SAND2015-1567C

Reconfigurable and Tunable Micromechanical Filter Technologies for Adaptive RF Systems

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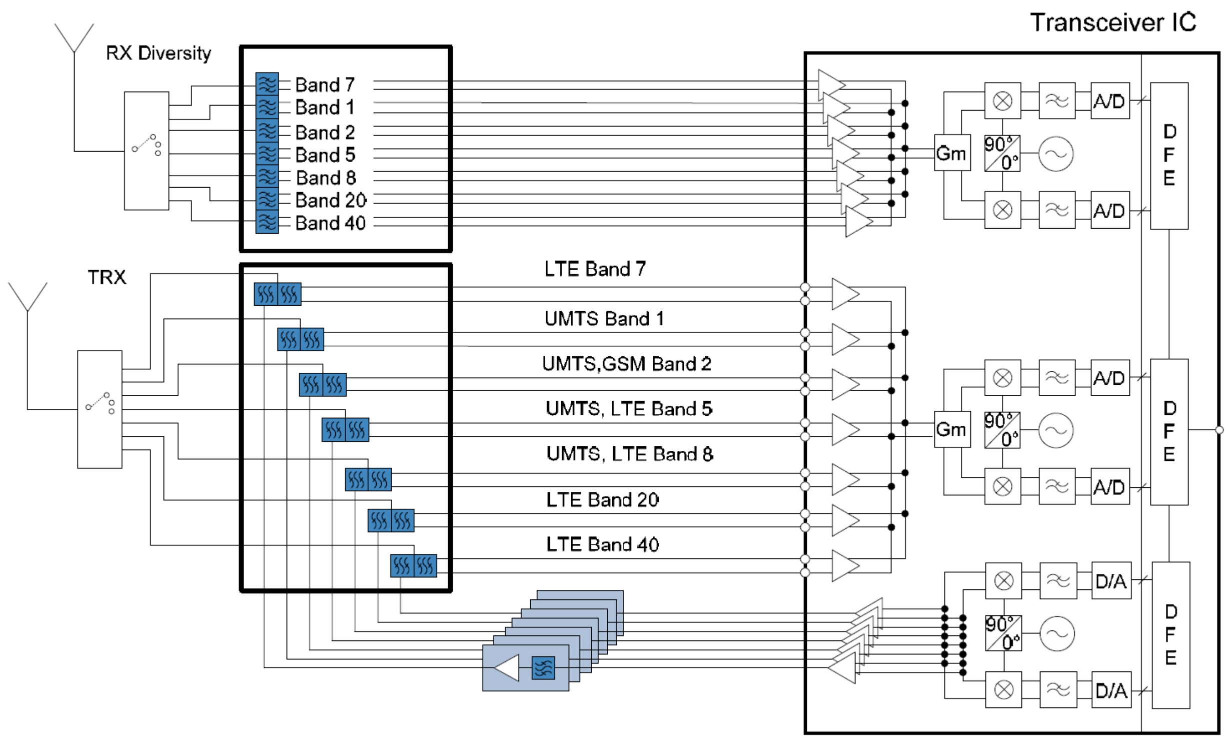
Adaptive RF Today

- Diagram Contains 28 Filters and 3 Operating in ~ 7 Bands (2010)
- Multi-Band RF is Accomplished by Switching Large Numbers of Discrete Acoustic Filters
- Configurations That Offer Resonator Reuse, Tunability and a Higher Degree of Adaptability (Beyond Mere Band Selection) are Desired

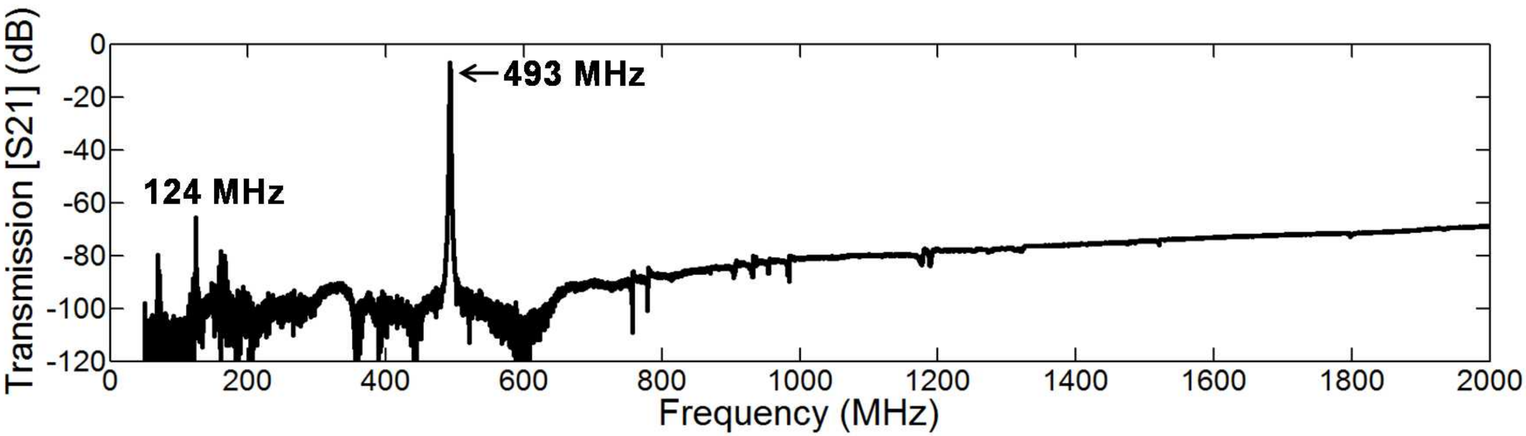


RF Front-End of a Modern Cellular Radio

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*

Outline

- Why is There Widespread Use of Inflexible Acoustic Resonator Filters in Multi-Band RF Systems
- What are the Different Types of Acoustic Resonators and How do They Compare
- What are the Prospects and Approaches for Tunable Acoustic Filters

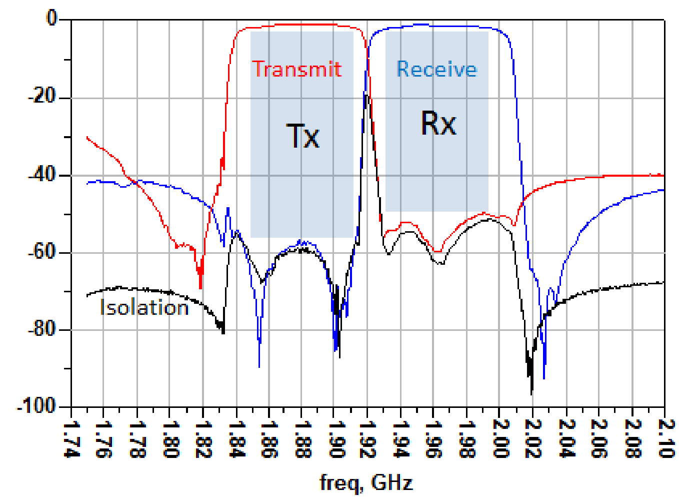


Response of an AlN Microresonator Filter

R. H. Olsson III, J. Nguyen, T. Pluym and V. Hietala, "A Method for Attenuating the Spurious Responses of Aluminum Nitride Micromechanical Filters," *IEEE Journal of Microelectromechanical Systems*, vol 23, no. 5, pp. 1198-1207, Oct. 2014..

Why Acoustic Resonators in RF Front-Ends

- Speed of Sound 4 Orders of Magnitude Slower Than the Speed of Light
  - *Can fit many acoustic filters in the volume of a single electromagnetic cavity*
- Acoustic Resonators Easily Achieve Q > 1000 in a Small Volume
  - *Required to meet duplexer loss and shape factor requirements*
- Acoustic Filter I.L. < 2 dB
- Acoustic Filters can Achieve High Linearity and Power Handling > 1W
- Acoustic Filters Achieve Steep Roll-Off and High Out-of-Band Rejection

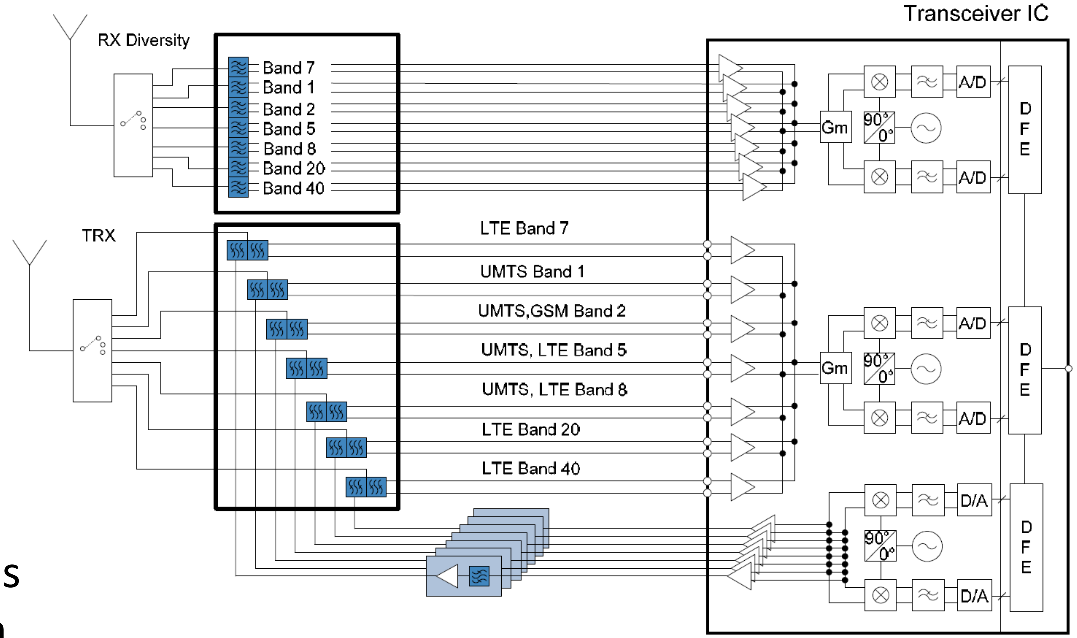


Filter Response of an Avago PCS Duplexer

G. Piazza, V. Felmetsger, P. Muralt, R. H. Olsson III and R. Ruby, "Piezoelectric Aluminum Nitride Films for Microelectromechanical Systems," *MRS Bulletin*, Vol. 37, pp.1051 – 1061, Nov. 2012.

Limitations of the Current Topology

- Adding Bands Eventually Becomes Un-scalable
  - *Filters Take up Disproportionate Volume and Cost*
  - *Losses from Routing and Switching Limit Further Scaling of this Approach*
- RF Switch Performance Is Poor In Emerging Bands at Higher Frequencies
- Carrier Aggregation is Desired Across Disjoint Channels and Bands Using a Minimum Number of Radios
- Wider Bandwidth Waveforms are Desired That are Beyond the Capabilities of Current Resonator Devices and Materials



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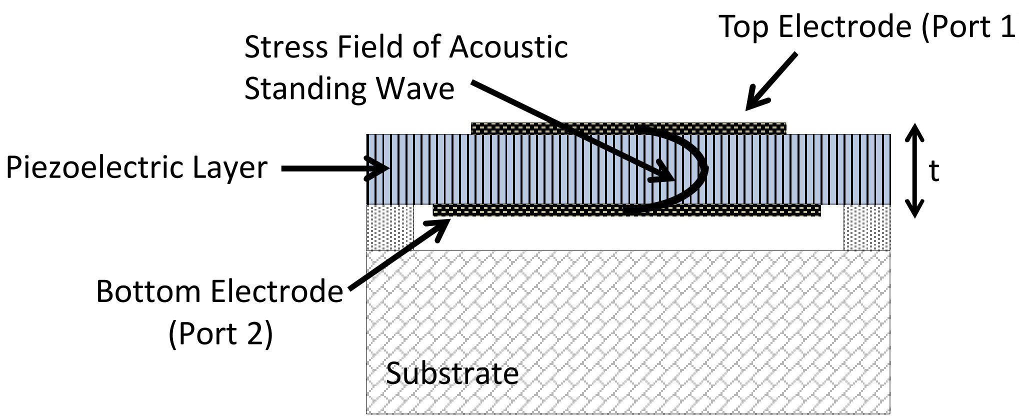
Film Bulk Acoustic Resonator (FBAR) and Bulk Acoustic Wave (BAW) Filters

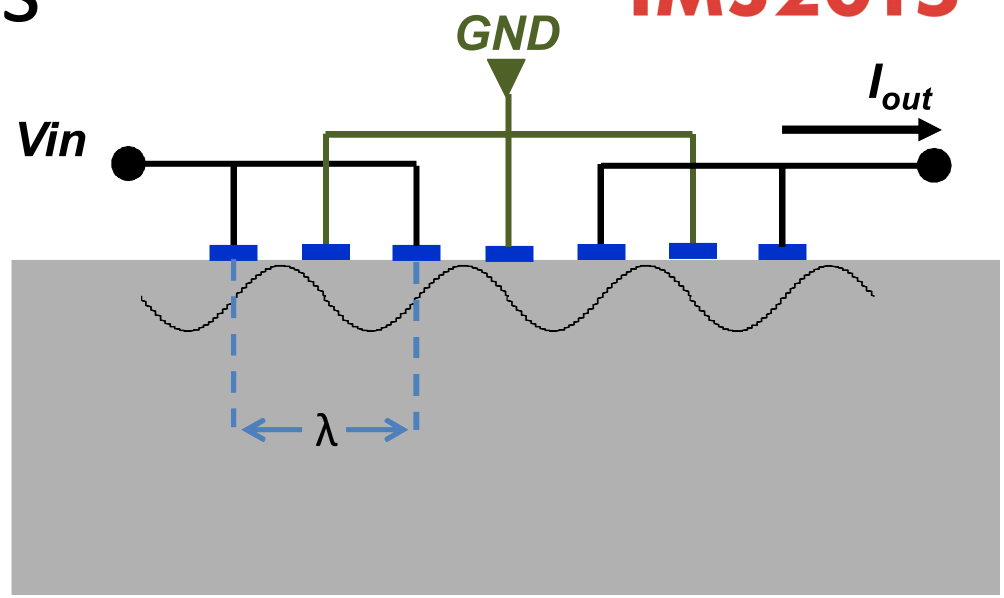
- Resonant Mode Through Thickness of a Piezoelectric Plate
  - *Requires a Different Total Thickness for Each Frequency*
  - *Wide Range of Thicknesses Required to Cover Existing and Emerging RF Bands*
- Aluminum Nitride is the Piezoelectric Material
- Widespread Use in Cellular Phone Handset Filters for the Most Challenging Filter Specifications
  - *Q = 1000 – 4000*
  - *K^2 ~ 6%*



Cross Section of a Film Bulk Acoustic Resonator

Surface Acoustic Wave (SAW) Filters

- Resonant Mode Propagating on Surface of Piezoelectric Plate
  - *Resonant Frequency Determined by Electrode Pitch*
  - *Wide Range of Frequencies on a Single Substrate*
- $LiNbO_3$ and $LiTaO_3$ are the most common materials for band select filters
- Widespread Use in Cellular Phone Handset Filters for Lowest Cost Filters
  - *Q ~ 500 - 1000*
  - *K^2 ~ 5 – 10 %*



Cross Section of a Surface Acoustic Wave Resonator

Electrostatic Microresonators

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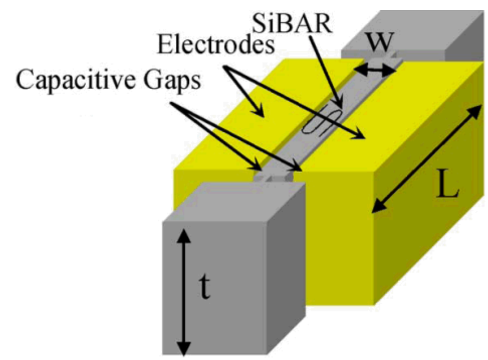
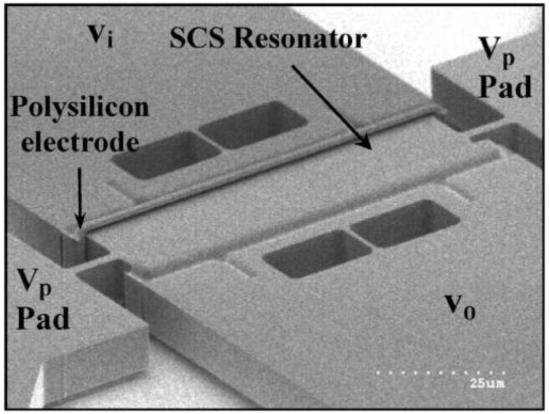
- Originally Pursued for Size Reduction and Integration with CMOS Foundry Materials and Processes
- Electrostatic Force Produced by Electric Field Across a Small Capacitive Gap
- Output Current Produced by Time Varying Capacitance with a Fixed Voltage
- Fundamentally Transduces Displacement
  - K^2 is Inversely Proportional to Center Frequency and is < 0.1% at RF Frequencies
  - Q > 10,000



Pourkamali et al. “Low-Impedance VHF and UHF Capacitive Si Bulk Acoustic Wave Resonators – Part I: Concept and Fabrication,” *IEEE Trans. On Electron Devices*, Vol. 54, No. 8, 2007.

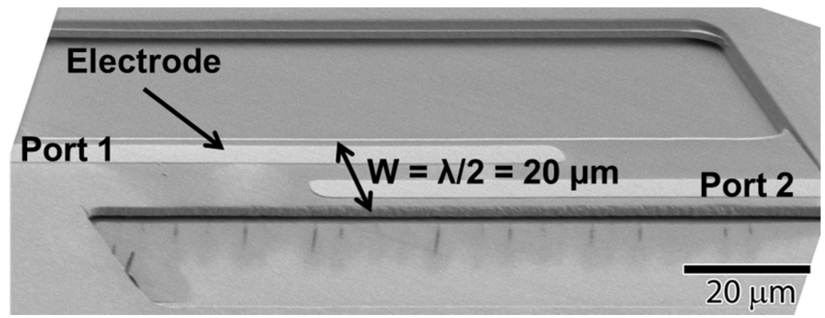


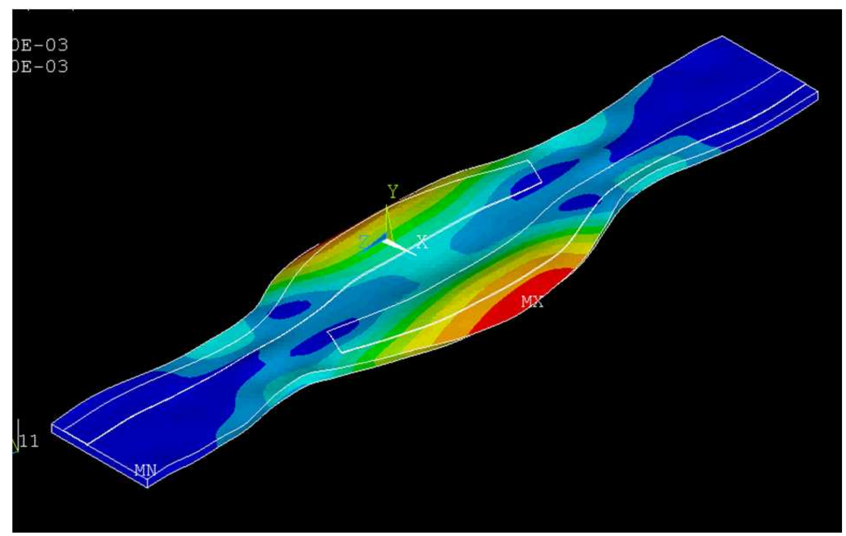
Images of an Electrostatic Extensional Resonator

Piezoelectric Microresonators

$$f = \frac{c}{\lambda} = \frac{6.0 km/s}{40 \mu m} = 150 MHz$$

- Driven Electrically into Vibration from an RF Source on the Device Electrodes Using the Piezoelectric Effect
- Vibrates at the Resonant Frequency Set by Mechanical Dimensions and Sound Velocity
- Much Smaller and Higher Q Factor (10x) Than LC Resonators
- Inverse Piezoelectric Effect Creates Time Varying Charge (i.e. Current) at the Output Electrodes
- May be Used for Miniature Filters in the Future
  - *Q ~ 1000 – 4000*
  - *K^2 ~ 1 – 20 %*

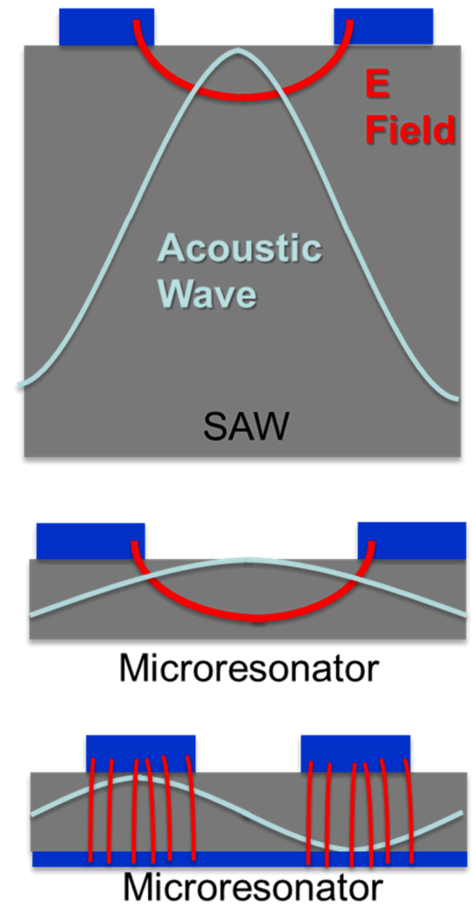




Microresonator Dimensions and S0 Mode Shape

Why Micromachining of Acoustic Resonators

- Increased interaction of the acoustic wave and electric field
  - ❑ ***Increased piezoelectric coupling***
  - ❑ ***Lower loss***
  - ❑ ***Wider bandwidth***
  - ❑ ***Higher tuning range***
- Decouple acoustic wavelength and transduction gap
  - ❑ ***Vastly Smaller Size***
  - ❑ ***Increased Transduction***
- 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***



Acoustic Resonator Fundamentals

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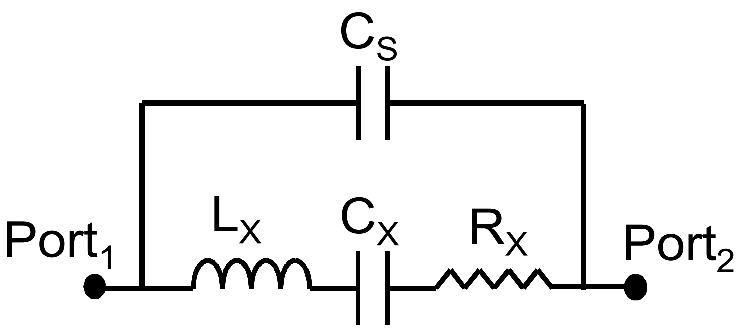
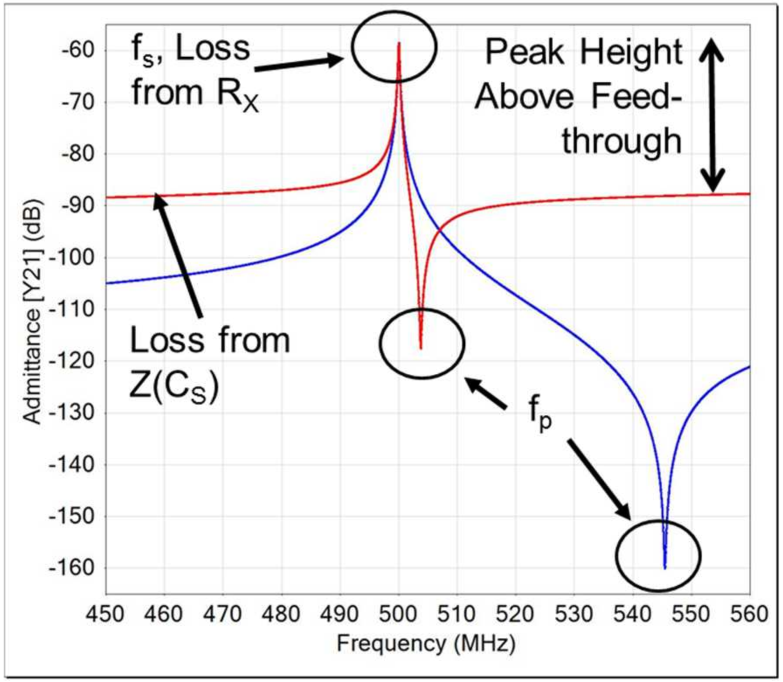
$$Minimum\ Insertion\ Loss \sim R_X = \frac{1}{\omega_0 C_s K^2 Q} = \frac{1}{\omega_0 C_s FOM}$$

$$Maximum\ Bandwidth \sim \frac{C_X}{C_s} = K^2 \sim \frac{f_p{}^2 - f_s{}^2}{f_p{}^2}$$

$$Isolation = \frac{Z_{C_S}}{R_X} = K^2Q = FOM$$



Resonator Equivalent Circuit Model



Simulation of Acoustic Resonators

- Aluminum Nitride Microresonators
  - C_s = 12.5 fF
  - K^2 = 1.5 %
  - Q = 2000
  - FOM = 30
- Lithium Niobate Microresonators
  - C_s = 1 fF
  - K^2 = 20 %
  - Q = 2000
  - FOM = 400

C. D. Nordquist and R. H. Olsson III, ""Radio Frequency Microelectromechanical Systems (RF MEMS)," *Wiley Encyclopedia of Electrical and Electronics Engineering*, pp. 1-31, Dec. 2014.

Piezoelectric Resonator Electro-Mechanical 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^2*
- Maximum Tuning Range ~ K^2

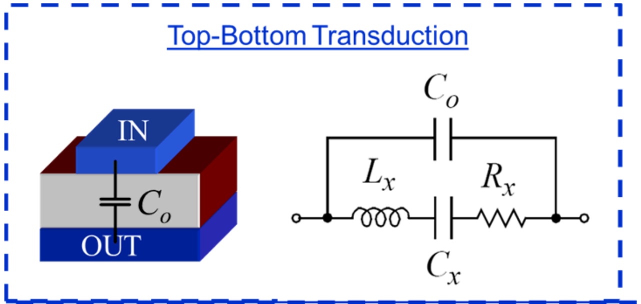
$$C_x = K^2 C_0$$

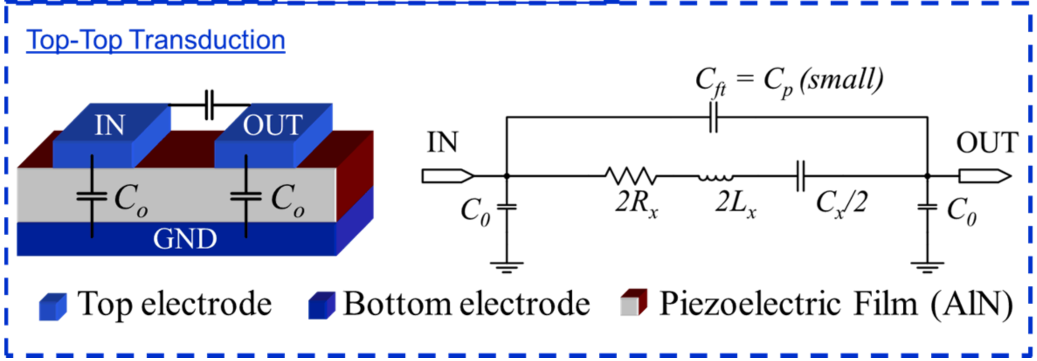
$$L_x = \frac{1}{\omega_0^2 K^2 C_0}$$

$$R_x = \frac{1}{\omega_0 C_0 K^2 Q}$$

$$K^2 = \frac{C_X}{C_0} = \frac{8}{\pi^2} \frac{d_{ij}^2 E_{ij}}{\varepsilon_{ij}}$$

$$FOM = K^2 Q$$





Connecting Minds. Exchanging Ideas.

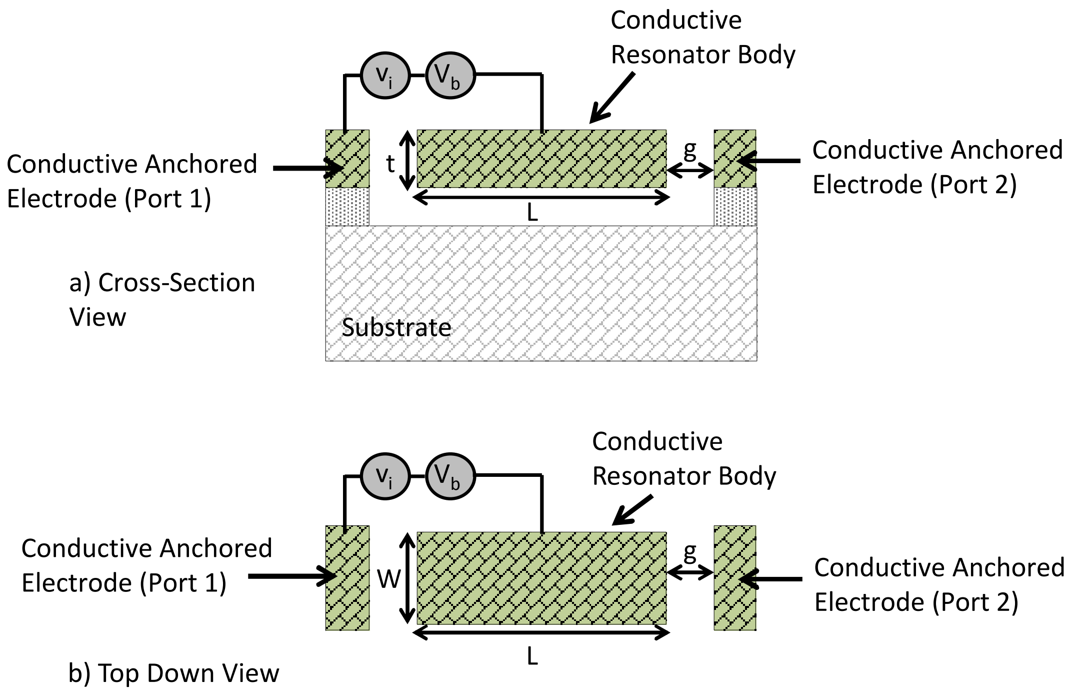
Electrostatic Resonator Electromechanical Transduction

Force $$F = \frac{V_b \varepsilon W t}{g^2} v_i = \frac{V_b C_S}{g} v_i$$

Displacement $$x = \frac{FQ}{k}$$

Current $$|i_o| = \frac{V_b \varepsilon W t}{g^2} 2\pi f_s x$$

$$|i_o| = \left(\frac{2\pi f_s Q}{k}\right)\left(\frac{V_b C_S}{g}\right)^2 v_i$$



Cross Section and Top Down View of an Electrostatic Resonator

Motional Impedance

$$2R_X = \frac{v_i}{i_o} = \frac{k}{2\pi f_s Q}\left(\frac{g^2}{V_b \varepsilon W t}\right)^2 = \frac{k}{2\pi f_s Q}\left(\frac{g}{V_b C_S}\right)^2$$

C. D. Nordquist and R. H. Olsson III, ""Radio Frequency Microelectromechanical Systems (RF MEMS)," *Wiley Encyclopedia of Electrical and Electronics Engineering*, pp. 1-31, Dec. 2014.

Electrostatic Resonator Transduction Cont.

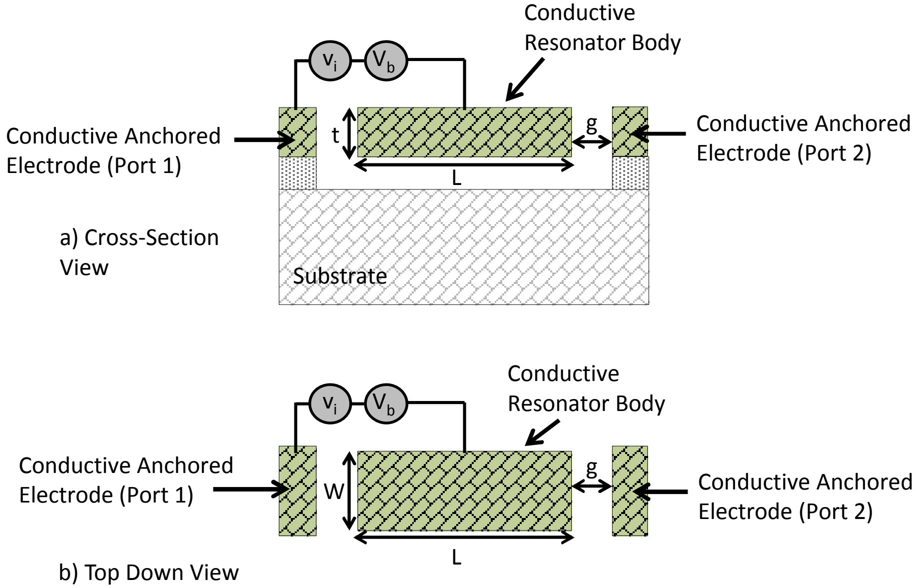
Motional Impedance

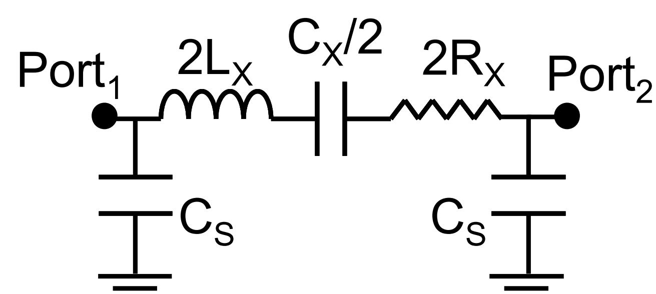
$$2R_X = \frac{v_i}{i_o} = \frac{k}{2\pi f_s Q}\left(\frac{g}{V_b C_S}\right)^2$$

Electromechanical Coupling

$$K^2 = \frac{{V_b}^2 \varepsilon}{\pi^2 f_s g^3 \sqrt{E\rho}}$$

- Electrostatic or Capacitive Resonators Transduce Displacement (As Opposed to Strain) and Therefore Have an Electromechanical Coupling That Degrades with Operating Frequency





Performance of Different Acoustic Resonator Technologies

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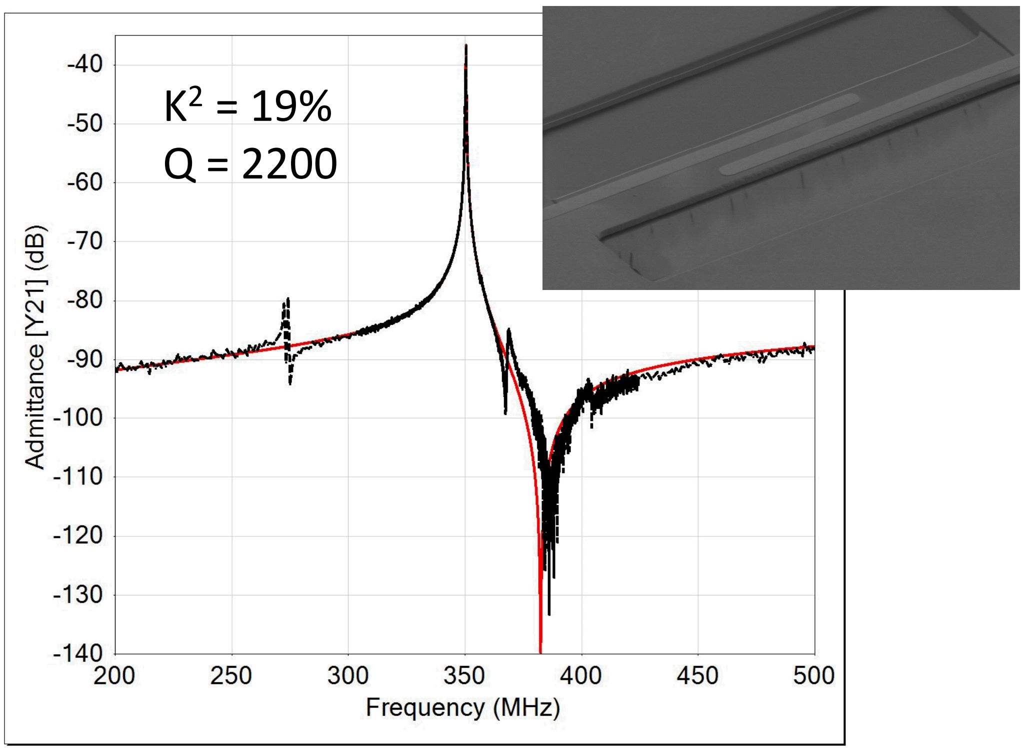
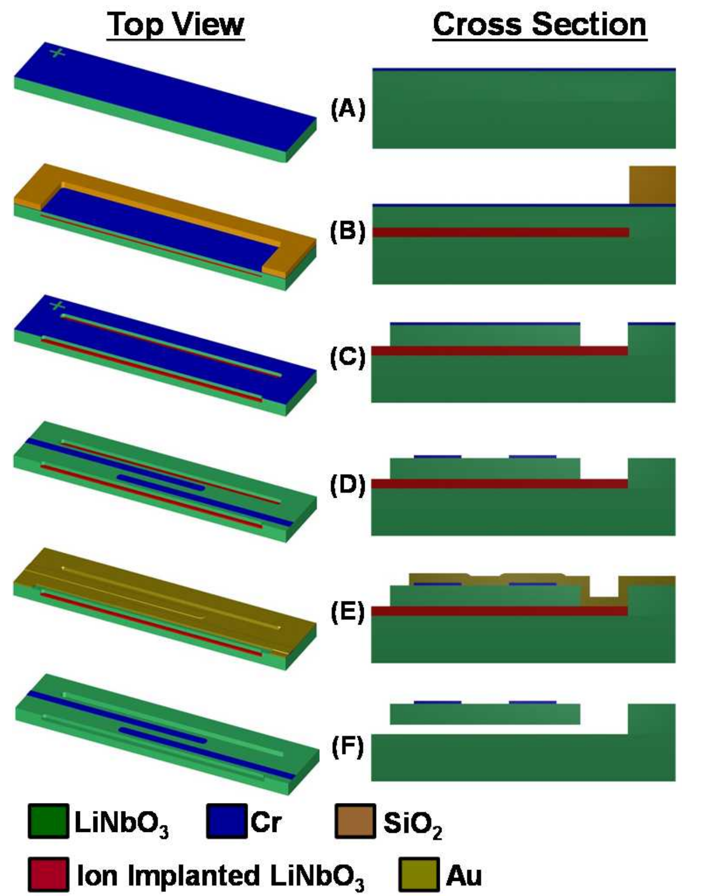
Technology/ Metric	K^2 Theory	K^2 Experiment	Q @ ~ 1 GHz	~FOM Measured	Max. Tuning Range	Multiple Frequencies on a Substrate
AlN BAW/FBAR	5.3%	5.7%	3000	170	2.85 %	High Cost
Standard $LiTaO_3$ SAW	5.3%	5.3%	600	32	2.65 %	Yes
Electrostatic Resonators	< 0.1%	<< 0.1%	~10,000	< 1	Very Low	Yes
AlN Microresonator	1.6%	1.5%	2350	35	0.75 %	Yes
Doped AlN BAW	***12.2***	***9.7***	***< 1000***	***< 170***	***4.85 %***	***High Cost***
Advanced SAW	***> 16 %***	***16.2 %***	***2000***	***324***	***8.1%***	***Limited***
$LiNbO_3$ Microresonator	***40%***	***19%***	***2200***	***420***	***9.5%***	***Yes***

$LiNbO_3$ Micromechanical Resonators

- Extremely High Coupling and Figure of Merit
- Low Loss and Wide Tuning Range

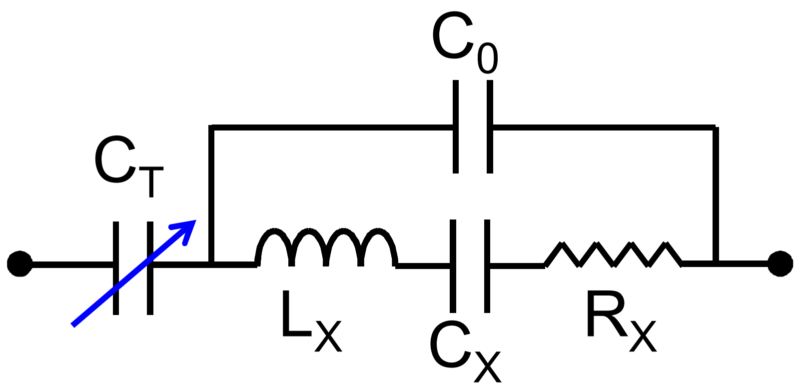




R. H. Olsson III, K. Hattar, M. S. Baker, M. Wiwi, J. Nguyen, C. Padilla, S. J. Homeijer, J. R. Wendt and T. A. Friedmann, “Lamb Wave Micromechanical Resonators Formed in Thin Plates of Lithium Niobate,” *Solid-State Sensor, Actuator, and Microsystems Workshop,* pp. 281-284, June 2014.

What are the Prospects for Tunable Acoustic Resonators and Filters

Electrical Tuning of Acoustic Resonators

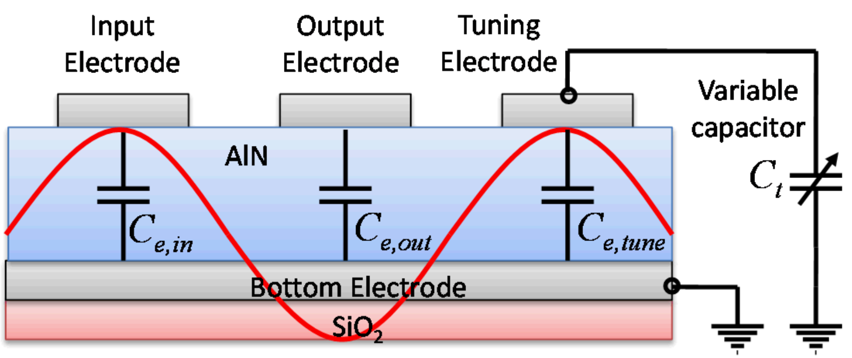


2-Port Tunable Resonator Model

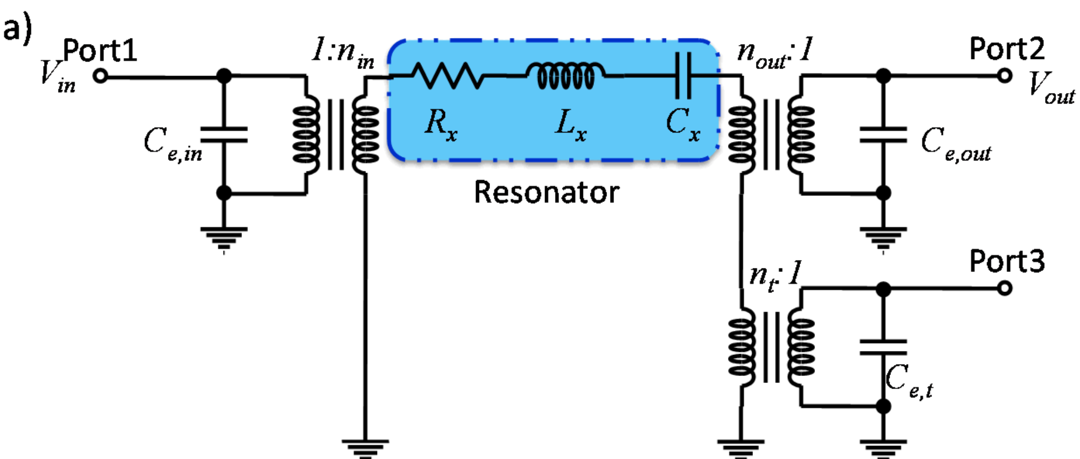
$$\frac{\Delta f}{f_0} \approx \frac{C_X}{2(C_0 + C_T)}$$

$$\frac{\Delta f_{MAX}}{f_0} \approx \frac{C_X}{2C_0} = \frac{K^2}{2}$$

Electrical Tuning of Acoustic Resonators



3-Port Tunable Micromechanical Resonator Cross-Section

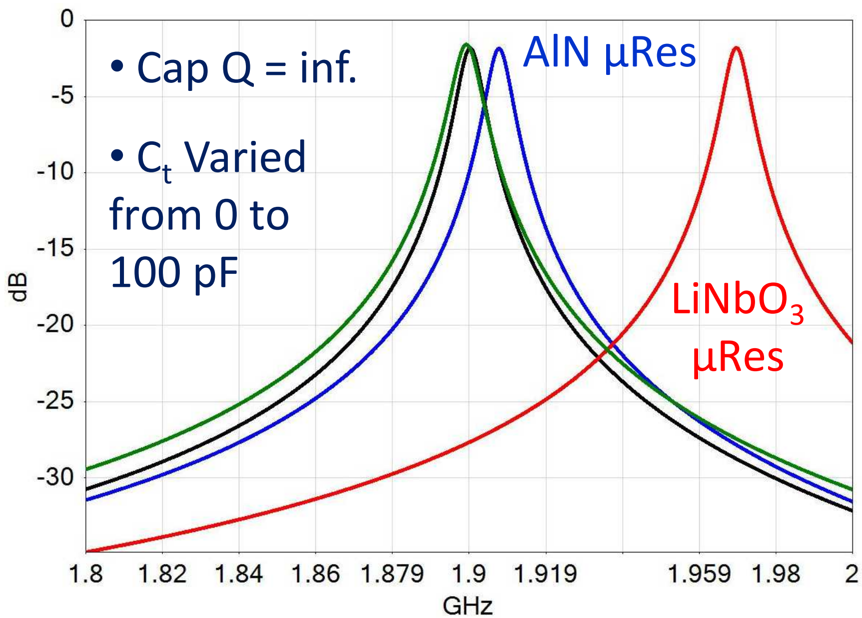


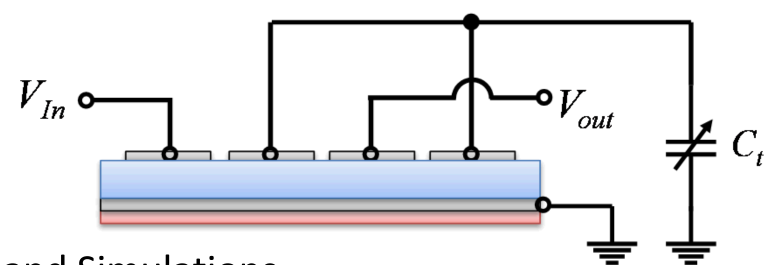
$$\frac{\Delta f_{MAX}}{f_0} \approx \frac{n_t}{n_t + n_{in} + n_{out}} \frac{K^2}{2}$$

Connecting Minds. Exchanging Ideas.

Ideal Resonator Tuning

- *AlN Microresonator*
  - K^2 = 1.6%
  - Tuning Range = 0.4%
- *$LiNbO_3$ Microresonator*
  - K^2 = 16%
  - Tuning Range = 4%
- *Q = 1500*
- *R_X = 5 Ω*
- *Using ½ of the K^2 for Bandwidth and ½ for Tuning*
- *C_t Varied From 0 to 100 pF*
- *Loss is the Same Regardless of Frequency for Lossless Capacitors*

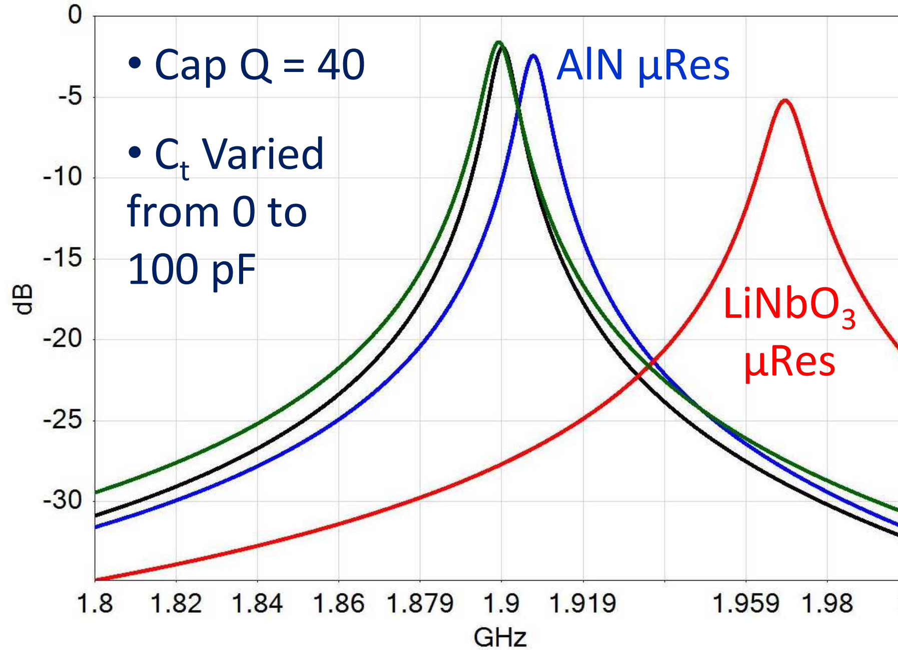


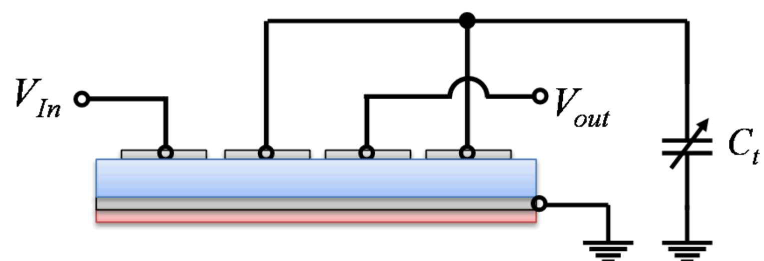


Example and Simulations of Acoustic Resonator Electrical Tuning

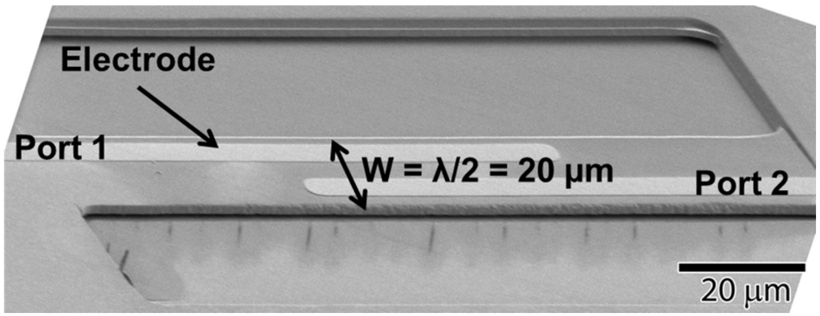
Resonator Tuning with Realistic Capacitors

- *AlN Microresonator*
  - $k_t^2 = 1.6\%$
- *$LiNbO_3$ Microresonator*
  - $k_t^2 = 16\%$
- *$Q_{Acoustic} = 1500$*
- *$R_X = 5\ \Omega$*
- *Q of all Capacitors = 40*
- *The Q and Value of the Intrinsic Resonator Capacitor is Critical*
- *The More the Resonator is Tuned Away From it's Natural Frequency, the More Energy That is Stored in the Shunt and Tuning Capacitors*
- *Low Capacitor Q Degrades Performance for Wide Tuning*
- *Electrical Tuning May Reach $F_s/10$ in Advanced Materials*

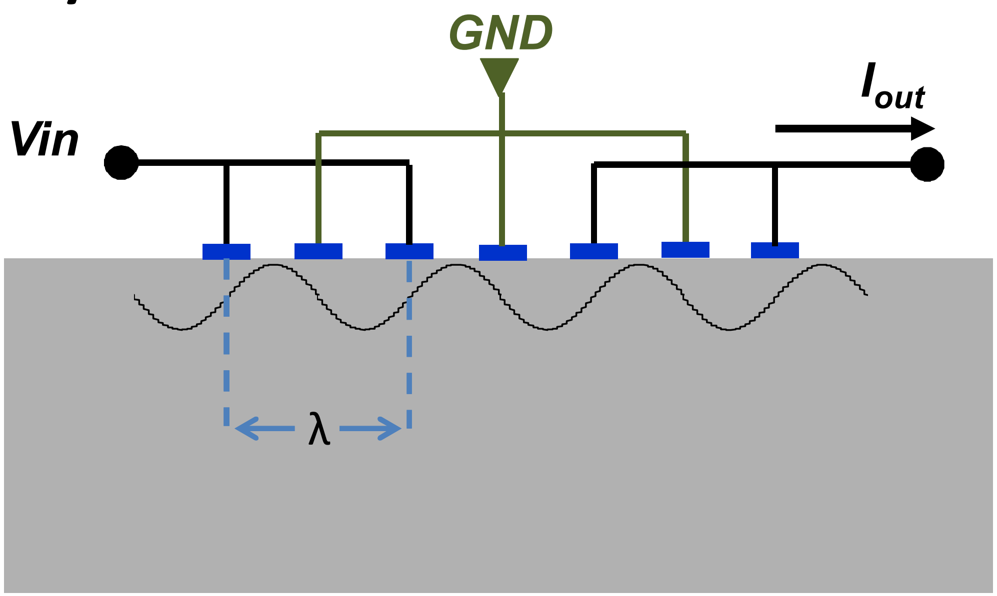




Can We Find a Way to Alter the Geometry?



SEM of a $LiNbO_3$ Micromechanical Resonator



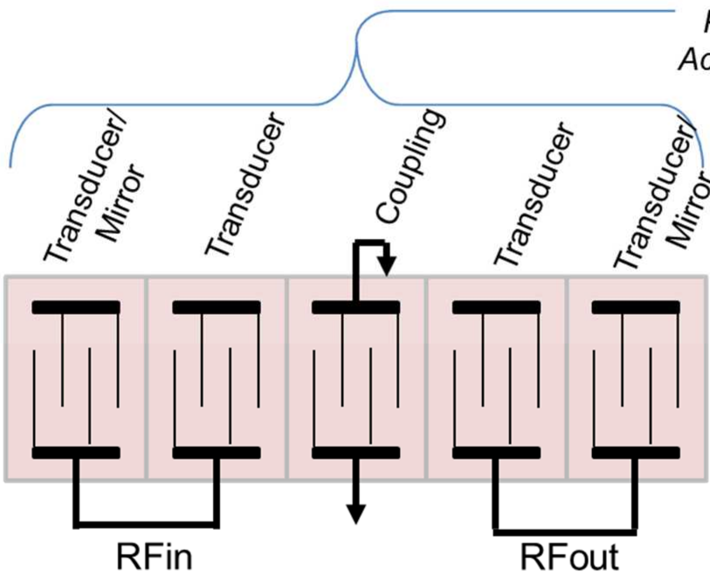
Cross Section of a Surface Acoustic Wave Resonator

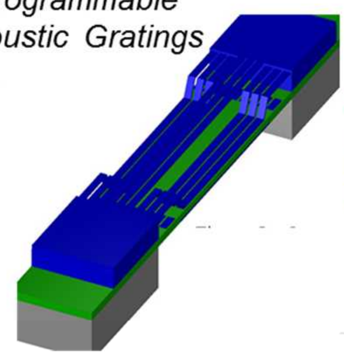
$$f = \frac{c}{\lambda}$$

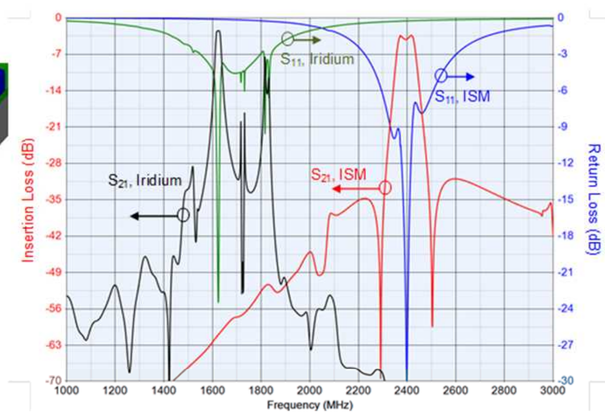
← Determined by Physical Dimensions

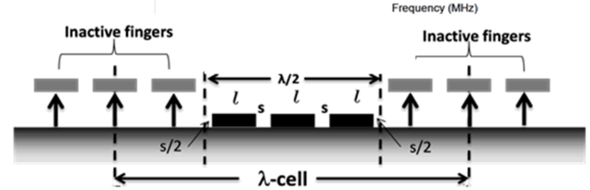
Field Programmable Acoustic Filter Elements

- We will realize a broadly reconfigurable acoustic filter by modulating the pitch and coupling of transducer fingers in real-time.
- Control of individual transducer fingers will allow complete flexibility of center frequency, bandwidth, and bandshape in a single high-Q element.
- Coupling-of-modes modeling will predict and synthesize filter response

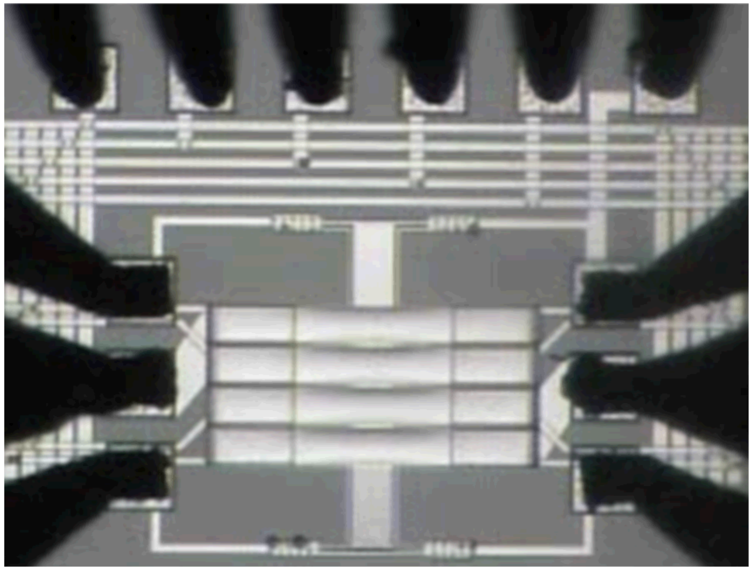




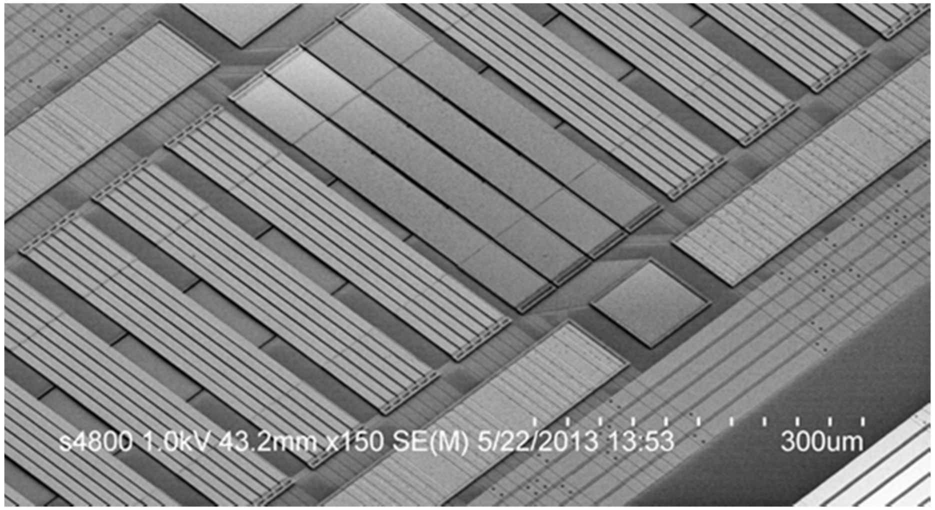




Programmable Acoustic Elements



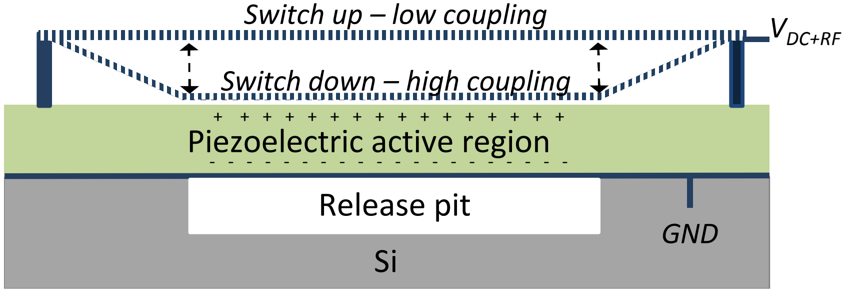
Individually Addressable Microresonator Electrode Fingers



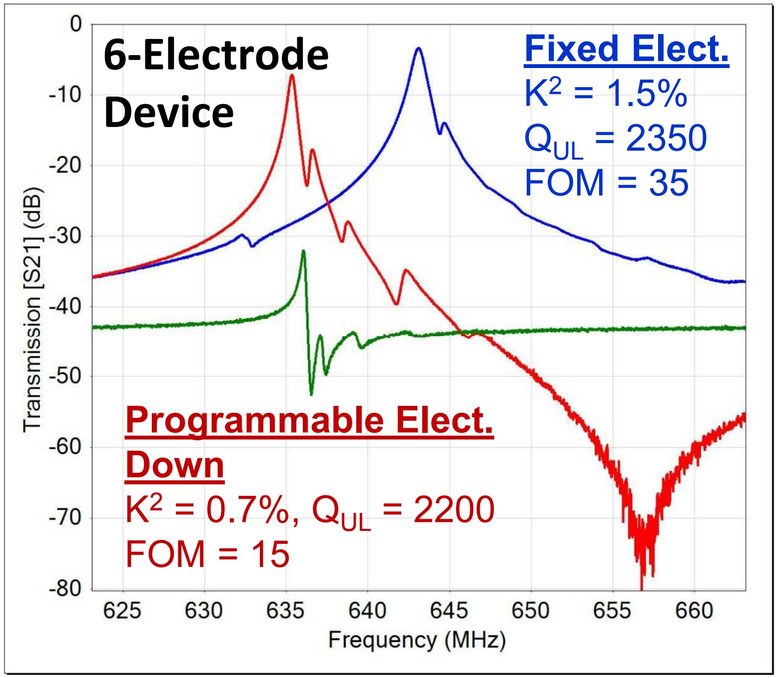
SEM Image of Filter Design Utilizing Multiple MEMS Switches

On-Off Switch Resonator: A First Step Towards Field-Programmable Acoustic-Filter Elements

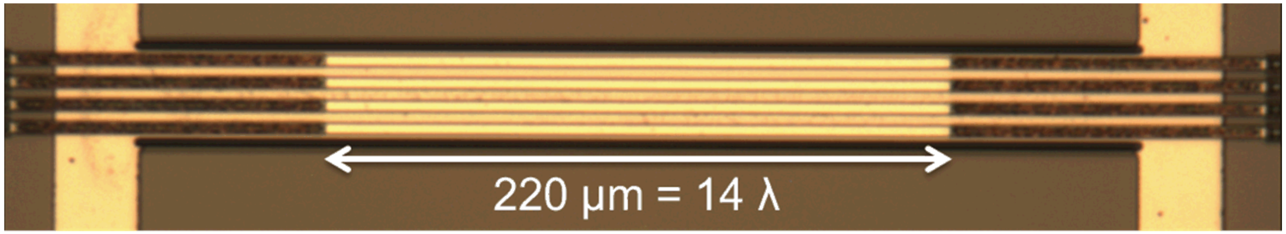
C. D. Nordquist, R. H. Olsson III, S. M. Scott, D. W. Branch, T. Pluym, and V. Yarberry, "On/Off Micro-Electromechanical Switching of AlN Piezoelectric Resonators," *IEEE International Microwave Symposium,* pp. 1-3, June 2013.



Switch Acoustic Filter Cross Section



Comparison of Fixed and Programmable Fingers



Resonator with Programmable Electrode Fingers

Summary

- Switched Banks of Acoustic SAW and BAW Filters Form the Frequency Control Functions at the RF Frontend of Cellular Handsets
  - Small Footprint, Steep Filter Skirts, Low Insertion Loss, High Linearity and Power Handling
- Each Additional Band Requires Adding a New Discrete Filter and Switch. This type of scaling in not sustainable
- New Resonator and Filter Architectures are Needed The Reuse Resonators Across Filters and Frequency Bands
  - New High Electromechanical Coupling Materials Will Lead to Electrical Tuning Up to 10% of Center Frequency
  - Methods for Altering the Resonator Geometry Are Being Pursued That Potentially Offer Many Octaves of Tuning Range