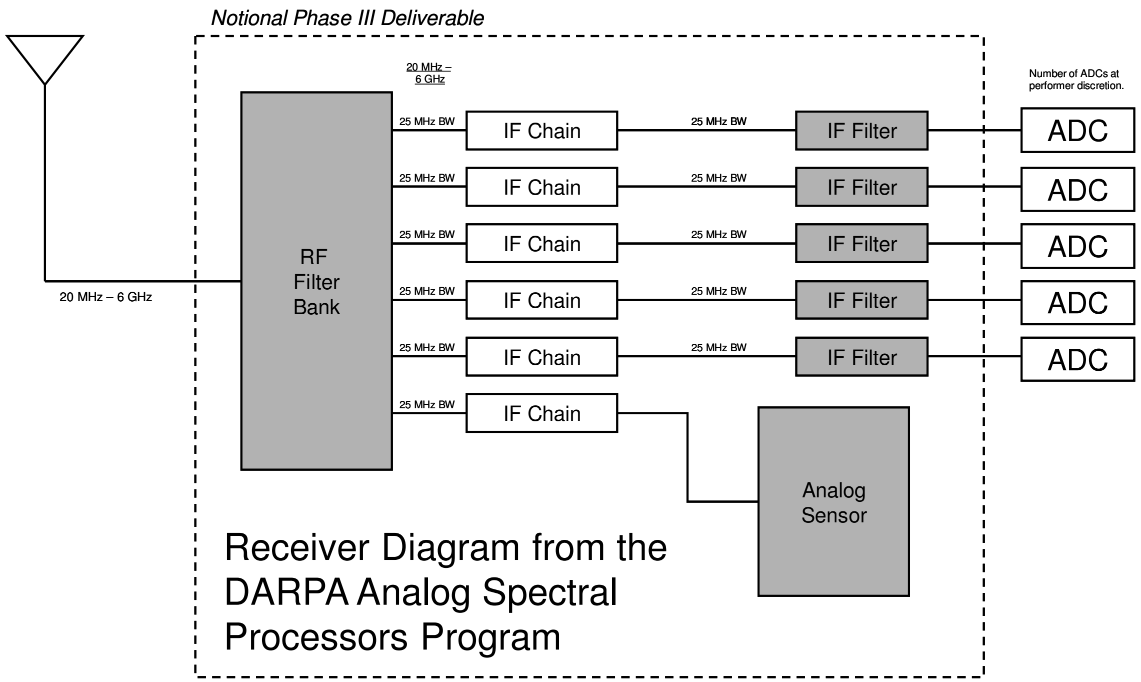
R. Vazny et al. "Front-End Implications to Multi-Standard Cellular Radios: State-of-the-Art and Future Trends", *Proc. Of the 2010 IEEE Ultrasonics Symposium, pp. 95 – 98, Oct. 2010*



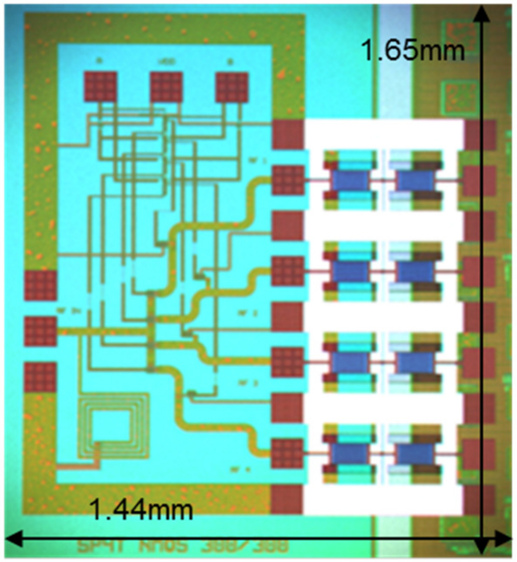
RF Front-End of a Modern Cellular Radio

Filters in Military Radios

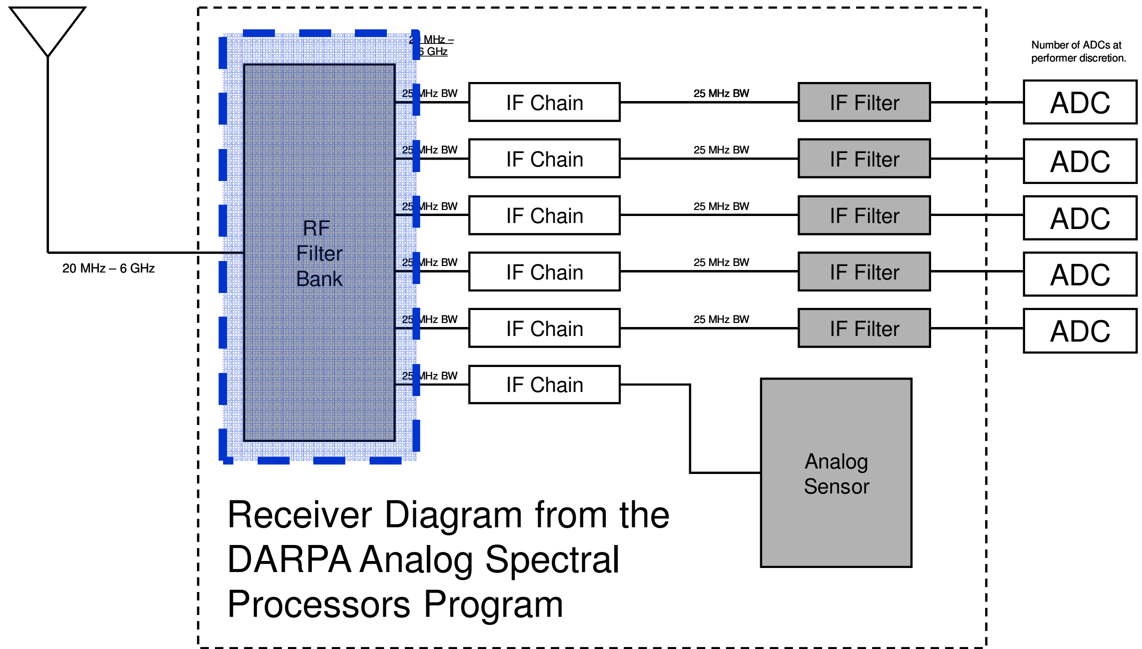
- Current Military Radios Are Mandated to be Backwards Compatible
  - *Legacy and Updated Frequencies and Waveforms*
    - *Many RF Frequencies and Bandwidths Required*
- Future Military Radios Will Require Spectral Knowledge and Real Time Adaptability to Mitigate Both Co-Site and Adversary Jamming



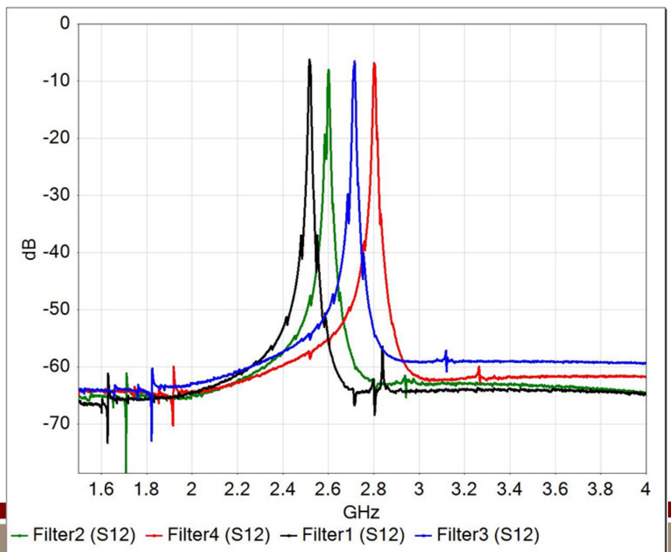
Frequency Adaptability on the RF Front-End



Notional Phase III Deliverable

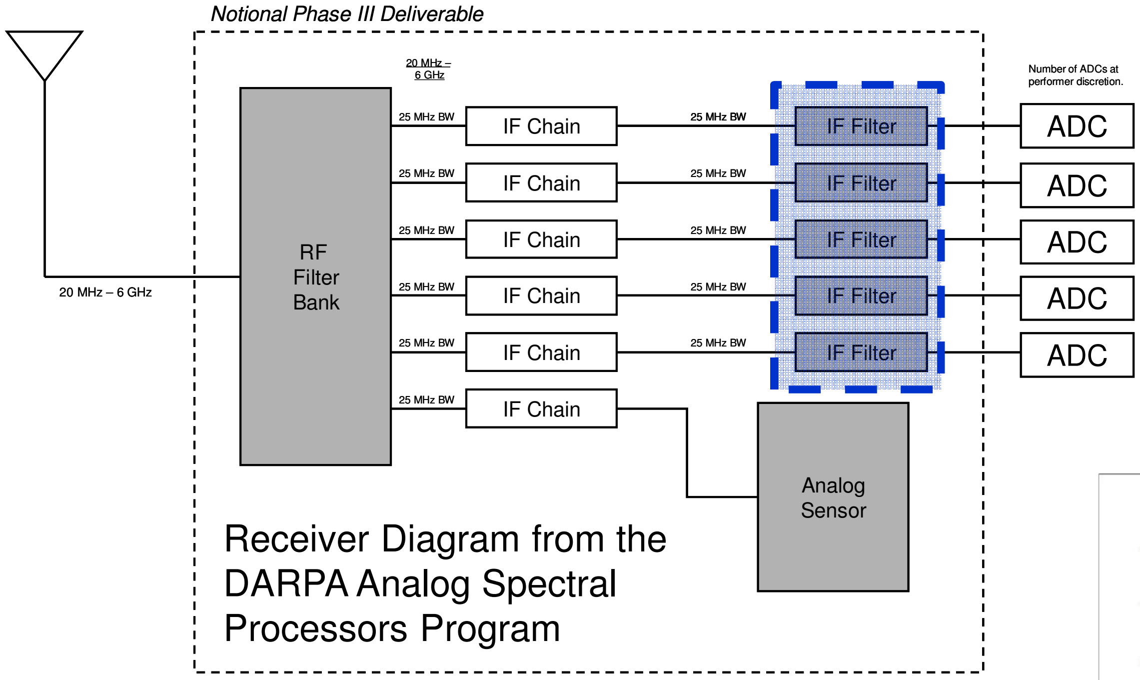


Receiver Diagram from the DARPA Analog Spectral Processors Program

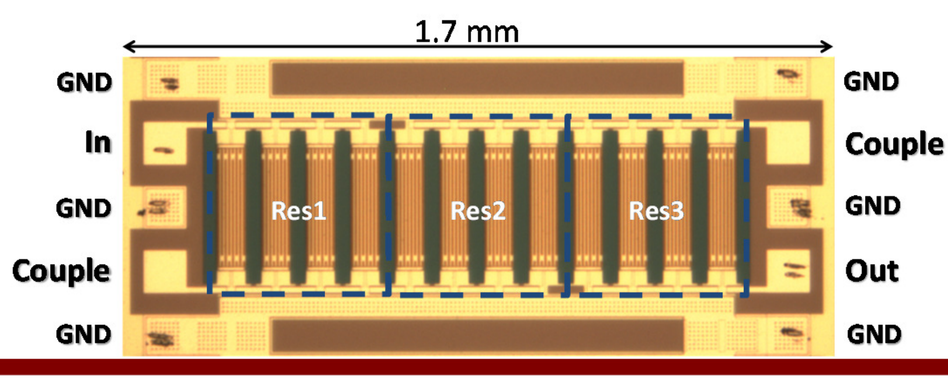


S-Band Switched Filter Array on CMOS for RF Center Frequency Adaptability

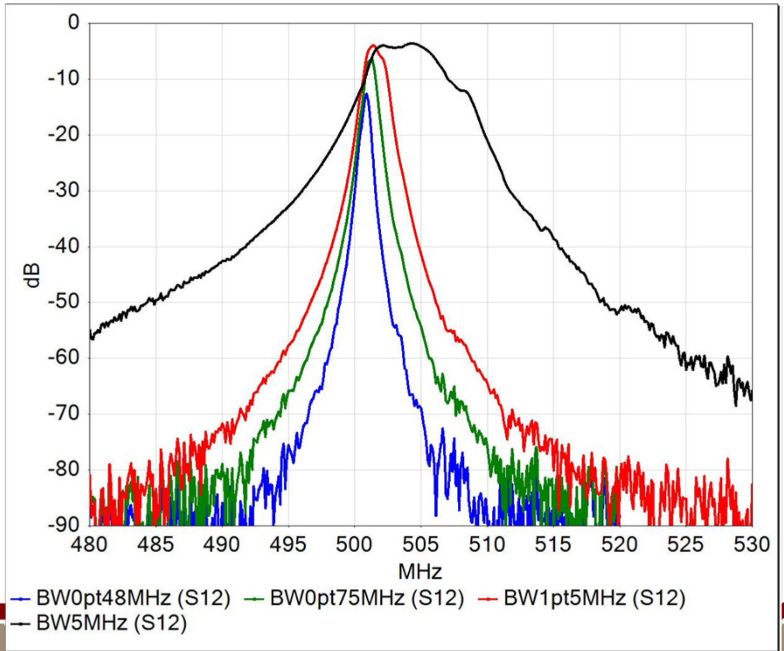
Waveform and Bandwidth Adaptability IF Filtering



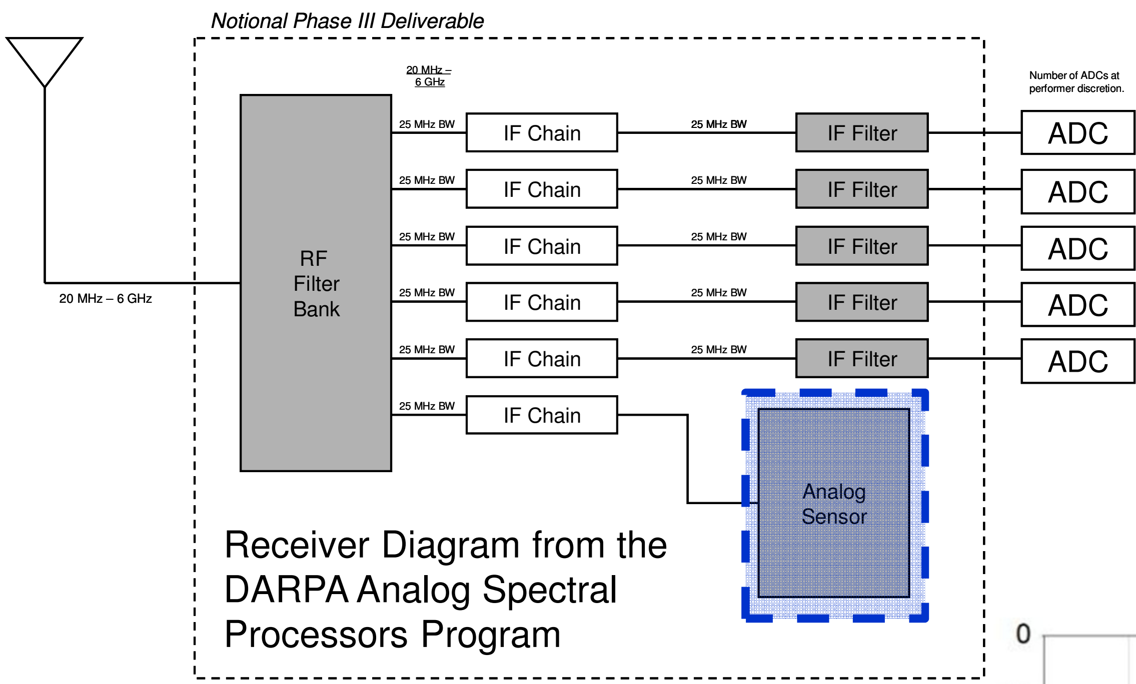
Receiver Diagram from the DARPA Analog Spectral Processors Program



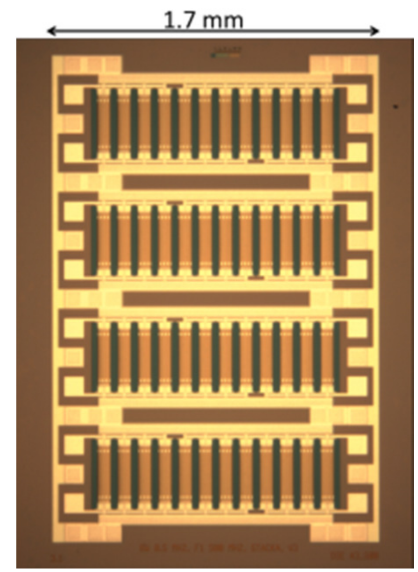
IF Filter with Programmable Bandwidth from 5.1 MHz to 0.48 MHz

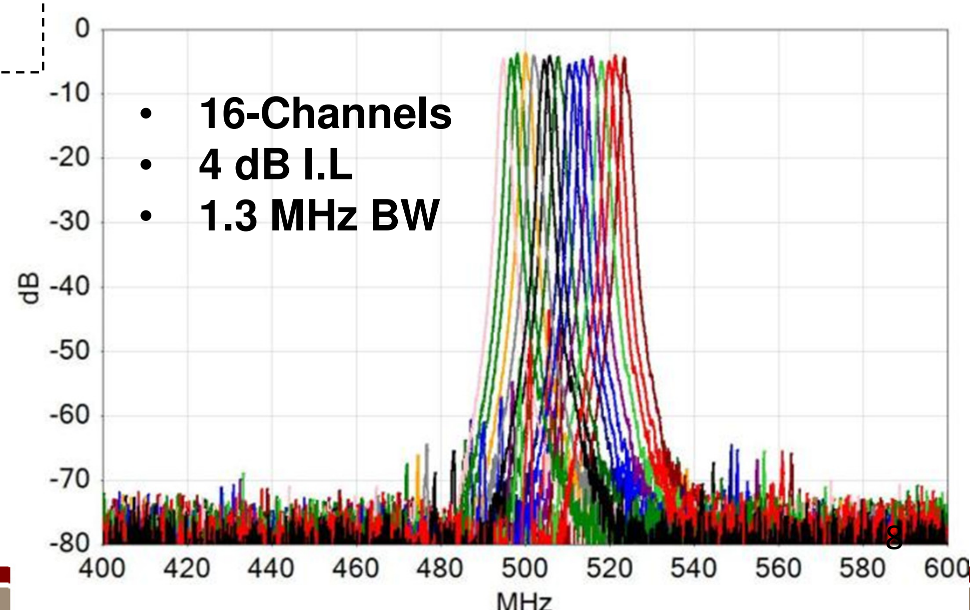


RF Spectral Awareness



Receiver Diagram from the DARPA Analog Spectral Processors Program





- **16-Channels**
- **4 dB I.L**
- **1.3 MHz BW**

16-Channel Filter Array for RF Spectral Sensing

Piezoelectric Resonator Transduction

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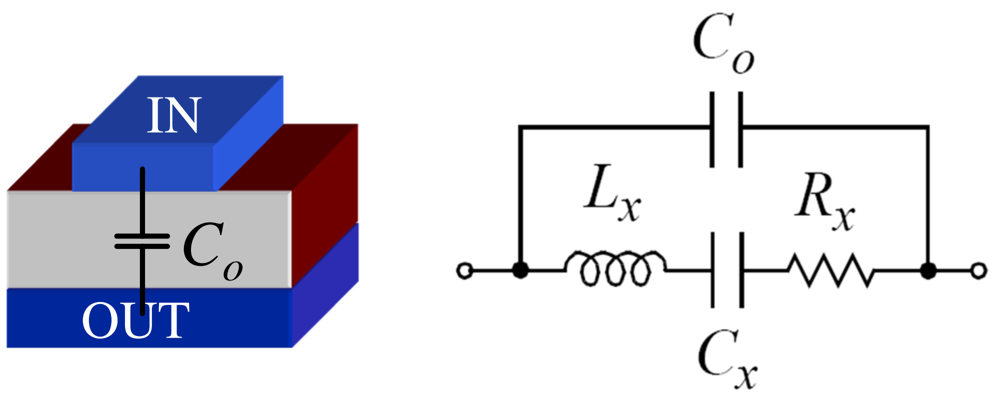
Top-Bottom Transduction



$$C_x = 0.8 k_t^2 C_0$$

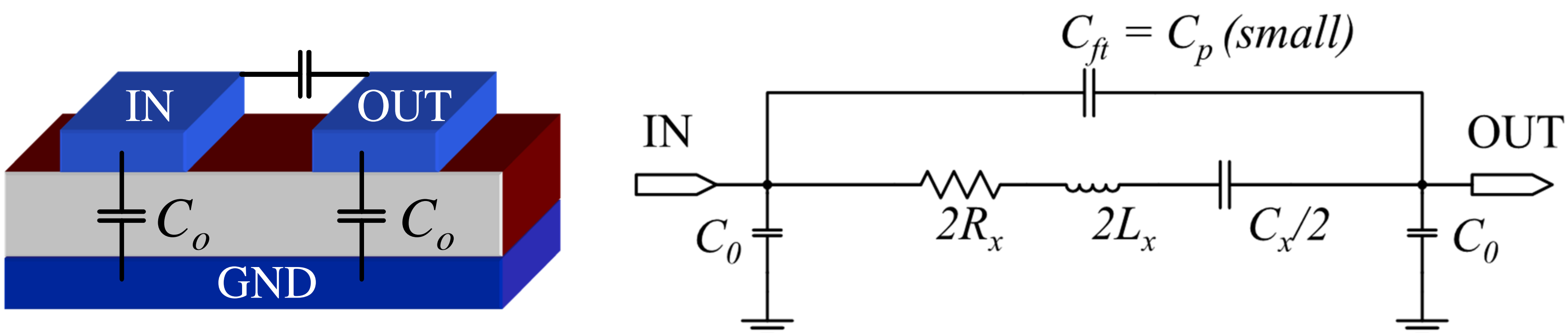
$$L_x = \frac{1}{0.8\omega^2 k_t^2 C_0}$$

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

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

$$FOM = k_t^2 Q$$

Top-Top Transduction



Top electrode   Bottom electrode   Piezoelectric Film (AlN)

Piezoelectric Resonator Transduction

- *Loss*
  - Proportional to FOM
  - R_X Set by FOM, Frequency, C_0 (Area)
- *Tuning*
  - Maximum Tuning Range is Determined by k_t^2
- *Bandwidth*
  - Minimum Practical Filter Bandwidth is Determined by Q
  - Maximum Practical Filter Bandwidth is Determined by k_t^2

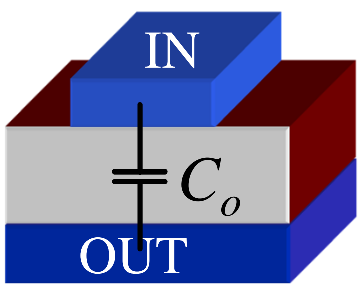
$$C_x = 0.8 k_t^2 C_0$$

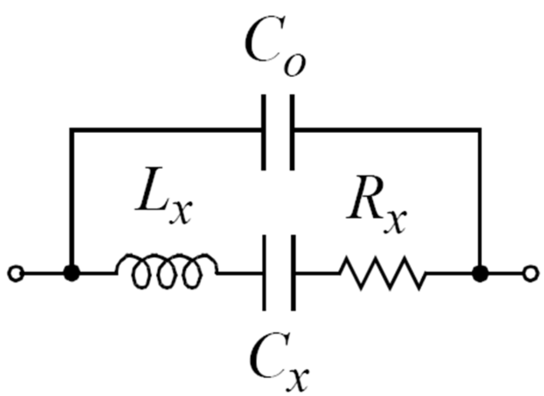
$$L_x = \frac{1}{0.8\omega^2 k_t^2 C_0}$$

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

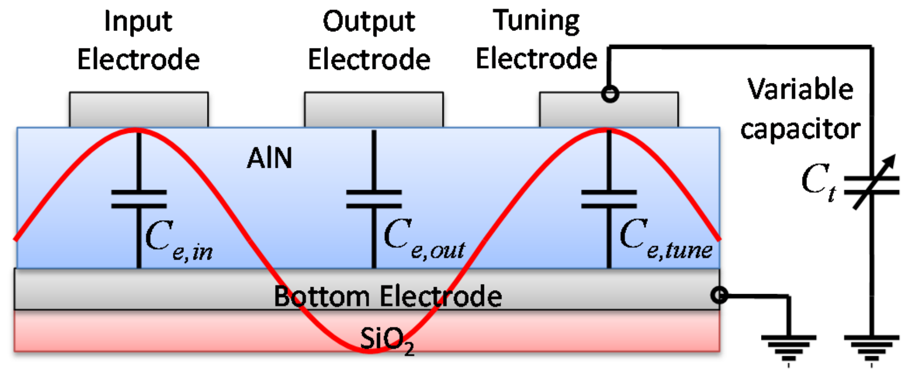
$$k_t^2 = \frac{d_{31}^2 \mathrm{E}}{\varepsilon}$$

$$FOM = k_t^2 Q$$

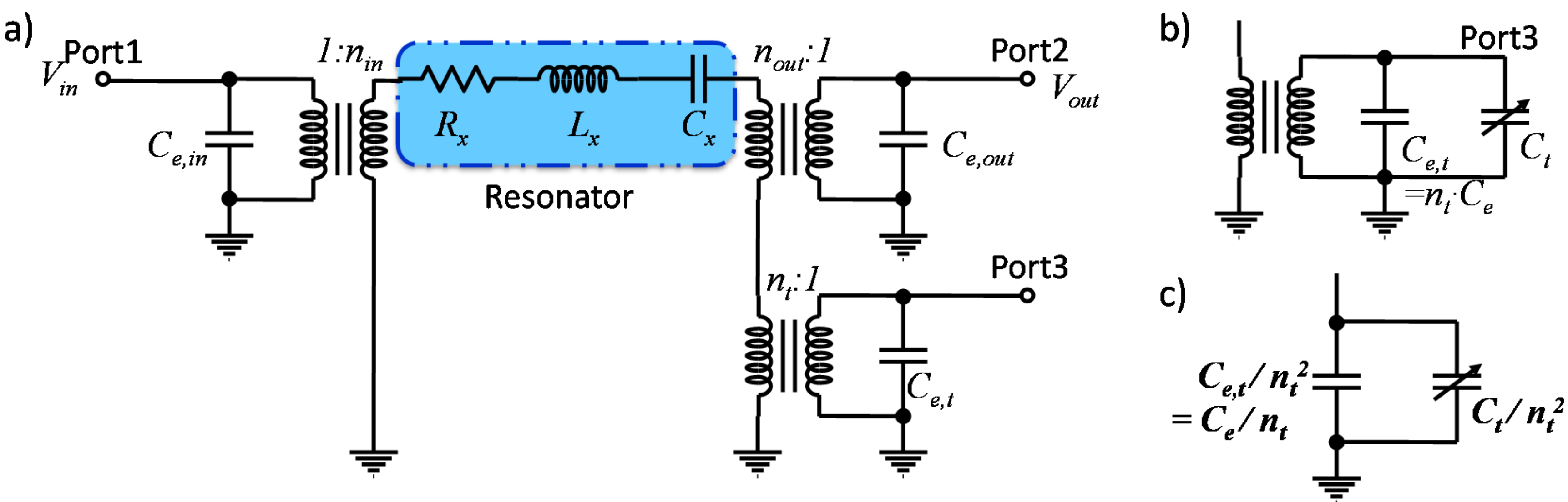




k_t^2 Limits the Tuning Range



3-Port Tunable Micromechanical Resonator Cross-Section



3-Port Tunable Micromechanical Resonator Equivalent Circuit Model

k_t^2 Limits the Tuning Range

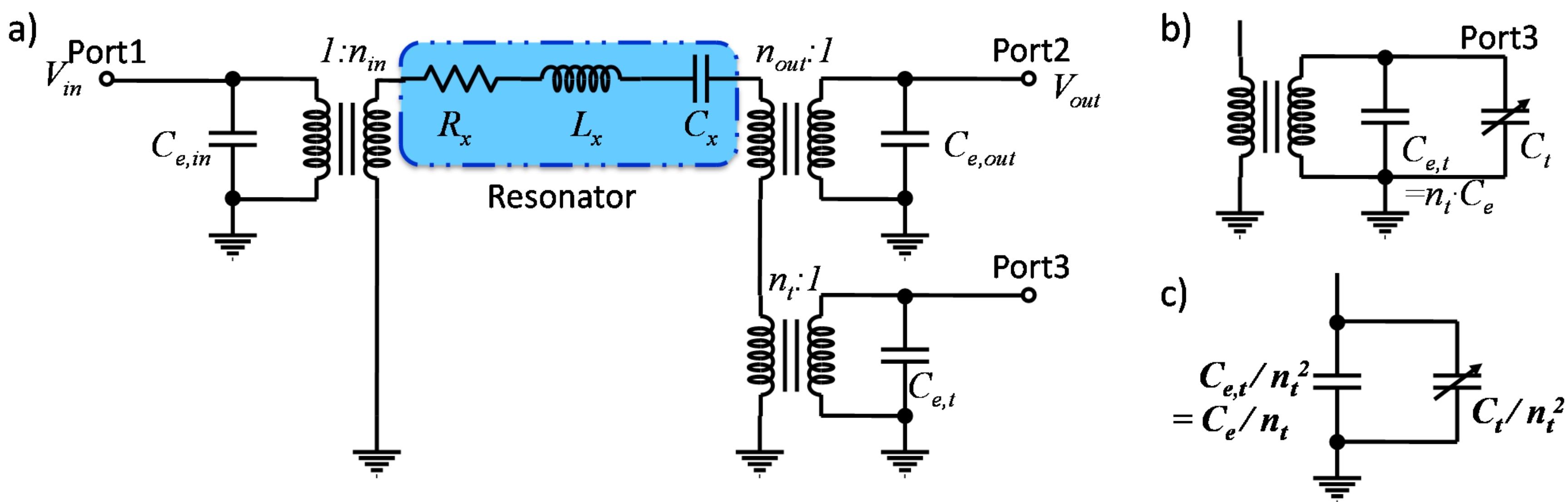
$$\frac{1}{C_x'} = \frac{1}{C_x} + \frac{n_t^2}{n_t C_e + C_t}$$

$$f' = \frac{1}{2\pi}\sqrt{\frac{1}{L_x C_x'}} = \frac{1}{2\pi}\sqrt{\frac{1}{L_x}\left(\frac{1}{C_x} + \frac{n_t^2}{n_t C_e + C_t}\right)}$$

$$\frac{\Delta f}{f} = \frac{1}{2}\frac{n_t^2 \cdot C_x}{n_t C_e + C_t}$$

$$0 < \frac{\Delta f}{f} < \frac{n_t}{2}\frac{C_x}{C_e}$$

$$\frac{C_x}{C_e} = \frac{8}{\pi^2} k_t^2$$



Multi-Port Resonators for Tuning

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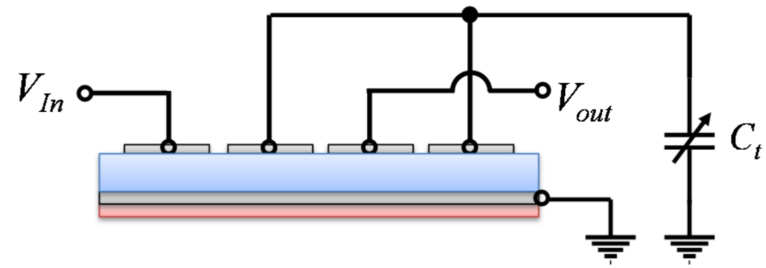
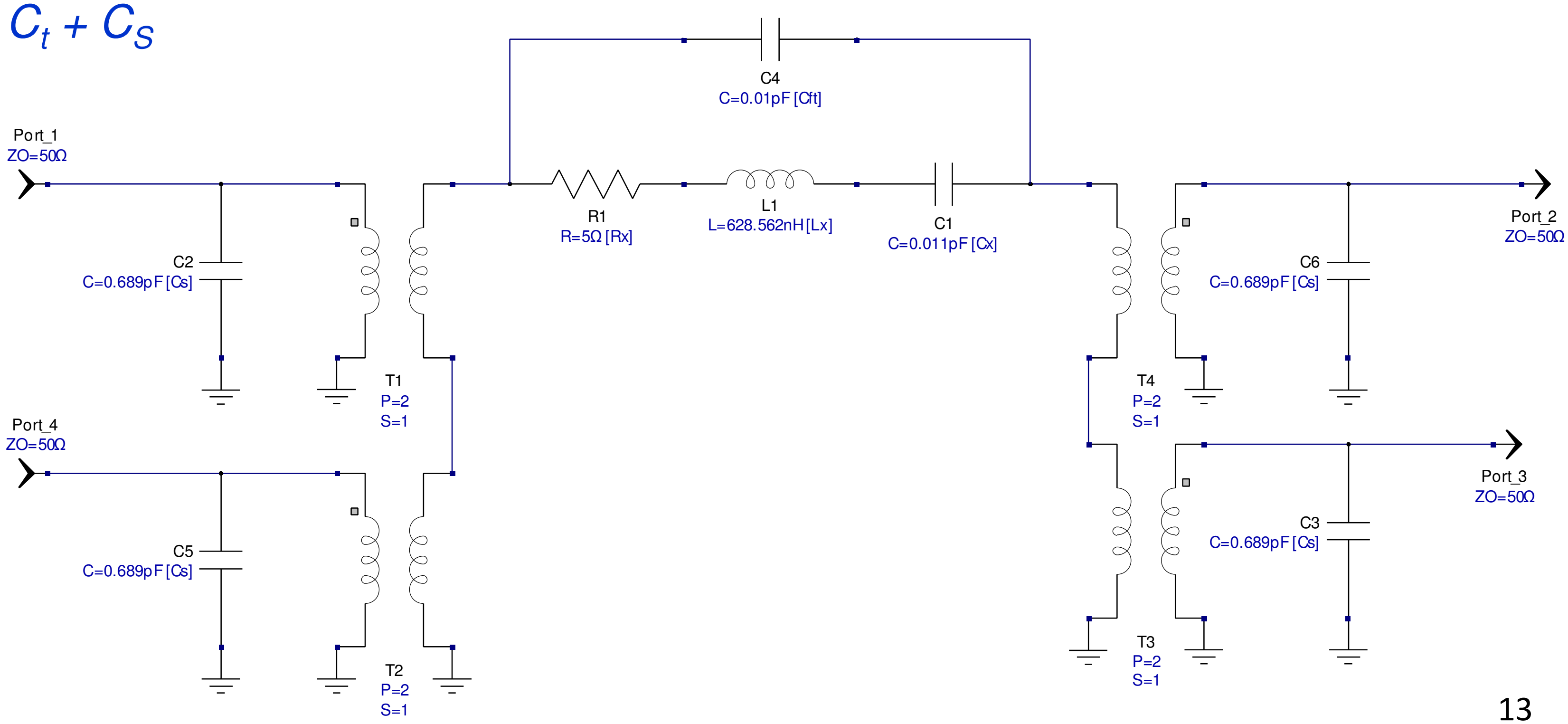
- *½ of Electrodes Used for Filtering*
- *½ of Electrodes Used for Tuning*
- *Tuning Range Limited by C_X/C_S or k_t^2*
- *Feedback Signal on C_t is 90 deg. Out of Phase with the Input and is Maximized for Small $C_t + C_S$*

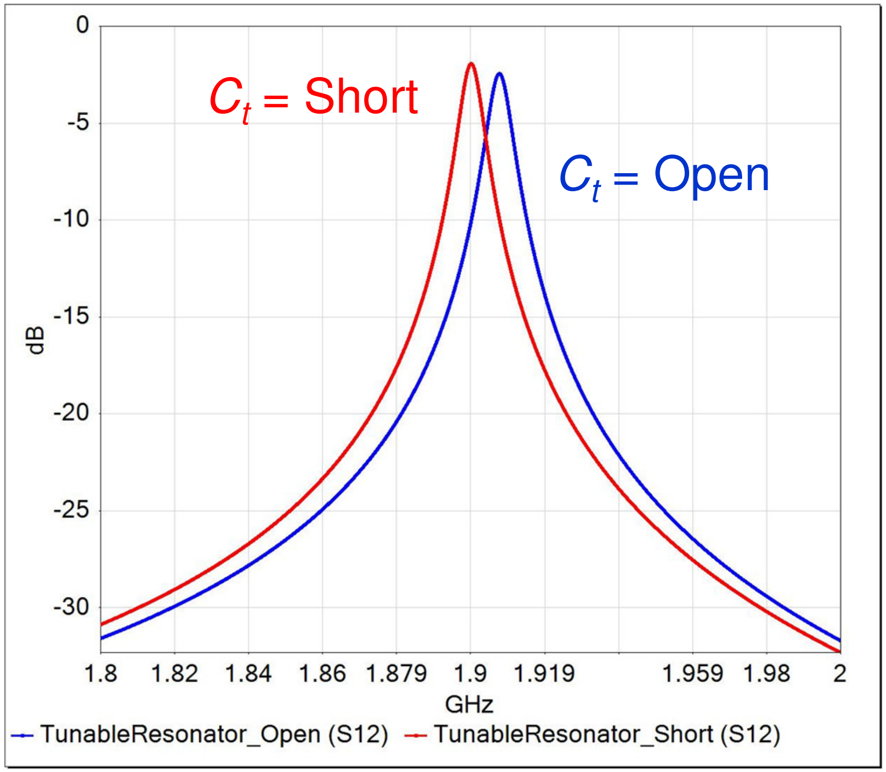
a) **Configuration A**



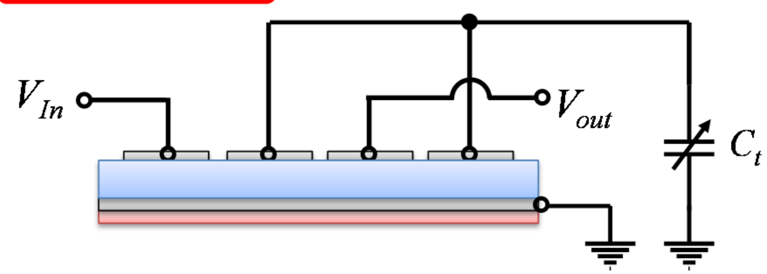


AlN Microresonator Tuning

- *AlN Microresonator*
  - k_t^2 = 2%
  - Q = 1500
  - R_X = 5 Ω
  - Tuning Range = 0.4%
- *Using ½ of the k_t^2 for Bandwidth and ½ for Tuning*
- *C_t Varied From Open to Short*
- *Additional 0.5 dB Loss is From the Finite Q of the Electrode Capacitors*
- *As We Tune Away From the Acoustic Resonance*
  - More Energy Stored in the Capacitors
  - Higher Capacitor Q Required
  - Trade Off Between Acoustic and Capacitor Q With Metal Thickness

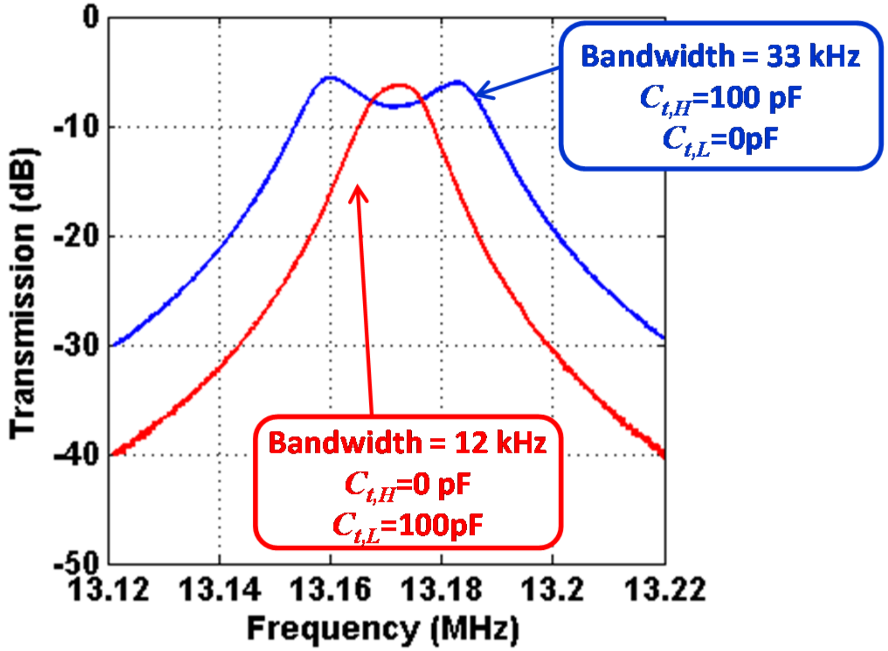


a) Configuration A

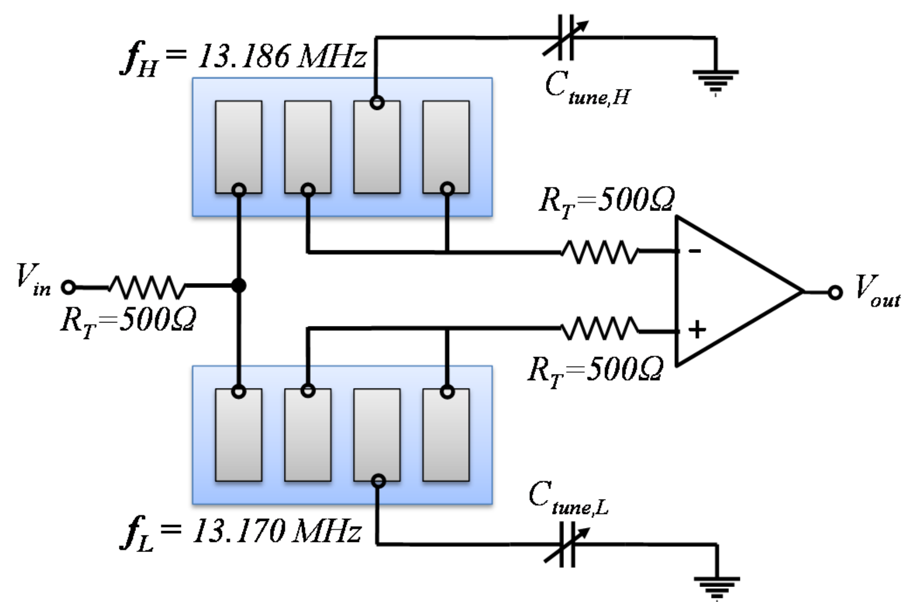


Tunable Bandwidth Lattice Filter

- *Achieved ~ 3x, 3 dB Bandwidth Tuning Range*
- *Parallel Lattice Filter Architecture*
- *Resonator Tuning Range Limited to < $k_t^2/2$*

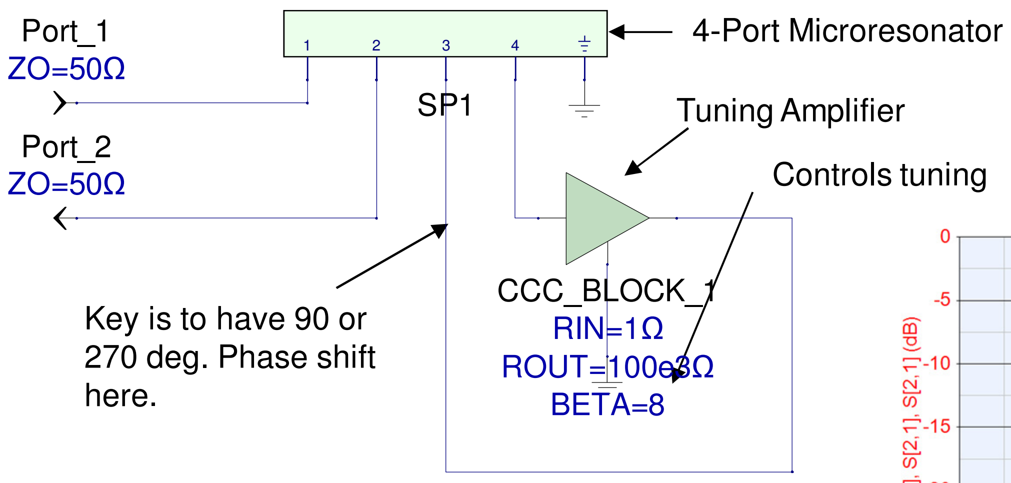


Tunable Bandwidth Filter Response



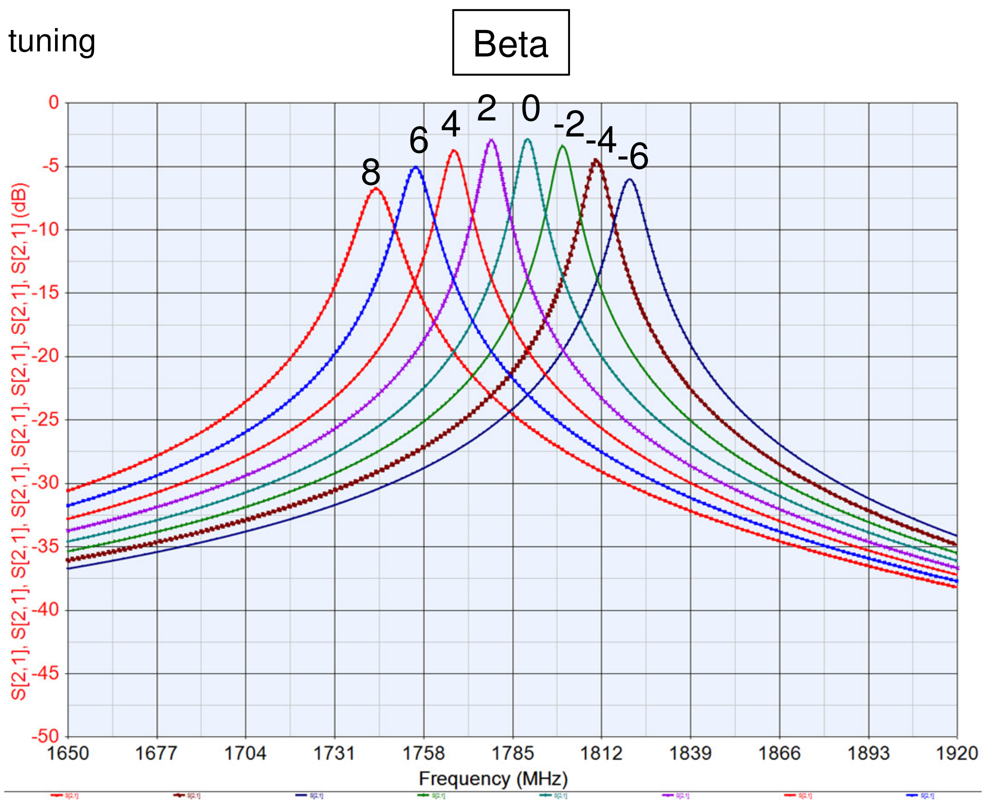
Tunable Bandwidth Filter Schematic

Active Resonator Tuning



Initial Tuning Schematic

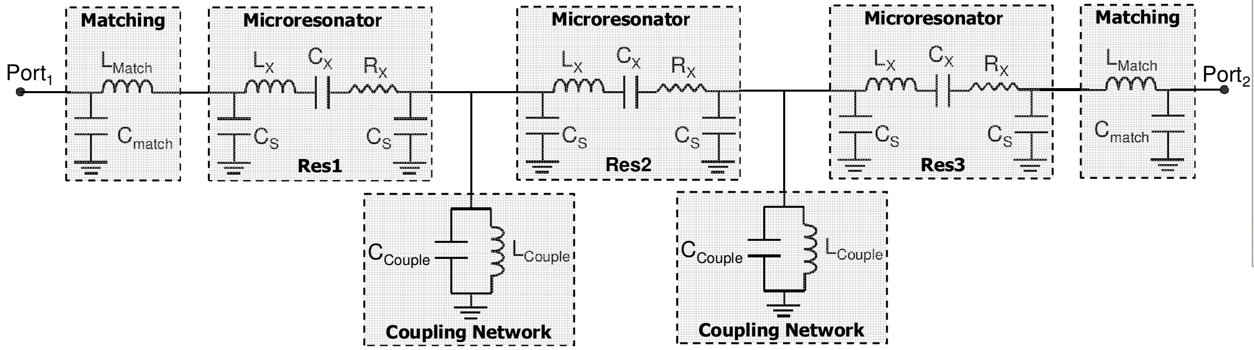
- Active Tuning
  - AlN Microresonator with a k_t^2 of 1.5%
  - RF filters can be tuned >7.0%
  - Passive Tuning was 0.3%
  - Can be implemented in several ways using existing transistors
  - Requires realistic current gains of 8



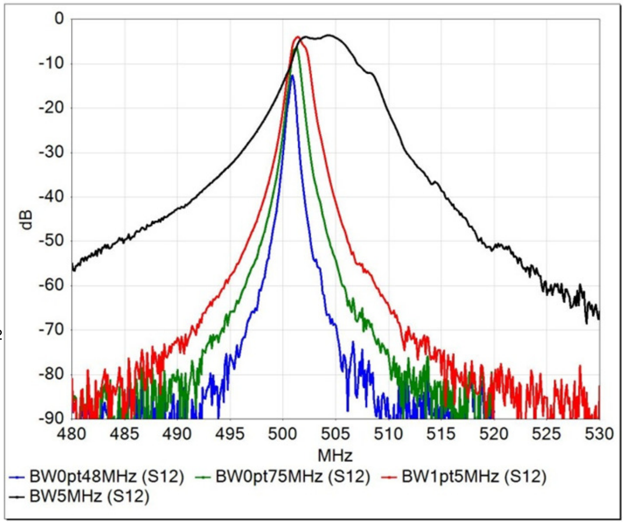
Utilizing Active Gain to Extend the Tuning Range of Microresonators

Programmable Bandwidth Filter

- *Alters Resonator Coupling by Tunable Coupling Networks*
- *Over 10x Bandwidth Programmability Using COTs Passives with Q = 50*
- *Working to Integrate Switched Coupling and Matching Capacitors Under Resonator to Enable Tunable Bandwidth*



Programmable Bandwidth Filter Schematic



Programmable Bandwidth Filter Measured Response

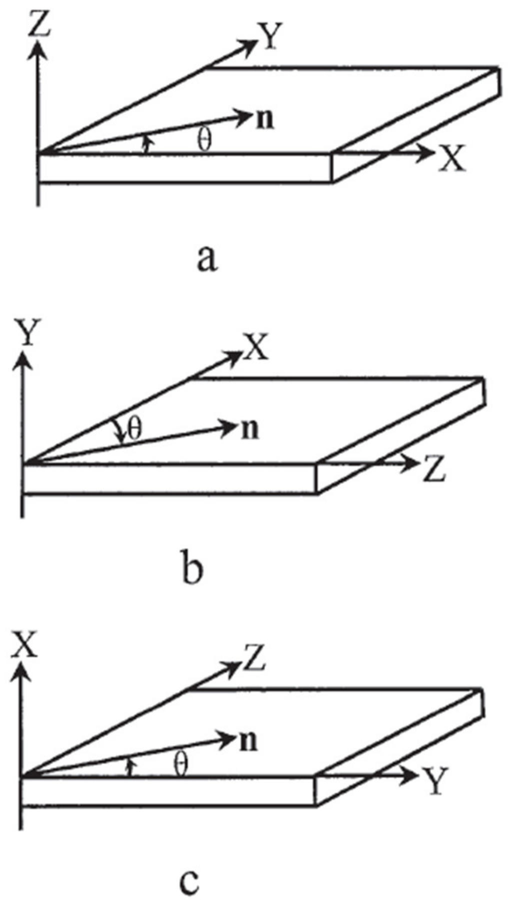
3 dB Bandwidth (MHz)	Insertion Loss (dB)	Stop Band Rejection (dB)	L_{couple} (nH)	C_{Couple} (pF)	L_{match} (nH)	C_{match} (pF)
0.475	12.6	75	0	14	11	6
0.75	6.3	80	0	5	0	0
1.5	4.0	80	0	0	0	0
5.1	3.6	76	22	0	37	0

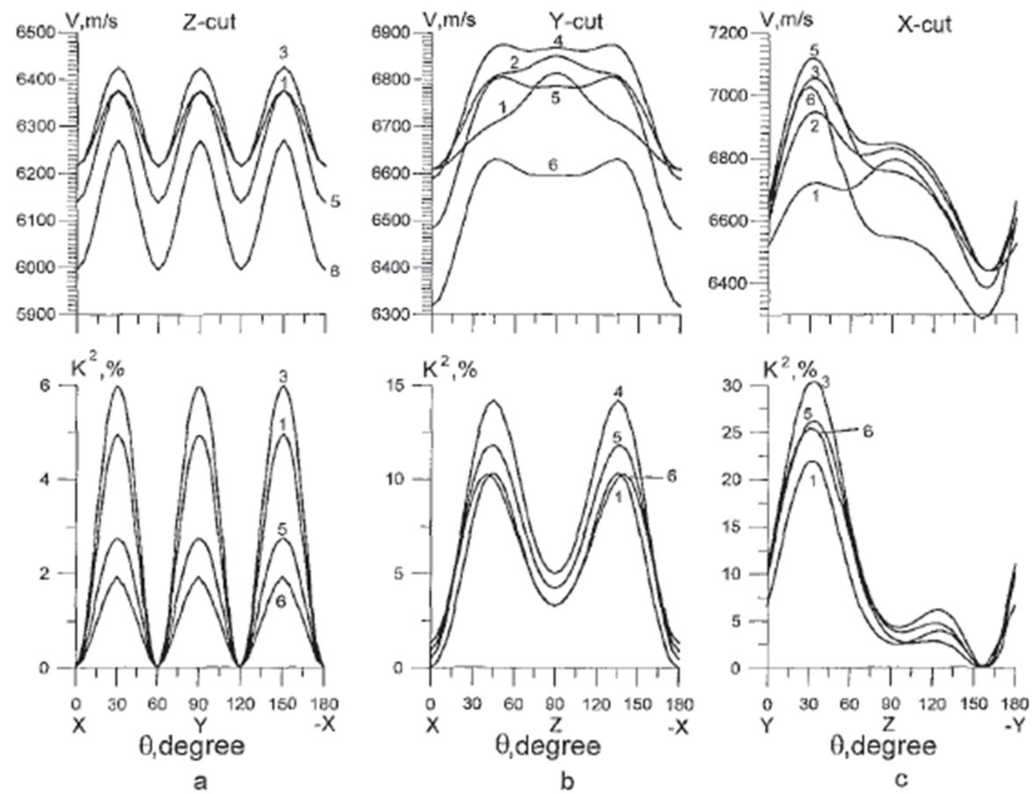
Increasing the Tuning Range

Types of Acoustic Resonators

Technology/ Metric	k_t^2 theory	k_t^2 experiment	Q @ ~ 1 GHz	FOM	Multiple Frequencies on a Substrate
AlN BAW/FBAR	6.5%	7%	3000	~200	High Cost
Standard $LiNbO_3$ SAW	5.5%	5.5%	2000	~100	Yes
AlN Microresonator	2%	2%	2000	~40	Yes
Capacitive Microresonator	~Gap, Bias	< 0.1%	10,000	<1	Yes
Advanced SAW	> 20%	20%	2000	~400	Limited
PZT/BST BAW	7-12%	7-12%	60-250	~7-18	High Cost
Doped AlN BAW	15%	12%	< Undoped	TBD	High Cost
$LiNbO_3$ Microresonator	> 30%	20%	1200	TBD	Yes

$LiNbO_3$ S0 Mode Microresonators





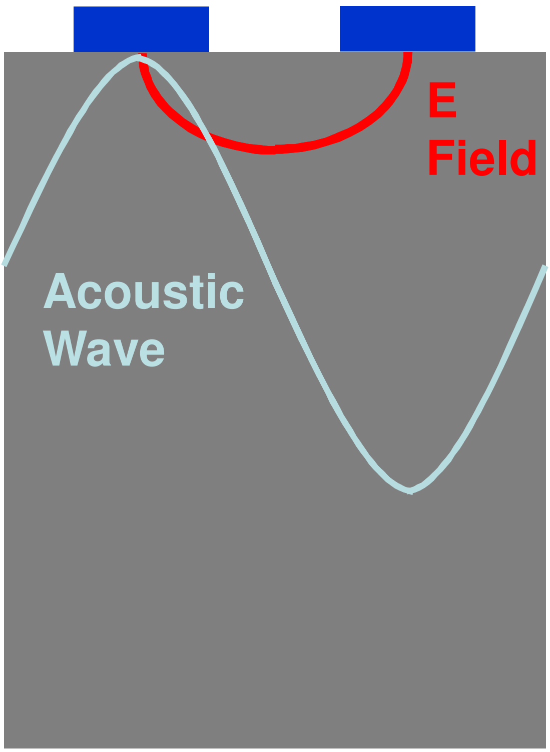
S0 Mode in $LiNbO_3$

1,2,3,4,5,7 (h/λ) = 0.01, 0.025, 0.05, 0.1, 0.25 and 0.35

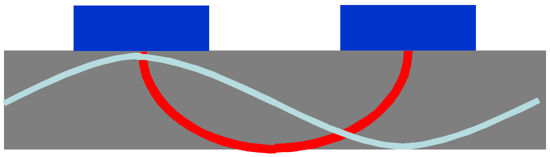
Kuznetsova et al., "Investigation of Acoustic Waves in Thin Plates of Lithium Niobate and Lithium Tantalate," *IEEE Trans. On Ultrasonics, Ferroelectrics and Freq. Cntrl., Vol 48, No. 1, January 2001.*

Why the Increase in Coupling?

- ***Increased Interaction of the Acoustic Wave With the RF Electric Field Compared to SAW as a Result of the Thin Plate***



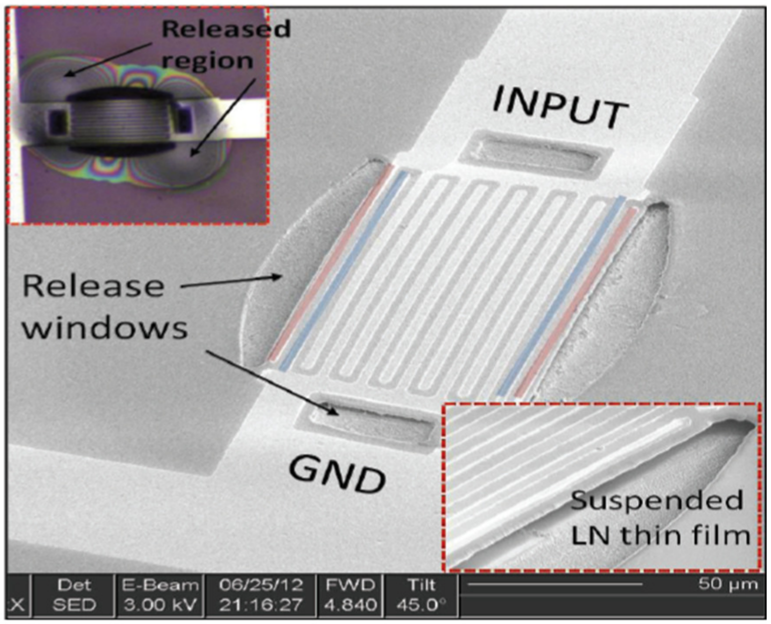
SAW

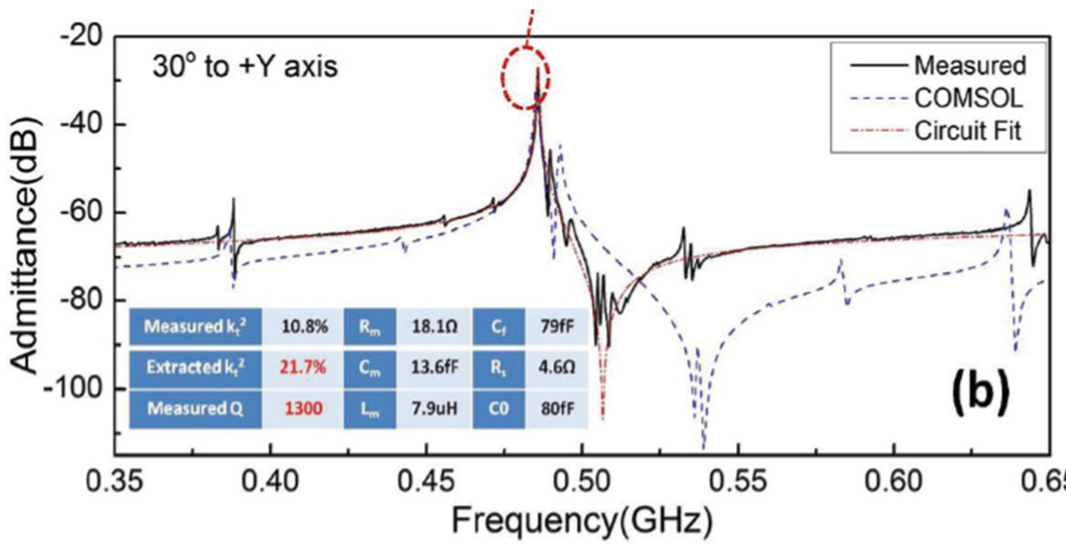


Microresonator

$LiNbO_3$ Microresonators

- ***k_t^2 Extracted ~ 22%***
- ***Q = 1300***
- ***X-Cut***
- ***Thin 3x3 cm^2 Pieces of $LiNbO_3$ on BCB on $LiNbO_3$ Provided by Srico***





S. Gong and G. Piazza., "Weighted Electrode Configuration for Electromechanical Coupling Enhancement in a New Class of Micromachined Lithium Niobate Laterally Vibrating Resonators," *IEEE Int. Elect. Dev. Meeting., 15.6.1-15.6.4, Dec. 2012.*

Tuning of High k_t^2 Microresonators

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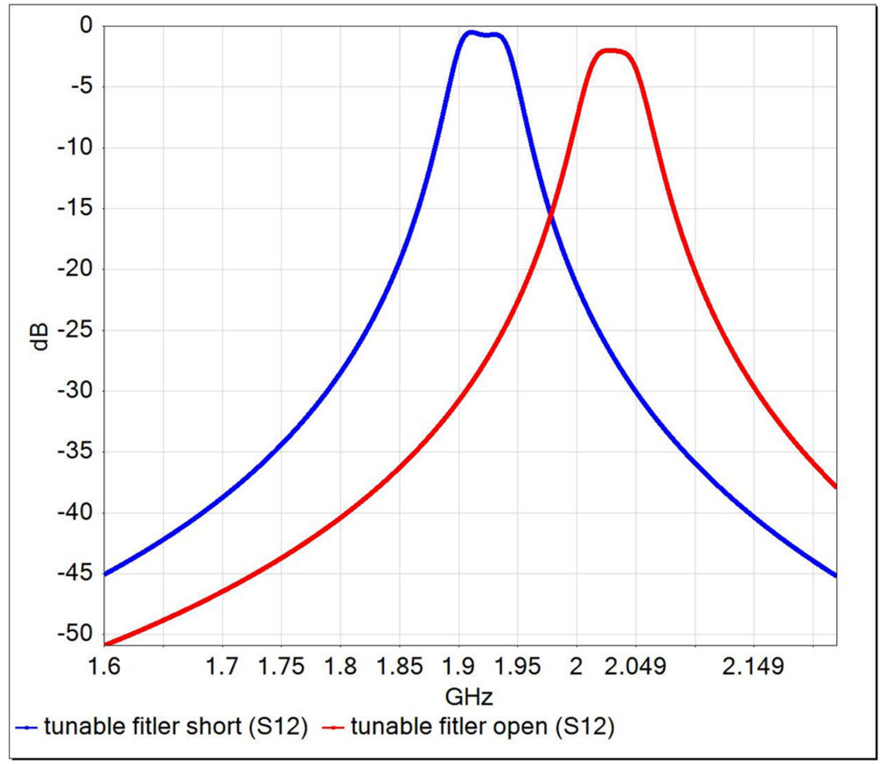
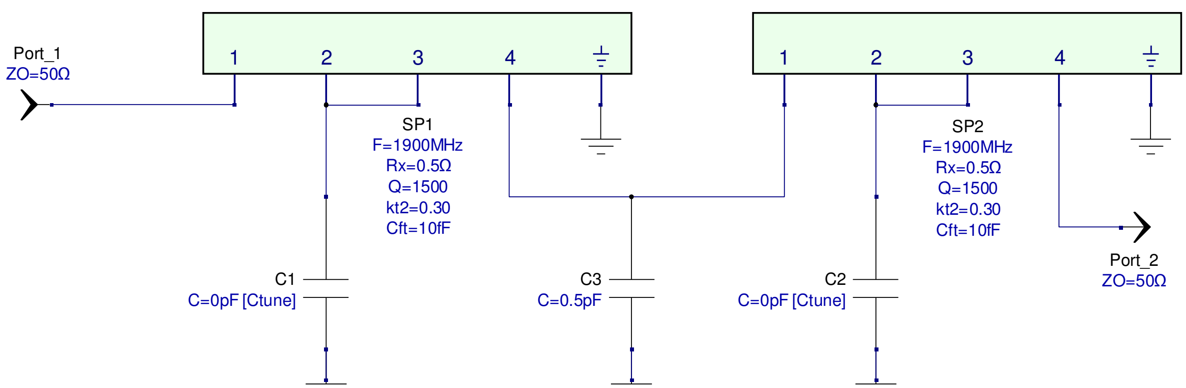
- *$LiNbO_3$ Microresonator 2-Pole Filter*
  - $k_t^2 = 30\%$
  - *Q = 1500*
  - *$R_X = 0.5\ \Omega$*
- *Q of all Capacitors = 40*
- *BW = 2.7%*
- *Tuning Range = 6.1%*
- *Significantly Reduces Number of Switched Acoustic Resonators*

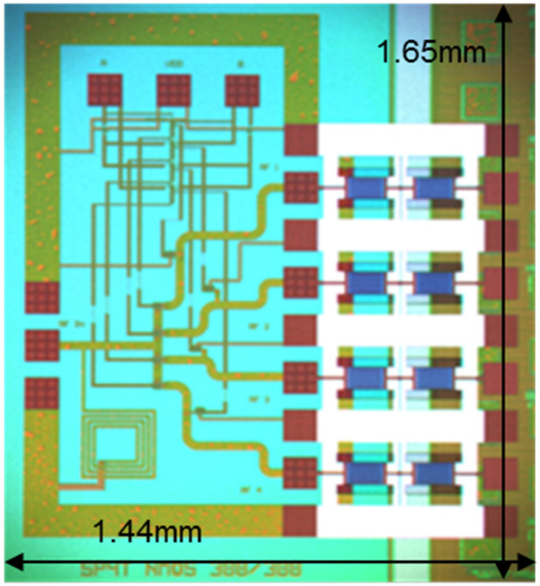




Tunable Filter Model and Simulated Response

Conclusions

- *Future Adaptive and Cognitive Radios Require Tunable Center Frequency and Bandwidth Filters*
- *Acoustic Filters Are Desirable Because of Their Small Size and High-Q in Common RF Bands*
- *The Fundamental Resonator Figures of Merit (k_t^2, Q) Limit Performance Metrics Such as Bandwidth, Tuning, and Insertion Loss*
- *Current Acoustic Resonator Technologies Can Achieve Tunable Bandwidth and Switchable Center Frequency*
- *New Materials With Higher Coupling Coefficient Will Enable Tunable Center Frequency Acoustic Filters*



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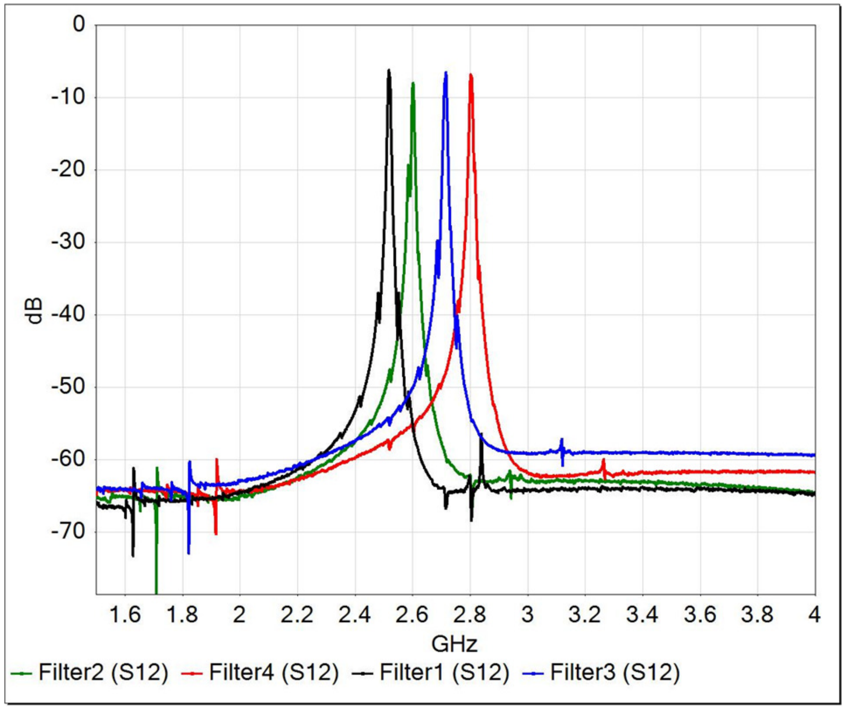
S-Band Switched Filter Array

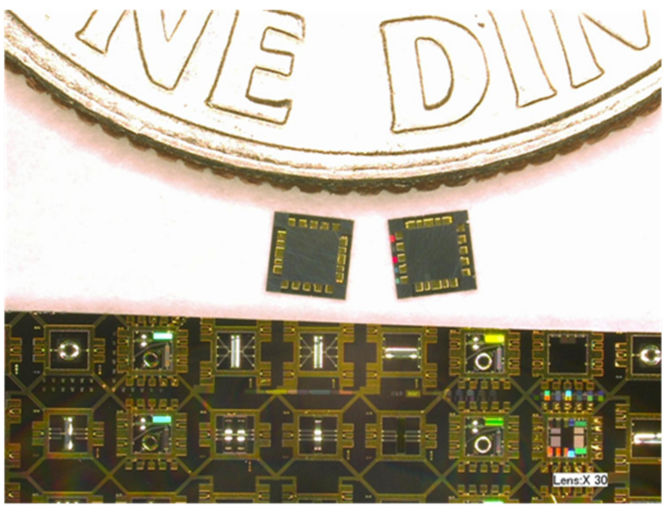


Acknowledgments

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