VHF and UHF Filters for Wireless Communications Based on Piezoelectrically-Transduced Micromechanical Resonators

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A Little Bit about Myself

BIOGRAPHICAL SKETCH

Name	Position Title
Jing Wang	Associate Professor

Professional Preparation

Institution and Location	Field of Study	Degree	Year
Tsinghua University, Beijing	Electrical Engineering	B.S.	1999
Tsinghua University, Beijing	Mechanical Engineering	B.S.	1999
University of Michigan, Ann Arbor	Electrical Engineering	M.S.	2000
University of Michigan, Ann Arbor	Mechanical Engineering	M.S.	2002
University of Michigan, Ann Arbor	Electrical Engineering	Ph. D.	2006

Appointments

2010-present	Graduate Faculty Scholar, Department of Electrical Engineering and Computer Science, University of Central Florida
2012-present	Associate Professor, Department of Electrical Engineering, University of South Florida
2006-2012	Assistant Professor, Department of Electrical Engineering, University of South Florida
2005-2006	Visiting Research Scientist, Department of Electrical and Computer Engineering, Michigan State University

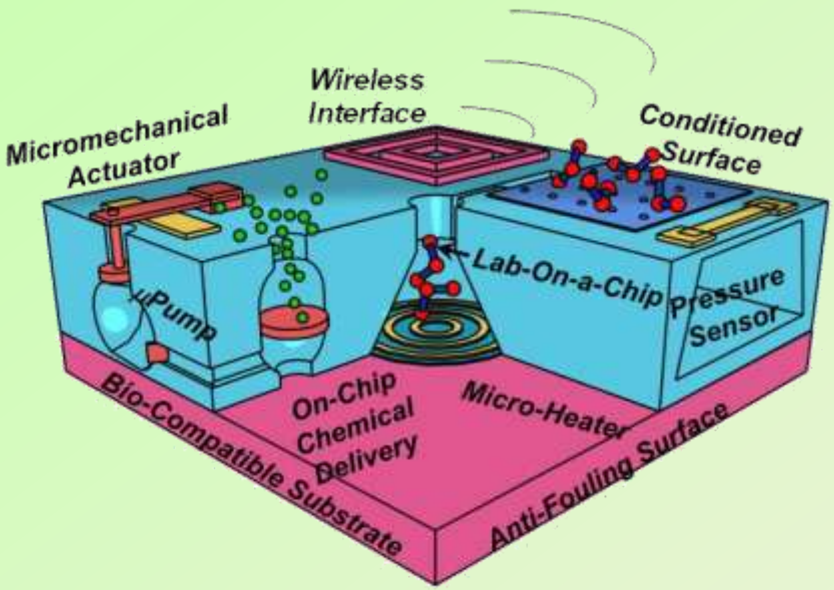
I just found out I was born the year UIA was established.
My work spans from ultrasonic to electromagnetic waves.

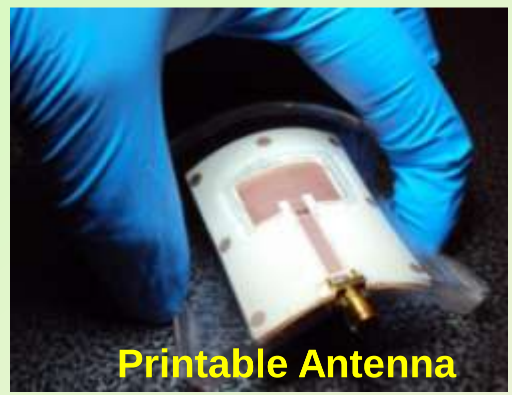
University of South Florida is Located at Tampa, FL

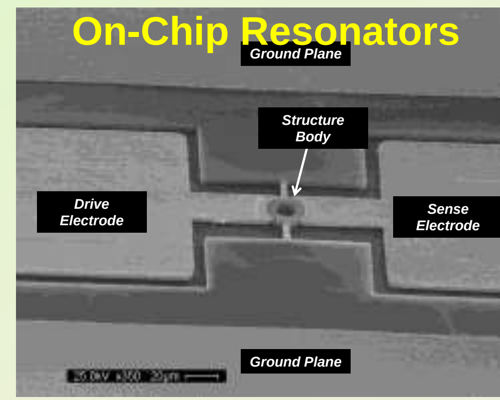
Tampa is a metropolitan city surrounded by beautiful state parks, pristine rivers, amazing wildlife, and breathtaking beaches. University of South Florida (USF) has >47,000 students.

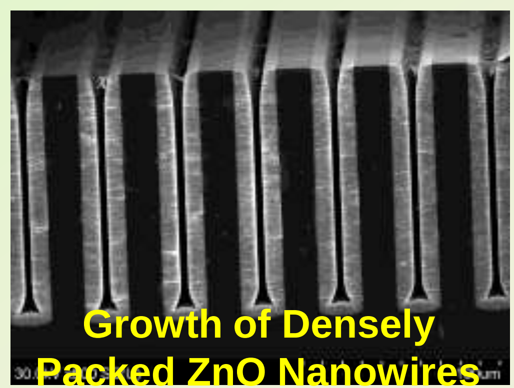
My Current Research Interests

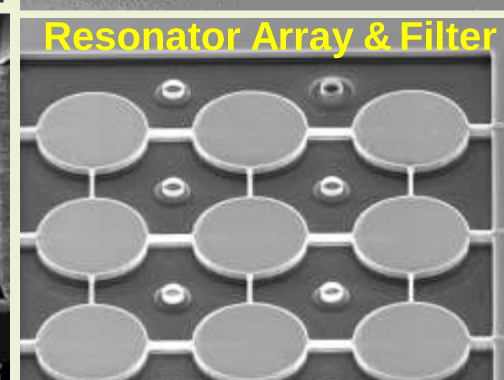
- **Functional Nanomaterials**
- **Micromachined Sensors and Actuators**
- **RF/Microwave/Bio MEMS/Electronic Devices**











Today's Topic:

Piezoelectrically-Transduced High-Q On-Chip μmechanical Resonators & Filters (100μm)

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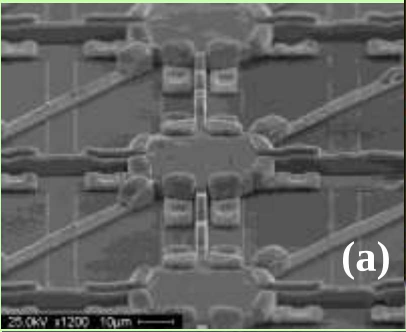
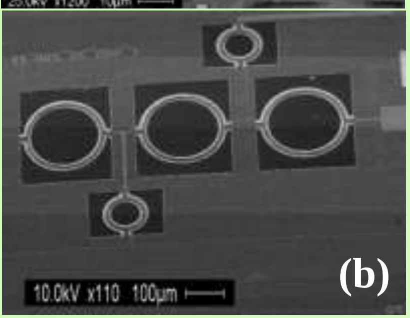
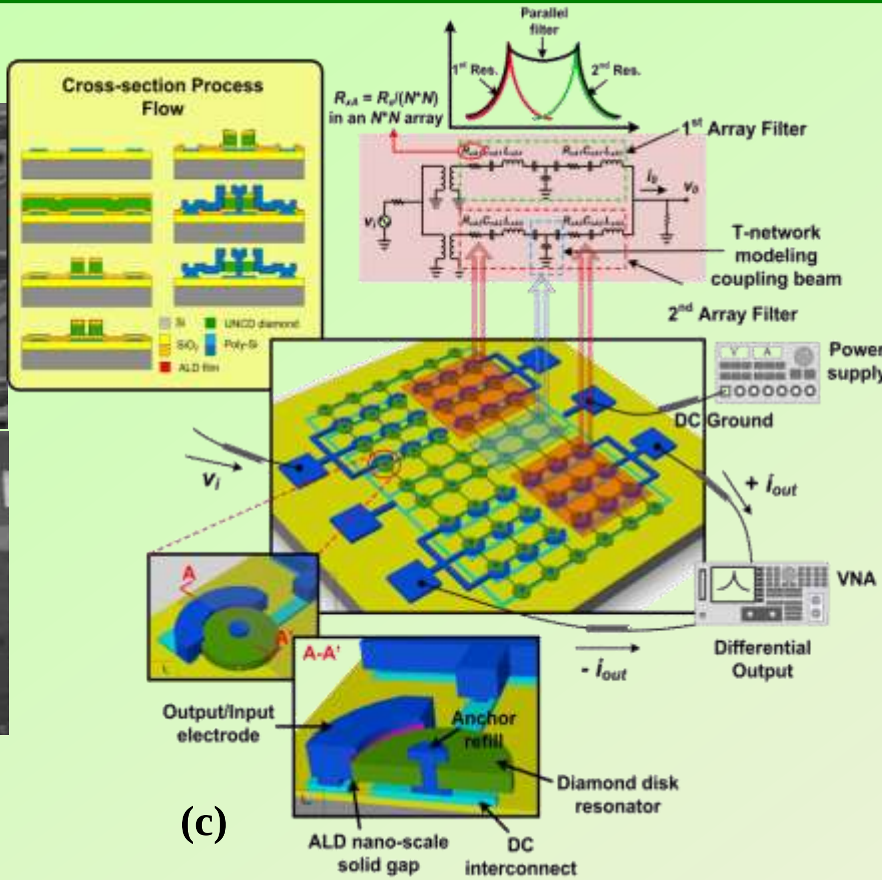
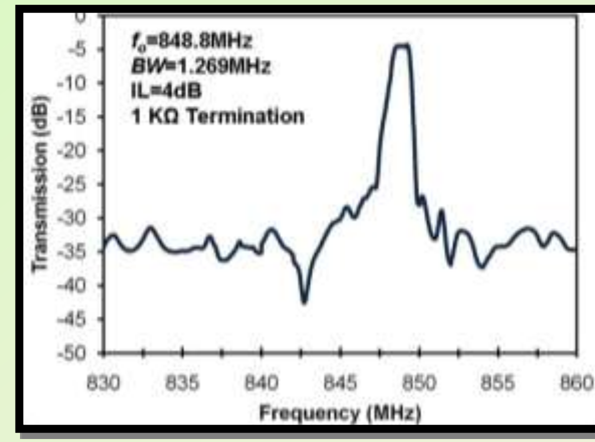
College of Engineering

Research: High-*Q* RF MEMS Resonators and Filters









Recent advent of RF MEMS filters developed at USF that can directly replace its counterparts in today's cell phones to extend battery life.

(a) Capacitively-transduced and mechanically-coupled micromechanical resonator development – Equivalent Circuit Extraction

(b) Piezoelectrically-actuated resonator array and filter – RF Characterization

(c) More complex micromechanical signal processor such as mechanically-coupled/electrically-coupled resonator filters can be developed by using high-*Q* resonators as building blocks.

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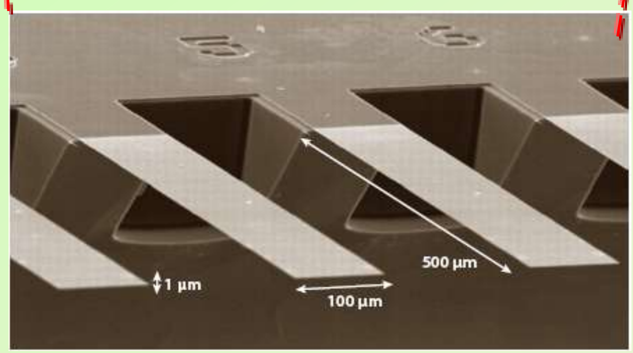
Fundamentals and Concepts of Micromechanical Resonant Sensors

From Macro to Micromechanical Transducers

- **Can a diving board be a functional sensor?**
  - http://www.youtube.com/watch?v=N3zA1bYqe3M

Size Reduction by ~10,000X or more



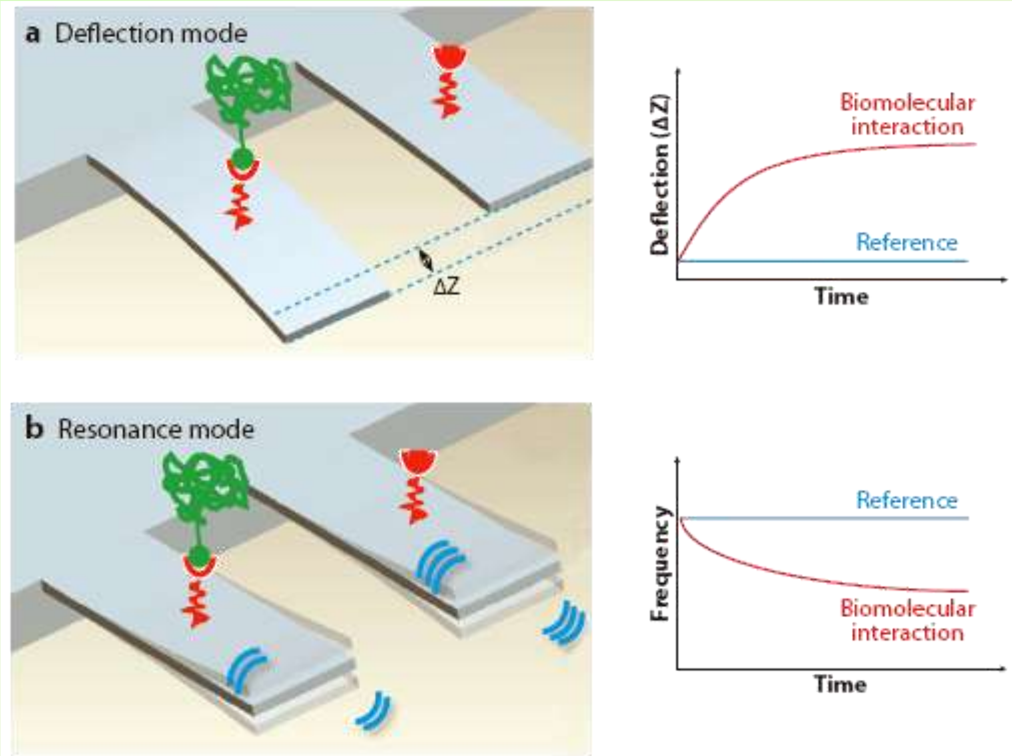


Figure 1

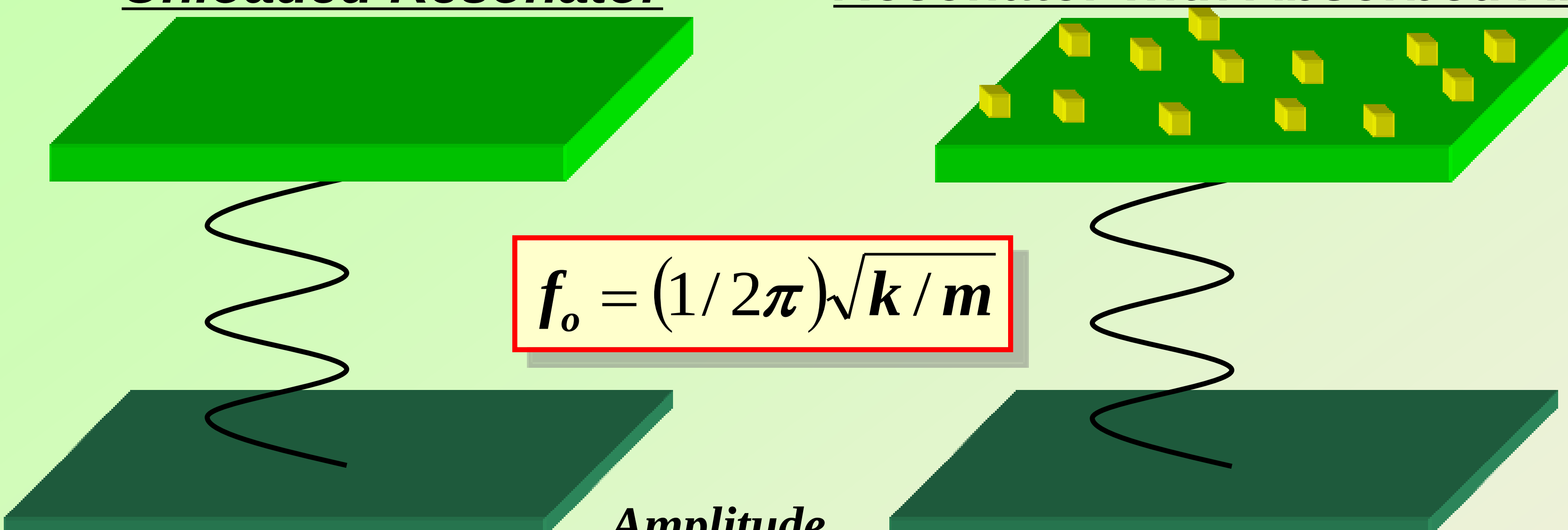
Two modes of cantilever-based biomolecule detection: (*a*) deflection mode and (*b*) resonance mode.

Static Mode vs. Resonant Mode Operations

As Moore's law in transistors, we are approaching the ultimate scaling limit!

Frequency Shift Induced by Mass Loading Effect

Unloaded Resonator ***Resonator with Absorbed Analyte***

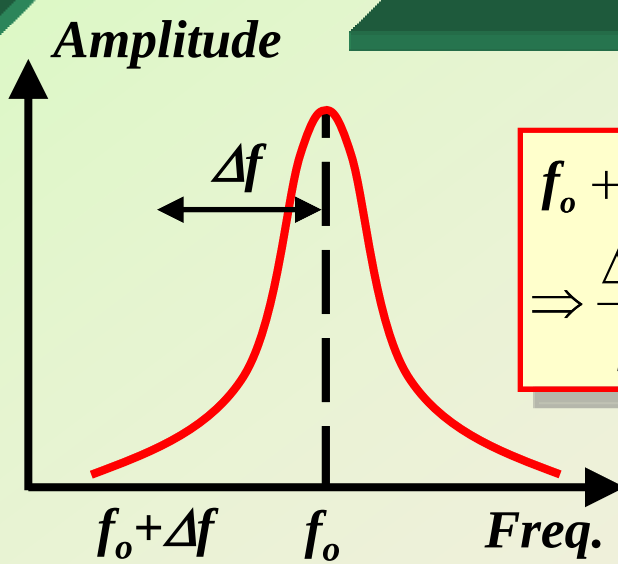


$$f_o = (1/2\pi)\sqrt{k/m}$$

$$\frac{x}{F} = \frac{1}{k}\frac{\omega_0{}^2}{(\omega_0{}^2 - \omega^2) + j\frac{\omega_0}{Q}\omega}$$

$$\frac{x}{F} = \frac{Q}{jk} \text{ (when } \omega = \omega_0\text{)}$$

$$\frac{x}{F} = \frac{1}{k} \text{ (when } \omega = 0\text{)}$$



$$f_o + \Delta f = (1/2\pi)\sqrt{k/(m+\Delta m)}$$

$$\Rightarrow \frac{\Delta f}{f_o} = \frac{-\Delta m}{2m} \Rightarrow \text{Proportional}$$

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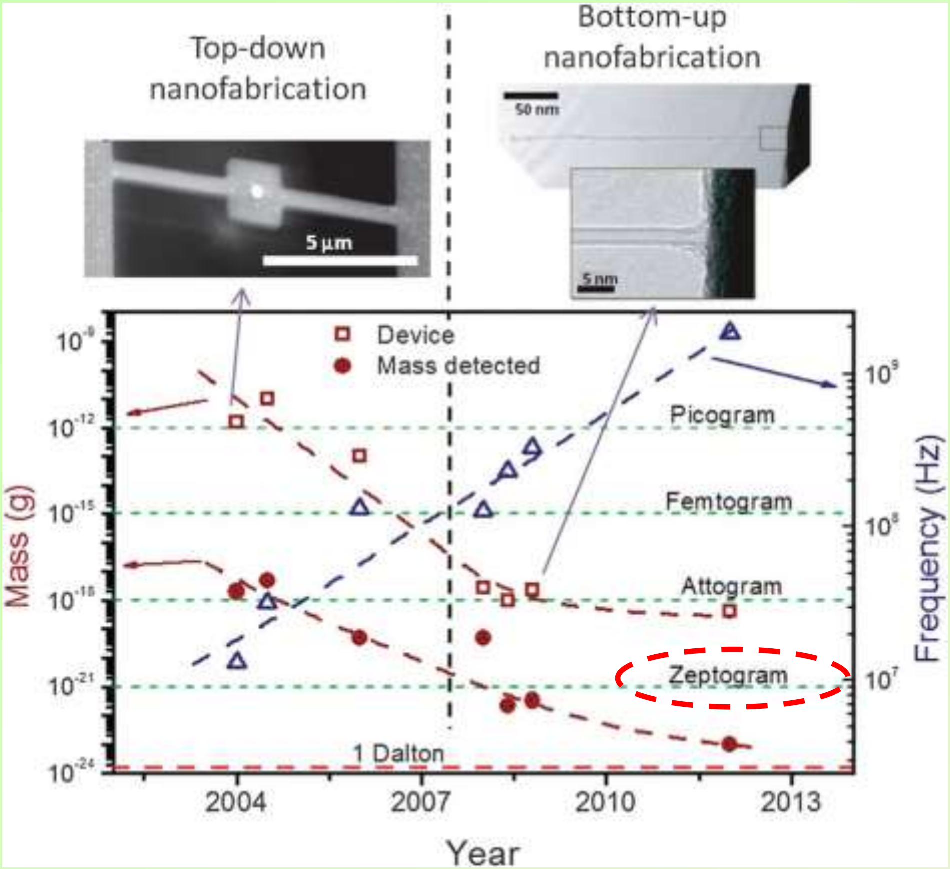
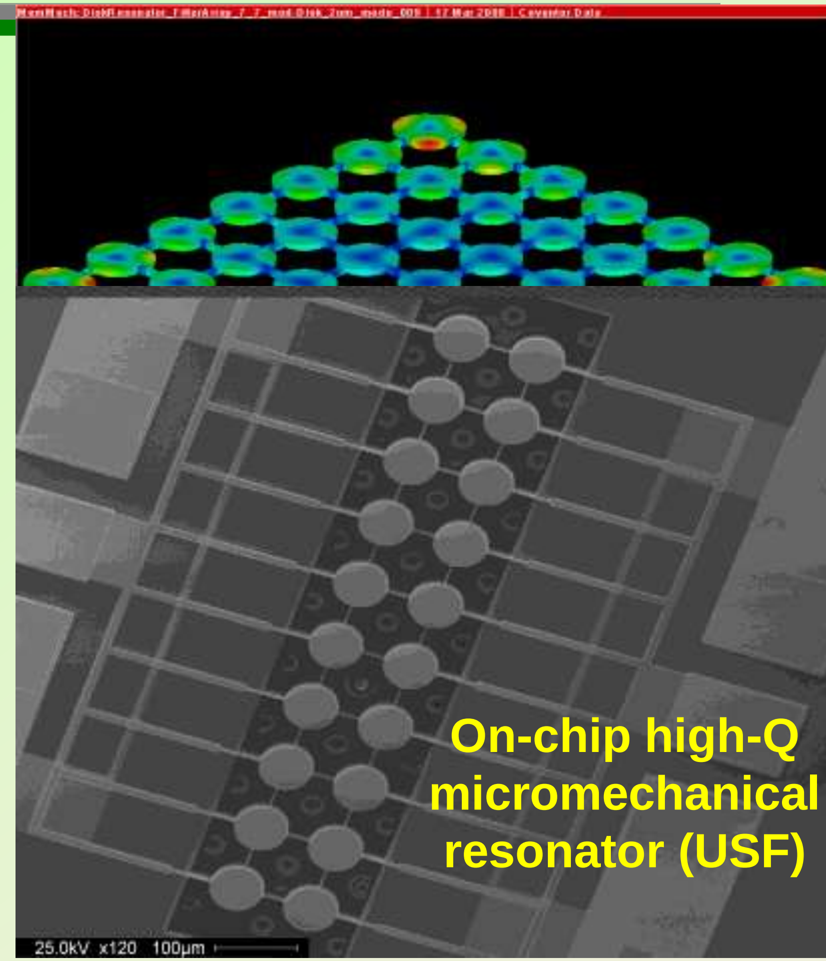
From a Diving Board to Micro/Nano-Cantilevers

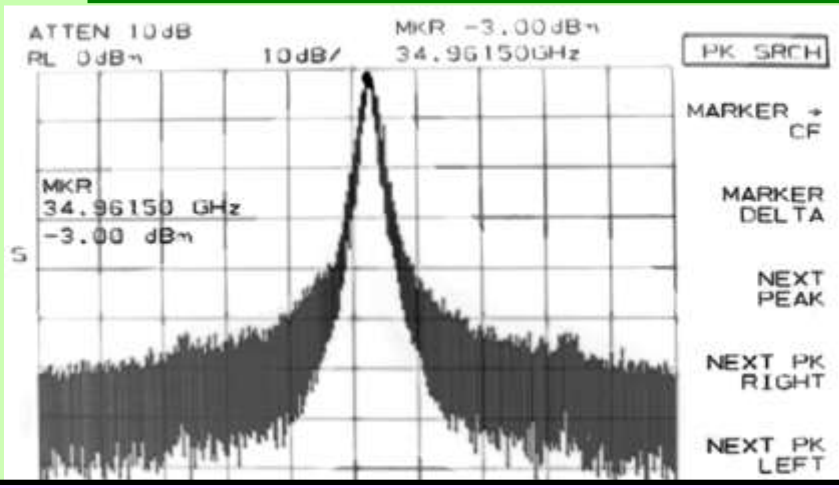




- Nano-cantilever reached zepto-gram (10^{-21}g) detection limit
- However, we are approaching the ultimate scaling limit.
- ***Solution***: replacing flexural mode by stiffer extensional mode.

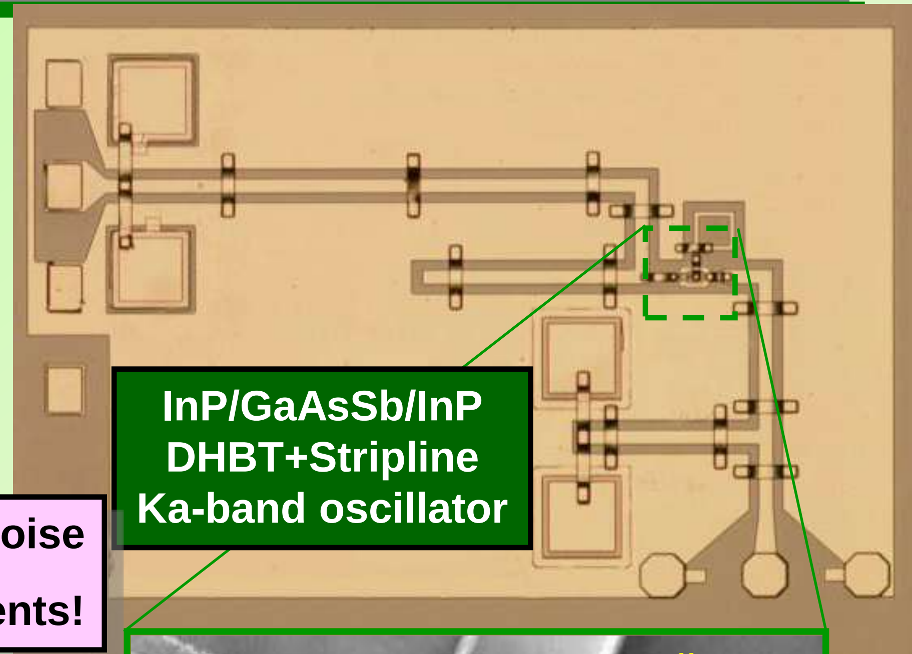
Piezoelectrically-Transduced Micromechanical On-Chip High-Q Resonators and Filters

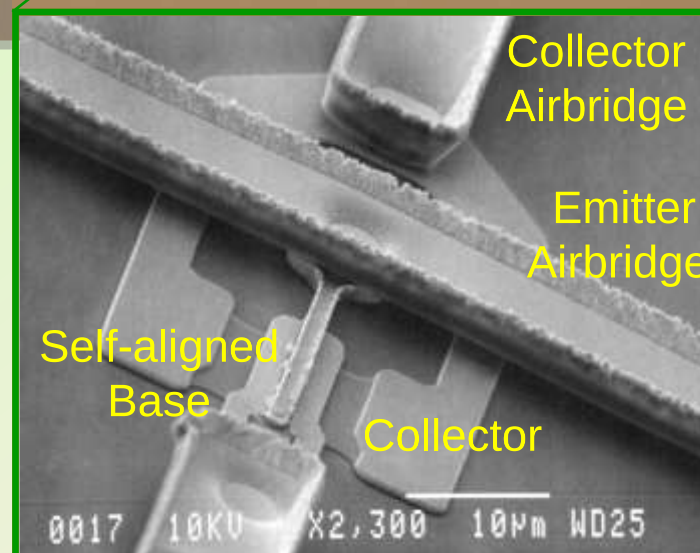
Design and Fabrication of InP DHBT MMIC's



Issue: **low-*Q* CPW resonator ⇒ high phase noise**

***Solution*: high-*Q* on-chip RF MEMS components!**

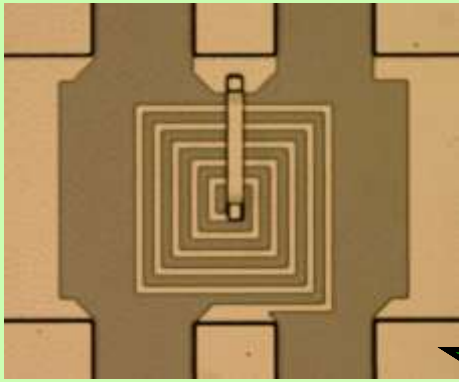




- **Active device size: 2×10μm^2**
- **Oscillation frequency: 34.9GHz**
- **Phase noise: -92dBc/Hz @ 1MHz offset**
  - **Need for high-*Q* on-chip resonator!**

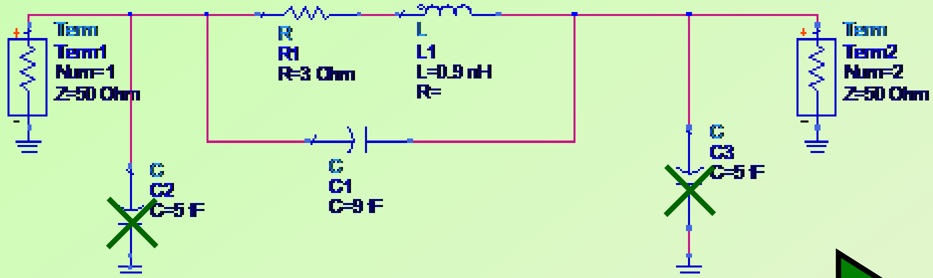
1. J. Wang et. al., "Low power InP/GaAsSb/InP DHBT cascode amplifier with GBP/Pdc of 7.2GHz/mW," IEE Electronics Letters, Vol. 42 , No.1, January, 2006.
2. J. Wang et. al., "InP/GaAsSb/InP DHBT monolithic transimpedance amplifier with large dynamic range," Proc. 2005 European Microwave Conf., Paris, France, pp. 141-144, Oct. 3-7, 2005
3. J. Wang et. al., "First demonstration of low-power monolithic transimpedance amplifier using InP/GaAsSb/InP DHBTs," Technical Digest IEEE MTT-S 2005 Int. Microwave Symposium, Long Beach, CA, pp.101-104, June 12-17, 2005.
4. J. Wang et. al., "Monolithic transimpedance amplifiers for low-power/low noise and maximum bandwidth using InP/GaAsSb/InP DHBTs," Proceedings of Workshop on Compound Semiconductor Devices & Integrated Circuits, Cardiff, UK, May 2005.

Challenge: Lack of High-*Q* On-Chip Components!



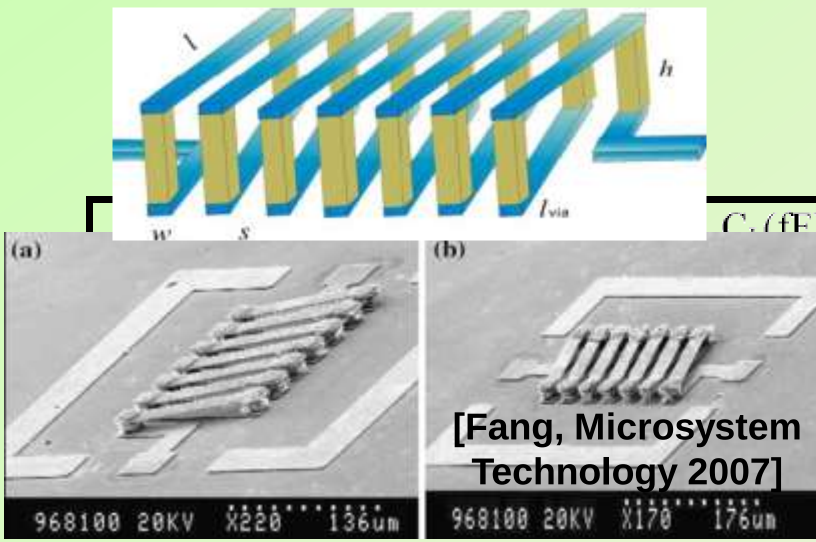
Planar Inductor

Inductor equivalent circuit

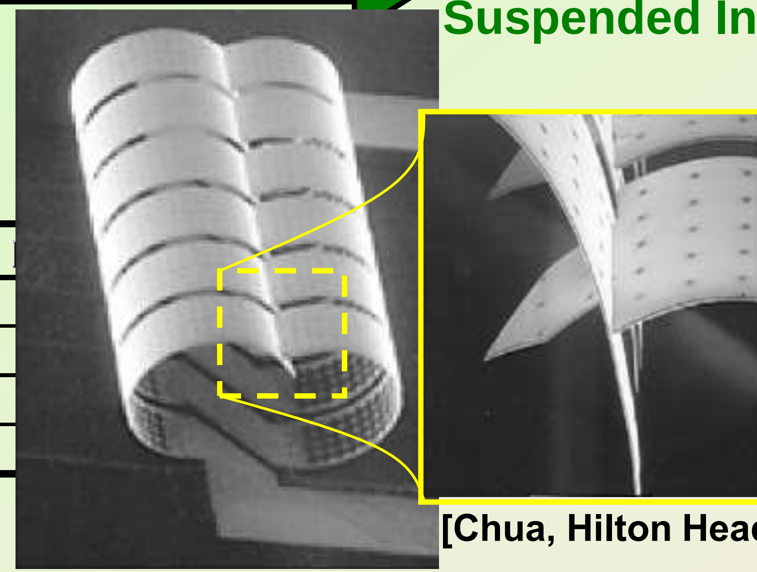


lower substrate loss ⇒ higher *Q*

Suspended Inductor



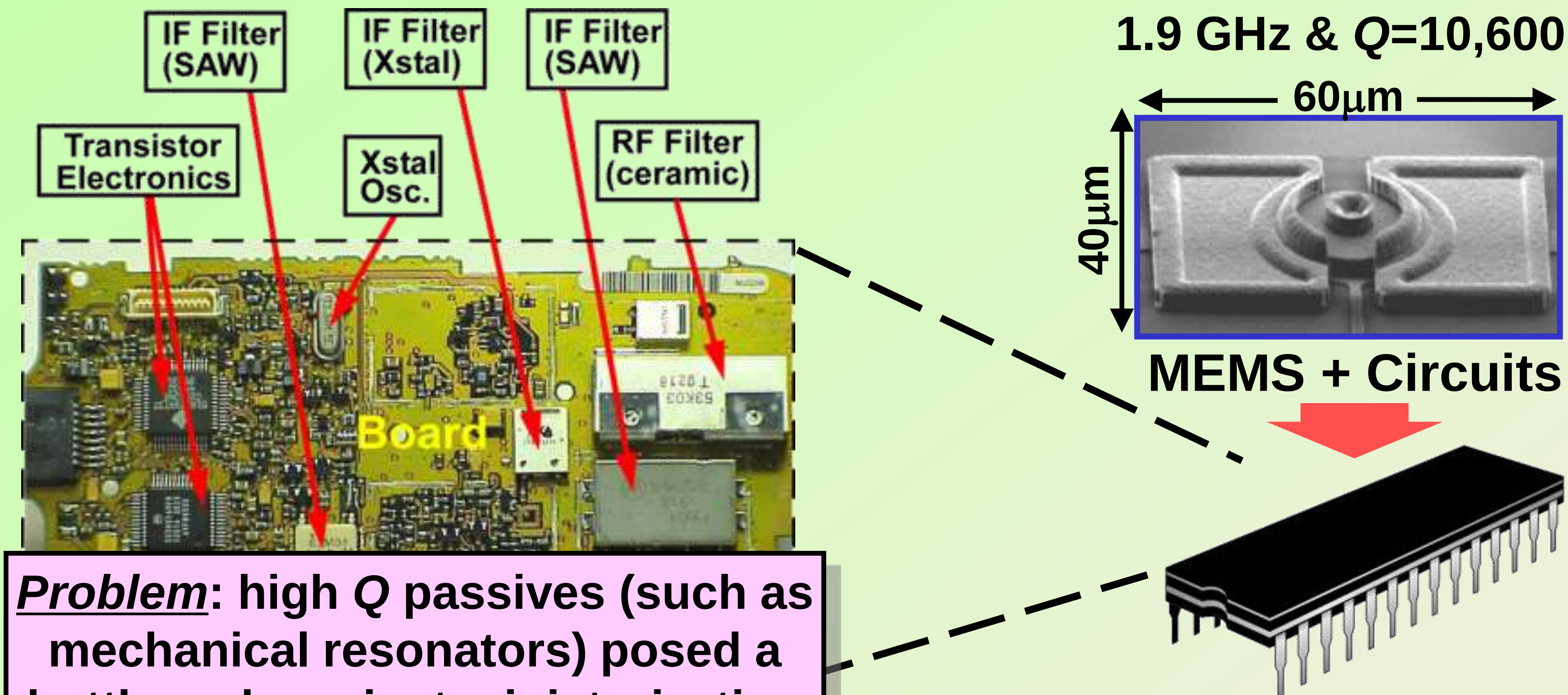
[Fang, Microsystem Technology 2007]



[Chua, Hilton Head’02]

- To improve *Q* of on-chip inductor → need to minimize parasitics
- Suspended airbridge inductor → reduced substrate loss → 2X increase in *Q*
- With more advanced MEMS technology → inductor with *Q* of 100 is possible

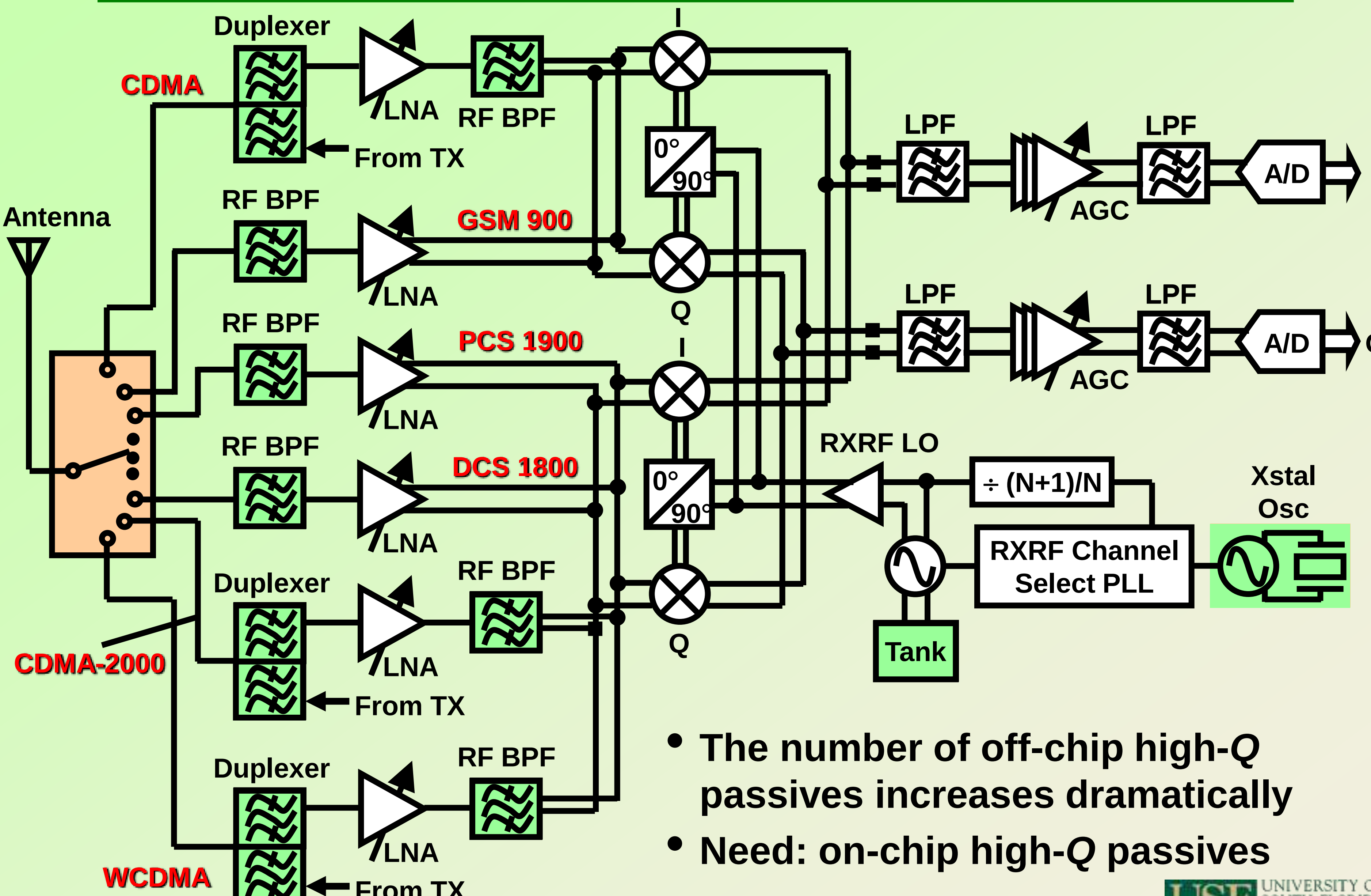
Motivation: Miniaturization of Transceivers



Problem: high *Q* passives (such as mechanical resonators) posed a bottleneck against miniaturization

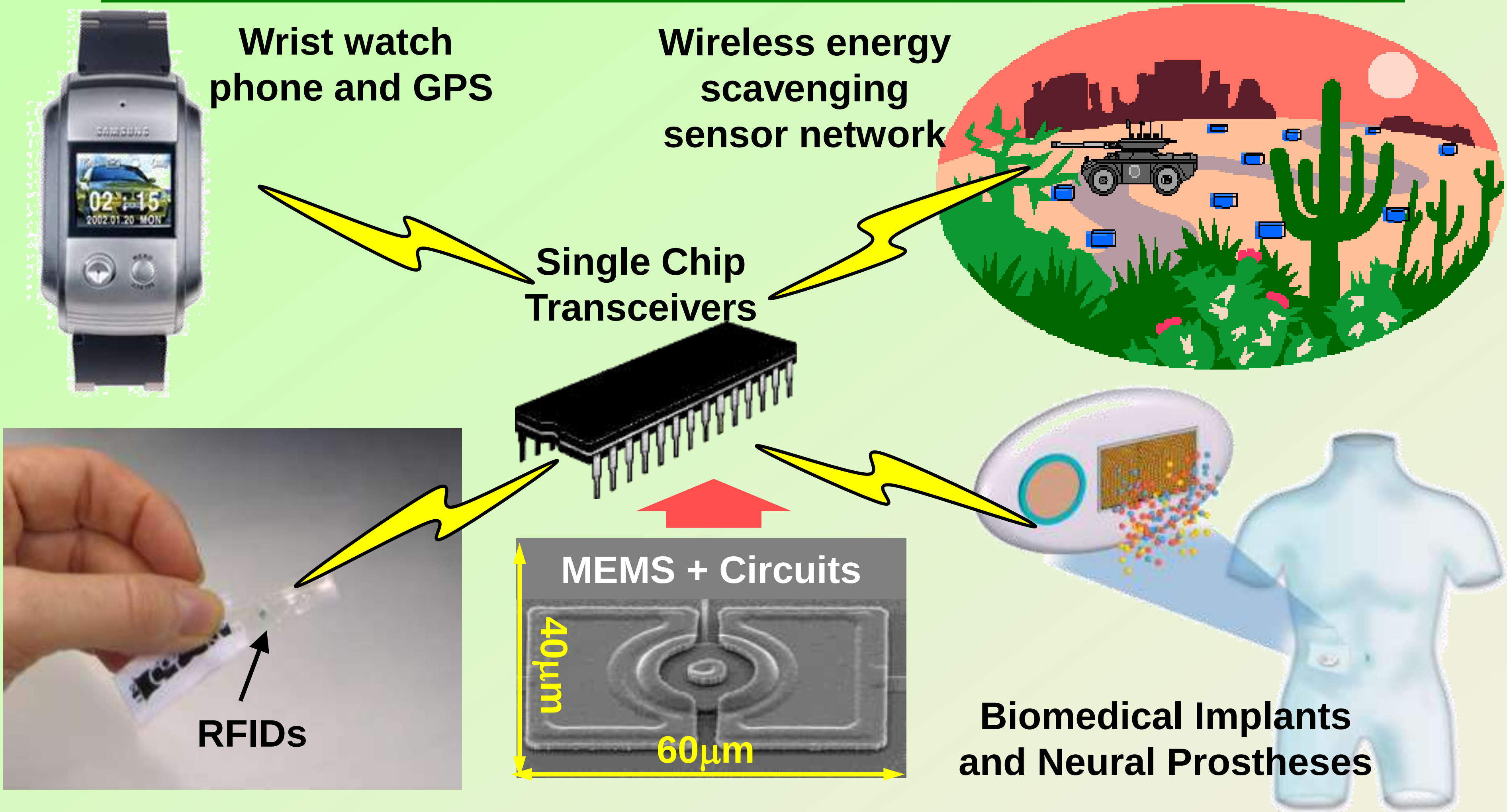
- Transistors or on-chip inductor → *Q* < 100
- High-*Q* frequency selective components (*Q* > 1000) required for frequency generation and filtering in wireless communications
- Replace off-chip high-*Q* components with on-chip high-*Q* μmechanical versions to enable miniaturization

Multi-Band and Multi-Mode Wireless Handsets



- The number of off-chip high-*Q* passives increases dramatically
- Need: on-chip high-*Q* passives

Next Generation Wireless Communicators



- ***Requirements***: ultra-low power, tiny size, high performance
- ***Needs***: system-on-a-chip able to communicate wirelessly

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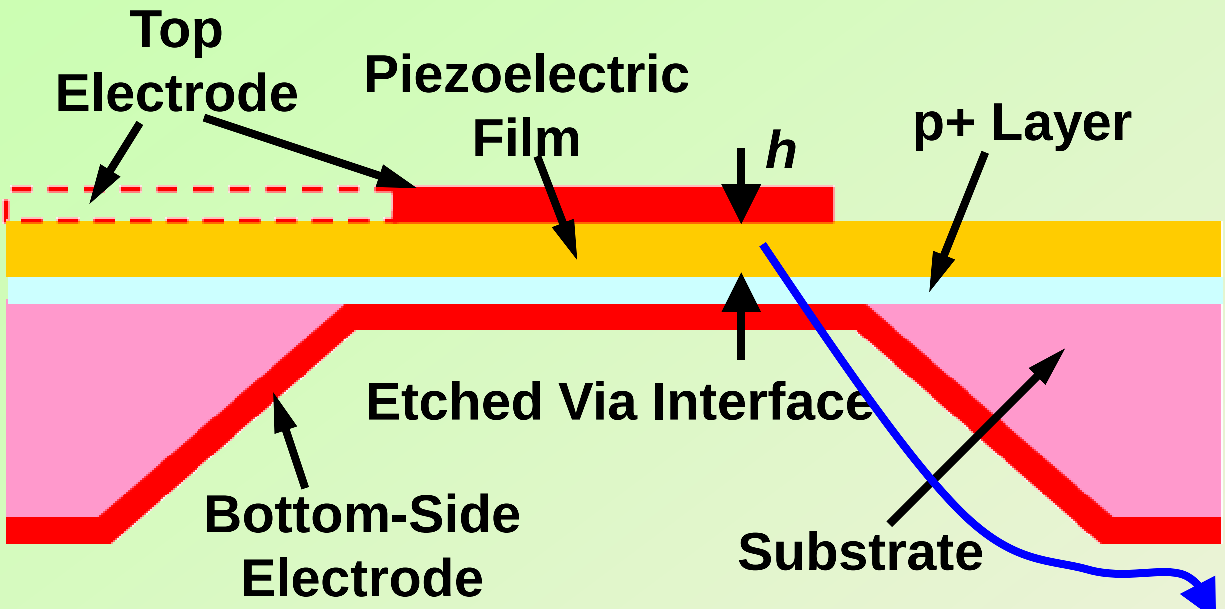
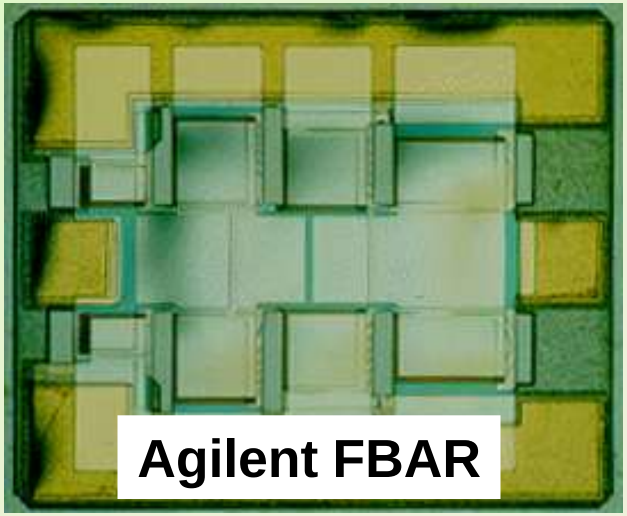
Thin-Film Bulk Acoustic Wave (BAW) Resonator

- Piezoelectric membrane sandwiched by metal electrodes
  - extensional mode vibration: 1.6 to 7GHz, *Q* ~500-1,500
  - dimensions on the order of 200μm for 1.6GHz
  - link individual FBAR's together in ladders to make filters





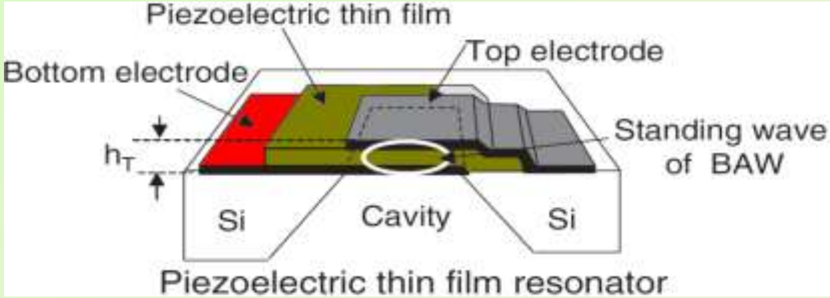
freq ∝ thickness (*h*)

- **Limitations:**
  - Q ~500-1,500, TC_f ~ 25-35 ppm/°C
  - difficult to achieve several different frequencies on a single-chip

Current State of the Art Resonator Technology

1. Thin Film Bulk Acoustic Resonators (FBAR)

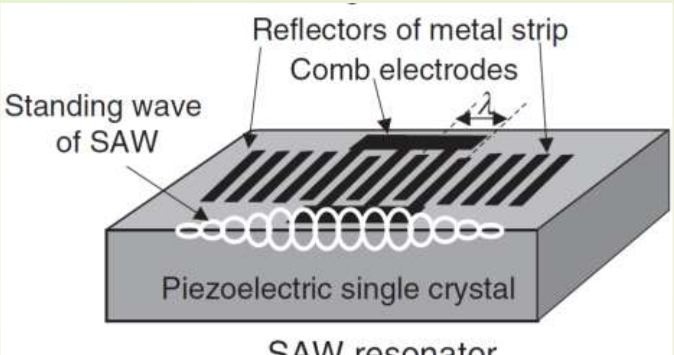
- Piezoelectric membrane embedded b/w 2 metal electrodes
- Operational frequencies (thickness mode): 800 MHz to 20 GHz
- Commercially available
- *Q* ~ 500-1,500
- One frequency per batch process



Piezoelectric thin film resonator

2. Surface Acoustic Wave Resonators (SAW)

- Surface acoustic wave propagating across a piezoelectric substrate material
- Operational frequencies: 10 MHz to 5 GHz
- Commercially available
- Moderate performance (*Q*'s, etc.)
- Not monolithically integrated with IC's.



SAW resonator

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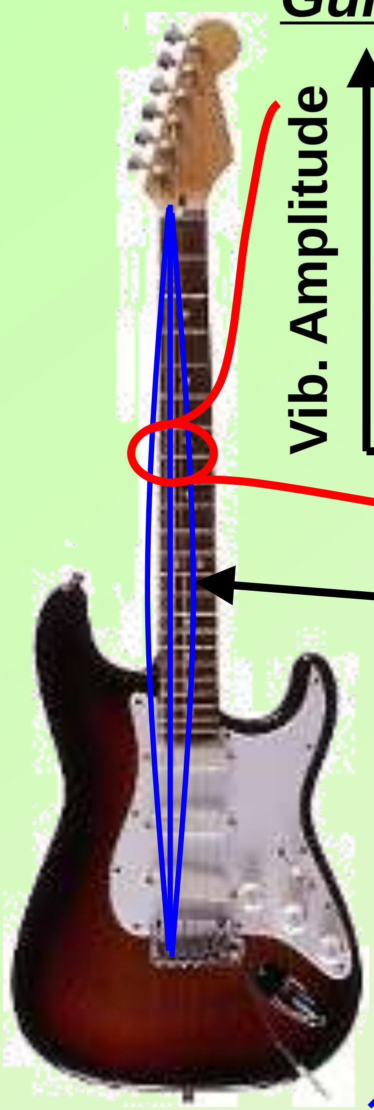
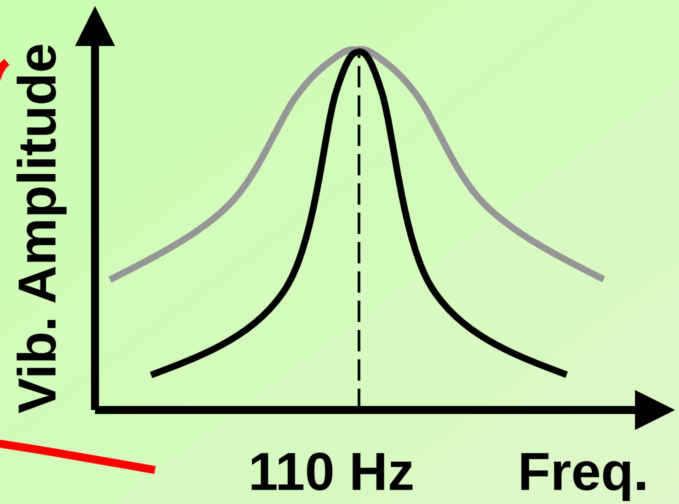
Basic Concept: Scaling of Guitar Strings

Guitar String





Vibrating "A" String (110Hz)

Freq. Equations:

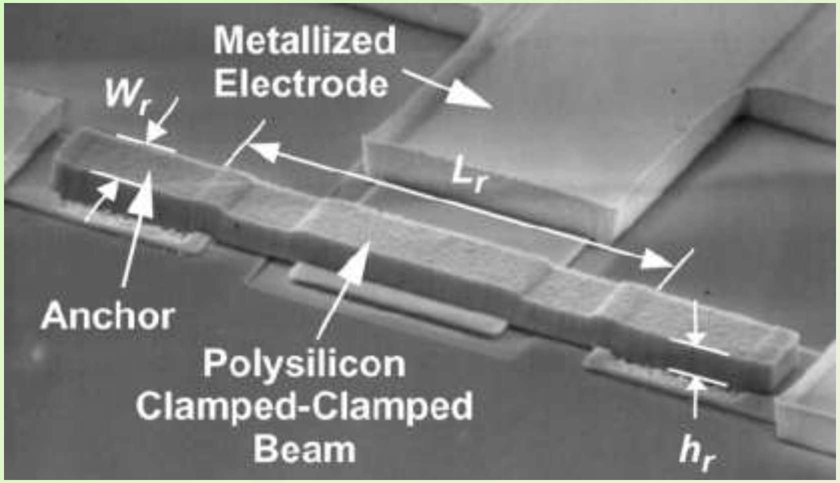
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

Stiffness

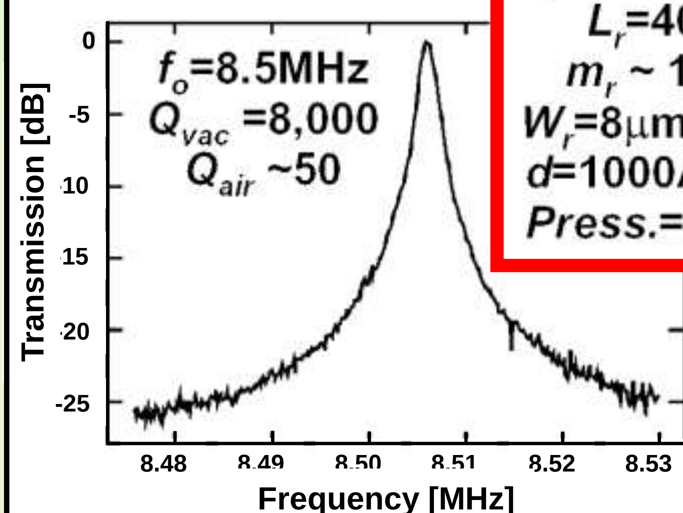
Freq.

Mass

μMechanical Resonator



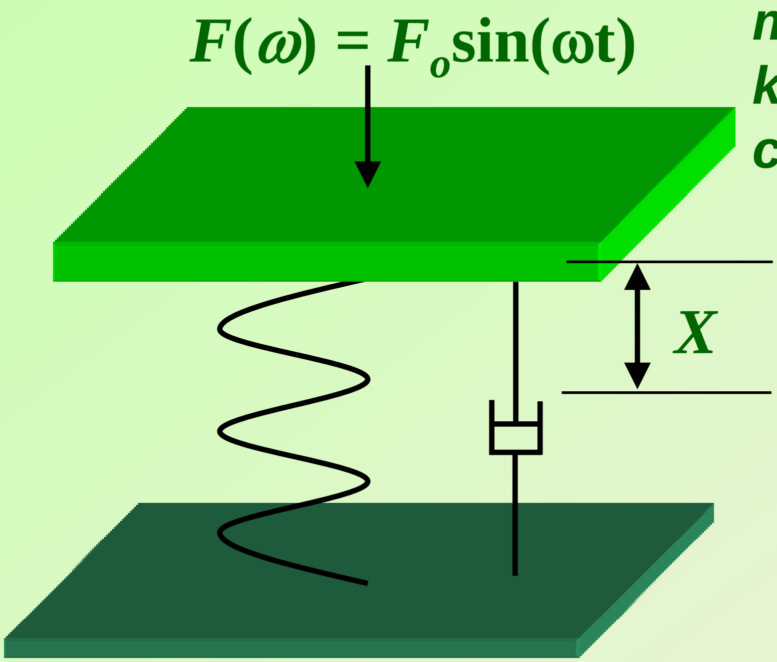
[Bannon 1996]



Performance:
L_r=40.8μm
m_r ~ 10^{-13} kg
W_r=8μm, h_r=2μm
d=1000Å, V_P=5V
Press.=70mTorr

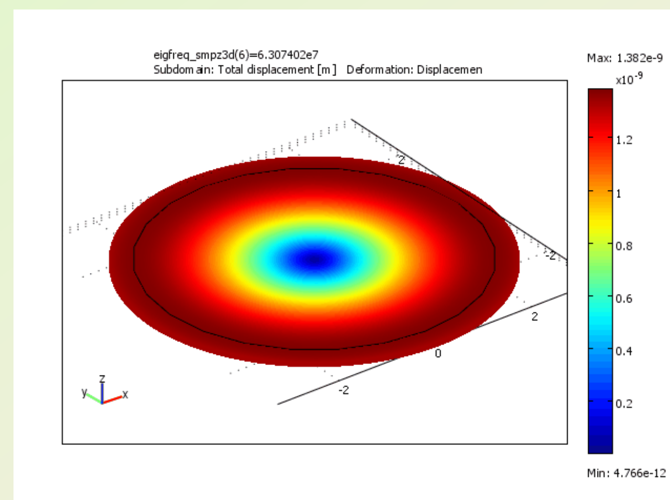
Lumped Element Model for a Mechanical Resonator

- **Forced harmonic vibration of a mechanical resonator can be modeled by a simple spring-mass-damper system.**
- **In-plane extensional modes offer higher stiffness than that of flexural mode, thus are more amenable for high frequencies.**

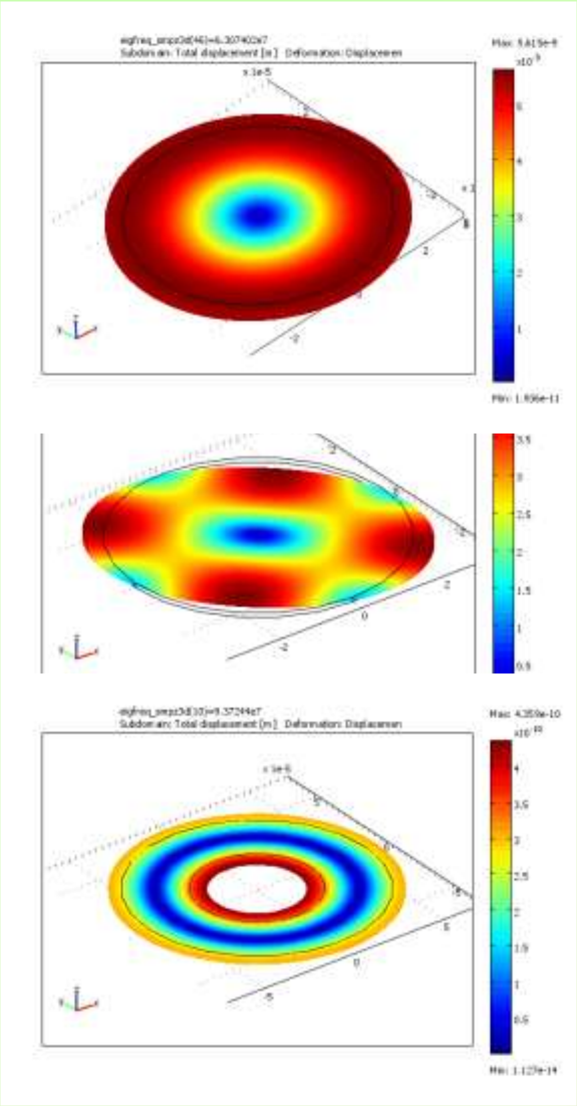


m_{eq} : Equivalent Mass
k_{eq} : Equivalent Stiffness
c_{eq} : Damping Coefficient

$$\omega_o = \sqrt{\frac{k_{eq}}{m_{eq}}}$$



Mechanical Design and Layout of μResonator



Radial Contour Mode Disk

$$f_o = \frac{\alpha_{1,1}}{R}\sqrt{\frac{E}{\rho}}$$

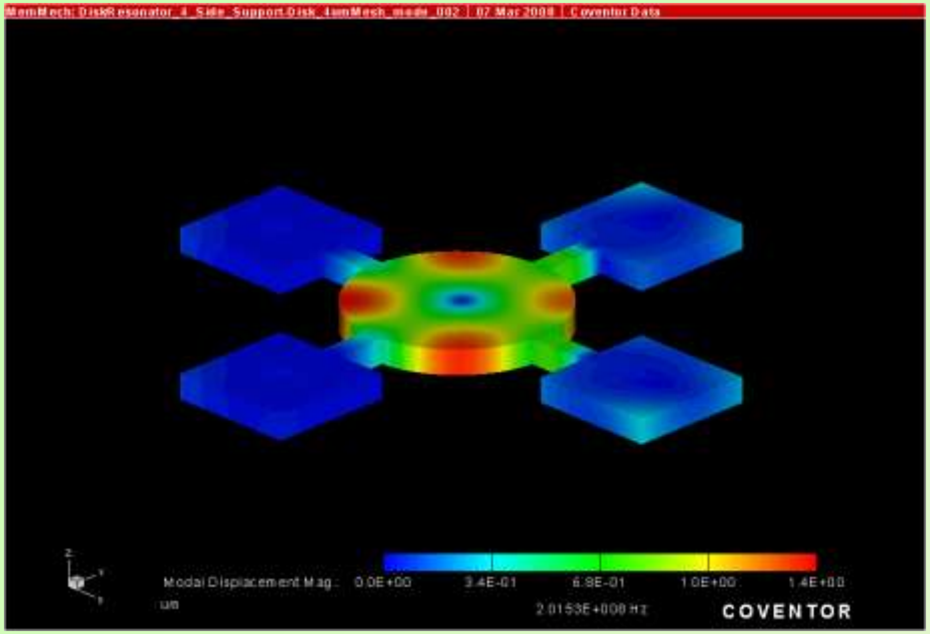
Wineglass Mode Disk

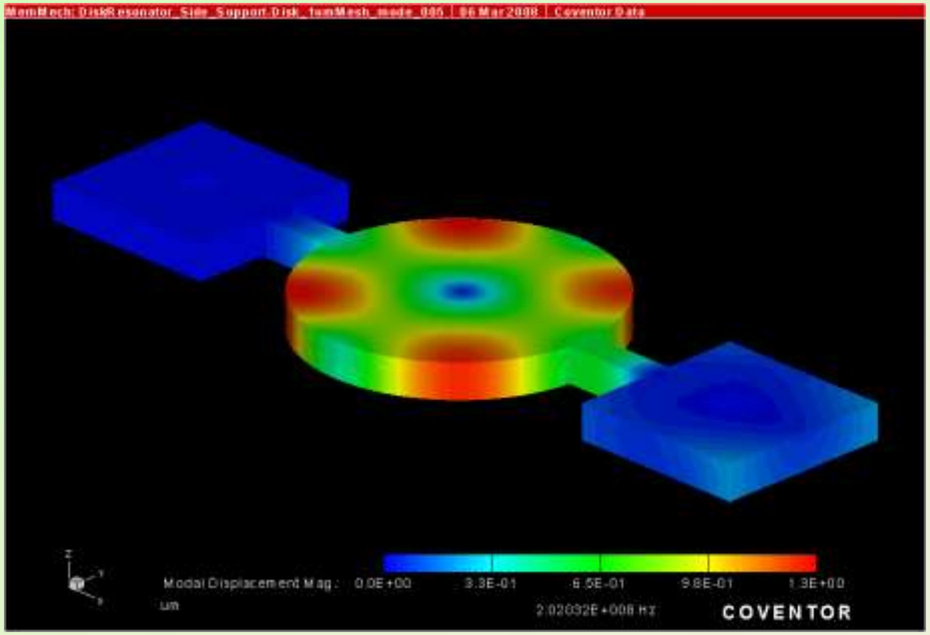
$$f_o = \frac{\alpha_{2,1}}{R}\sqrt{\frac{E}{\rho}}$$

Radial Contour Mode Ring

$$f_o = \frac{\alpha_{1,1}}{w}\sqrt{\frac{E}{\rho}}$$

Sometimes Asymmetric Mode Shape is Preferred.





- **So-called wine-glass mode (ecliptic mode).**
  - **It has four nodal locations that are ideal for anchor attachment.**
  - **It is capable of generating outputs with 180° phase offset.**
    - **One can take a single-end input and convert it to differential outputs.**

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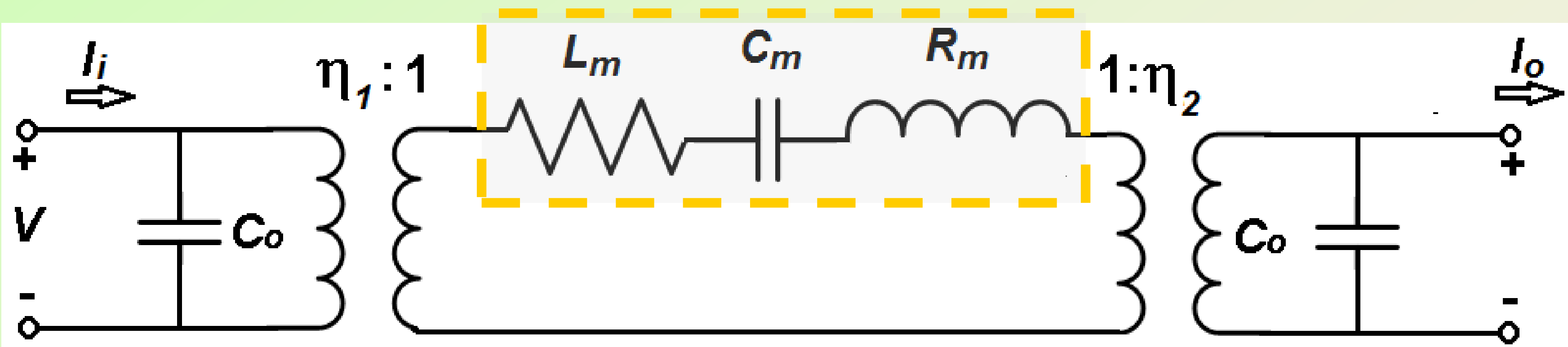
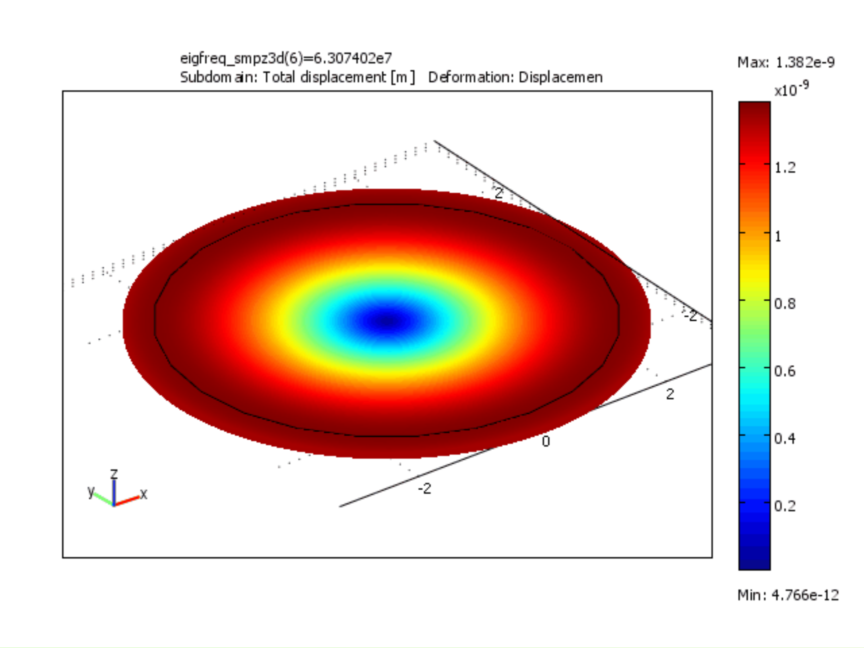
Design based on the Equivalent Circuit Model

- **The electrical behavior of the μmechanical resonator can be described by an equivalent LCR circuit**

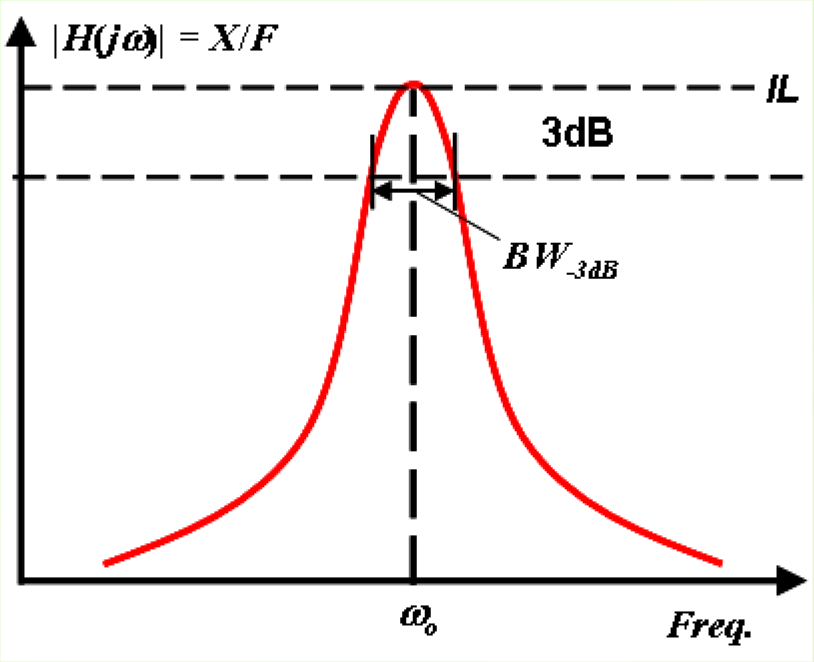
Mechanical Domain		↔	Electrical analog	
Force	F	↔	Voltage	V
Velocity	v	↔	Current	I
Mass	m_{eq}	↔	Inductance	L_m
Compliance	$1/k_{eq}$	↔	Capacitance	C_m
Damping	b_{eq}	↔	Resistance	R_m



Design based on the Equivalent Circuit Model



Mechanical Domain



Electrical Domain

$$IL \approx 20\log_{10}\left(\frac{2R_T}{2R_T + R_m}\right)$$

$$Q \approx \frac{f_o}{BW_{-3dB}} = \frac{\omega_o}{2\pi \cdot BW_{-3dB}}$$

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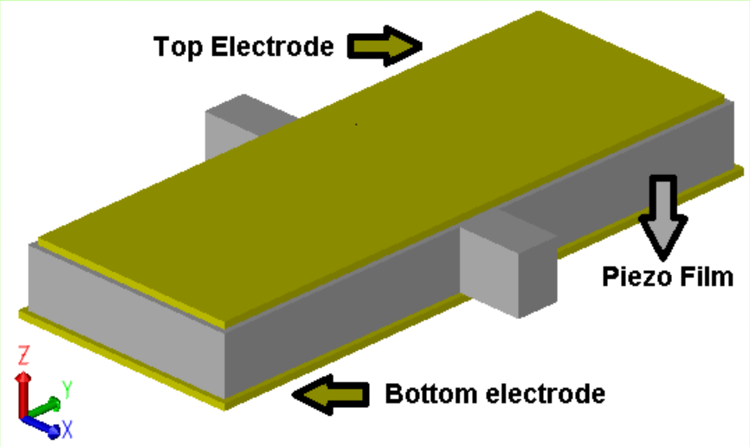
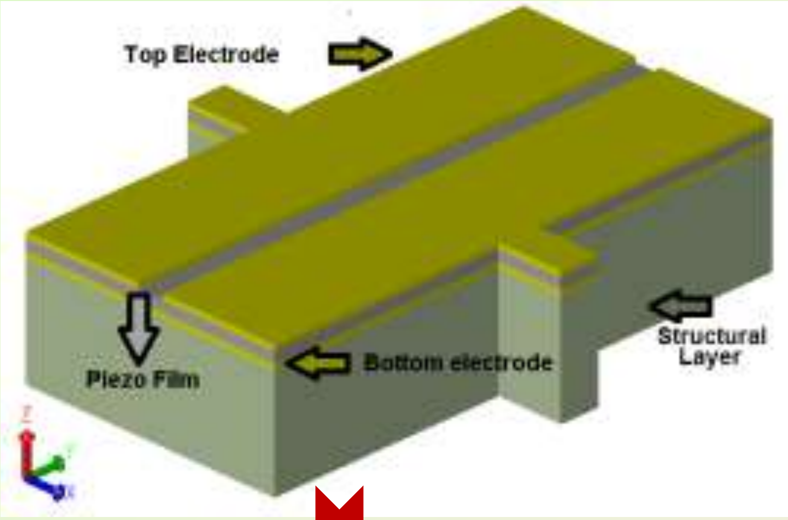
Basics of Piezoelectrically-Transduced Resonators

- A piezoelectrically-transduced contour-mode resonator consists of a piezoelectric transducer layer sandwiched b/w 2 metal contacts.
- The e-field is applied vertically, d_{31} induce in-plane lateral move.

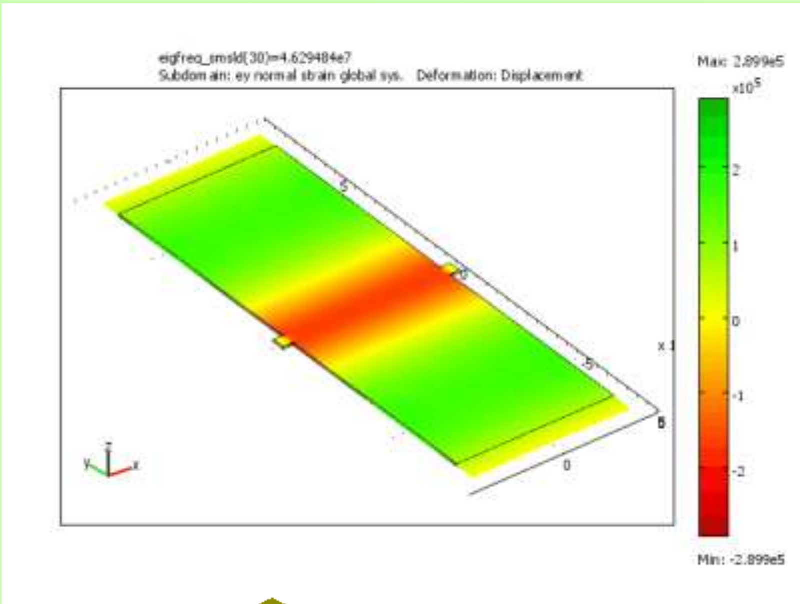


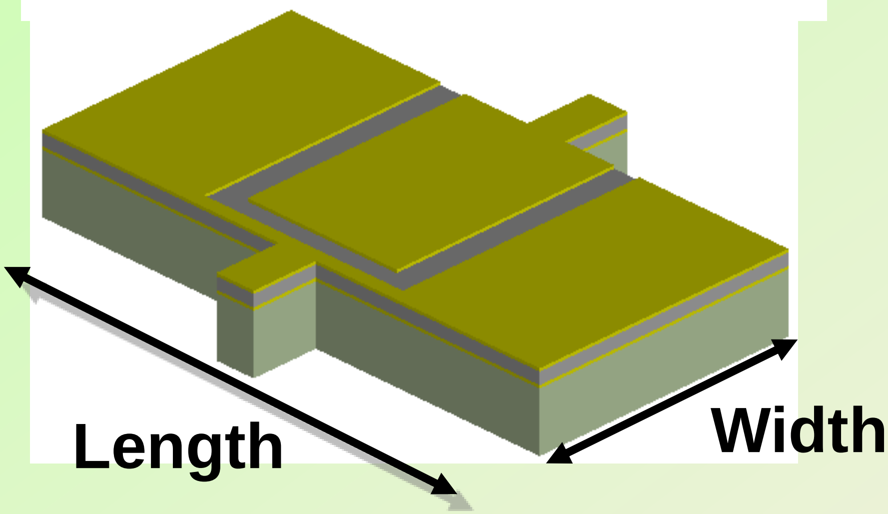


Thin-Film Piezoelectric Resonator

Piezo-on-Silicon Resonator

Design of Electrodes to Pick Up the Target Mode



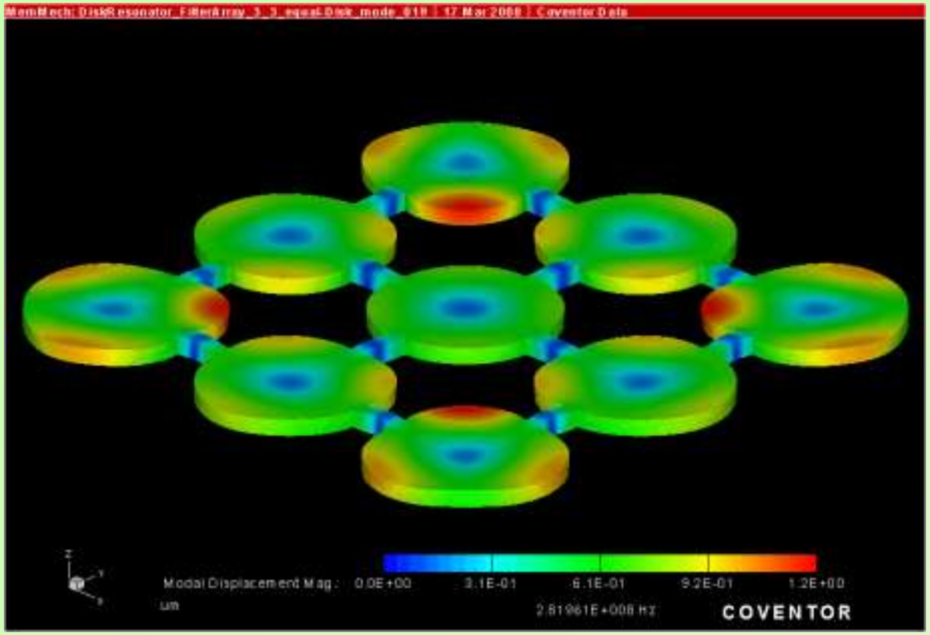


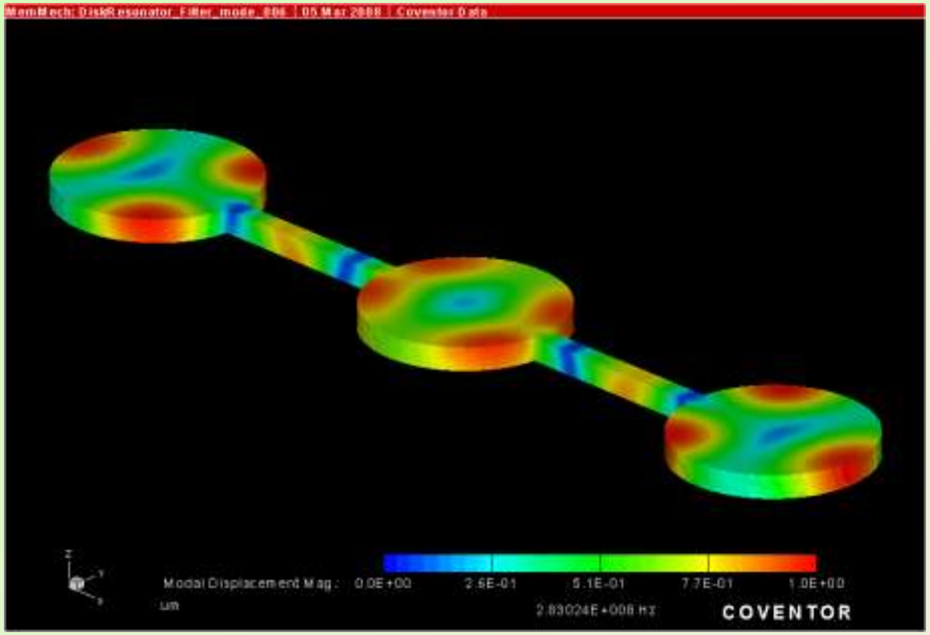
- Design of top electrodes must match the strain field at the target resonance mode
- Resonance frequency is set by the length of the structure
- A basic building block for filter

$$f_o = \frac{n}{2L}\sqrt{\frac{E}{\rho}}$$

E ⇒ Young's Modulus
ρ ⇒ Density
L⇒ length

Benefits from Array/Circuit Design Concept?





- Micro-Electro-Mechanical-Systems (MEMS) Technology
  - Enables miniaturization of micromachined transducer devices.
  - Like transistors in IC's, those miniaturized MEMS transducers now act as the building blocks for more complicated circuits/networks.
    - Example 1: cascade MEMS resonators in series → MEMS filter.
    - Example 2: parallel combination (Array) → A composite resonator.
    - Example 3: integration with IC's → precise timing & frequency control.

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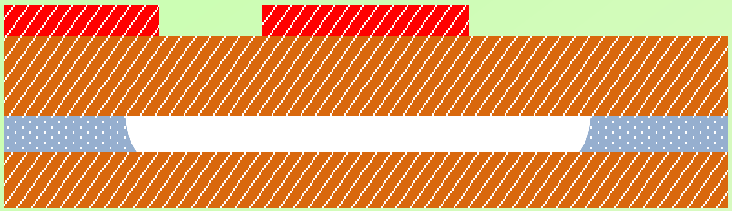
Selection of Piezoelectric Thin Film Transducers

- **Among three leading thin-film depositable candidates, sputtered ZnO was chosen for this work due to tradeoff.**
- **Desirable properties of piezoelectric film transducers**
  - **Low permittivity**
  - **High resistivity**
  - **Dielectric strength**
  - **High piezo-coefficient**
  - **High acoustic velocity**

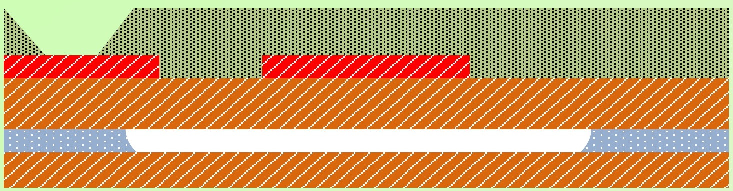
Material	AlN	ZnO	PZT
Dielectric Constant	9	10	1000
Acoustic Velocity (Km/s)	10.4	6.3	2.5
Piezocoeff. (d_{33}) [pC/N]	3.4~5	7.5~12	90~220
Piezocoeff. (d_{31}) [pC/N]	-2	-2.3~-5	-40~-90
Dielectric Strength (kV/mm)	20	10	100
Resistivity (Ω.cm)	10^{13}	10^{7}	10^{9}

Microfabrication Process

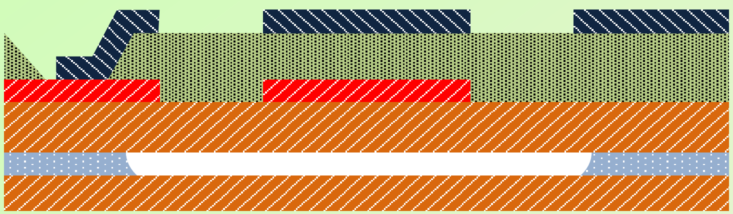
Piezo-on-Silicon Resonators Process Flow



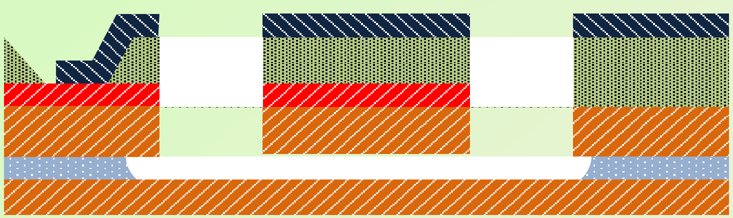
Pre-release followed by bottom electrode patterning by lift-off



ZnO Sputtering deposition and open via access to bottom electrode through ZnO

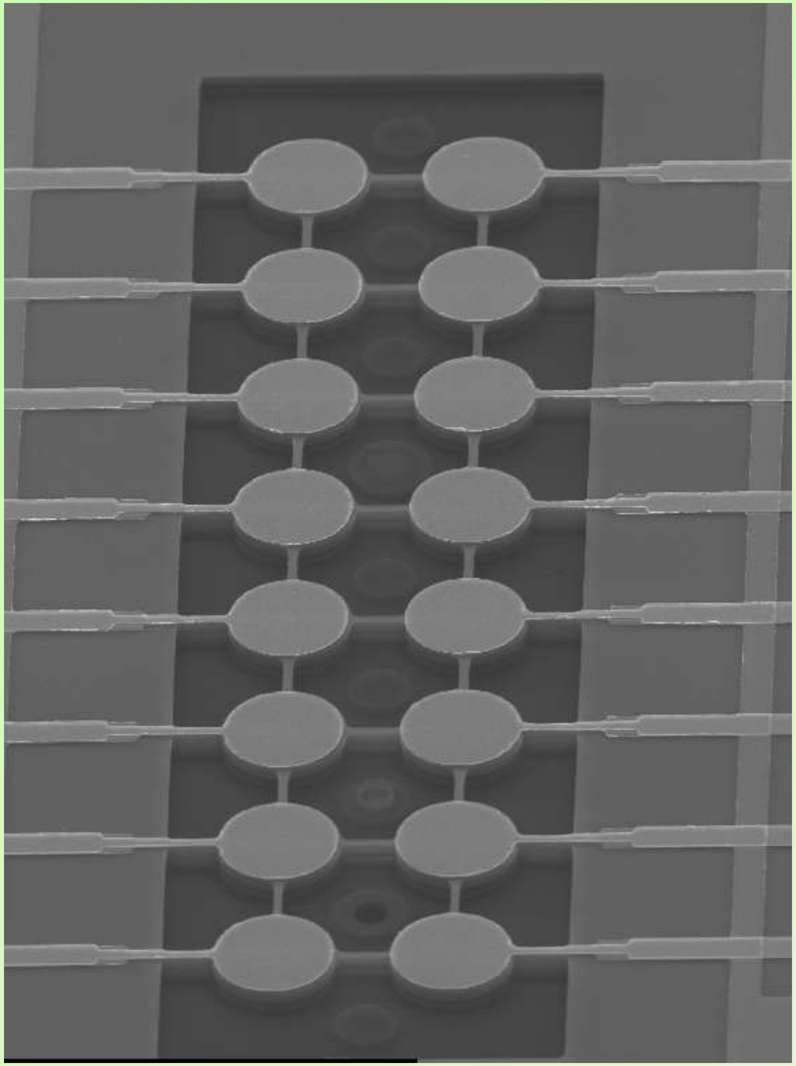


Top electrode patterning by lift-off



ZnO anisotropic dry etching in CH_4-Ar followed by anisotropic silicon etch of the device layer

Microfabricated Piezo-on-Silicon Resonators

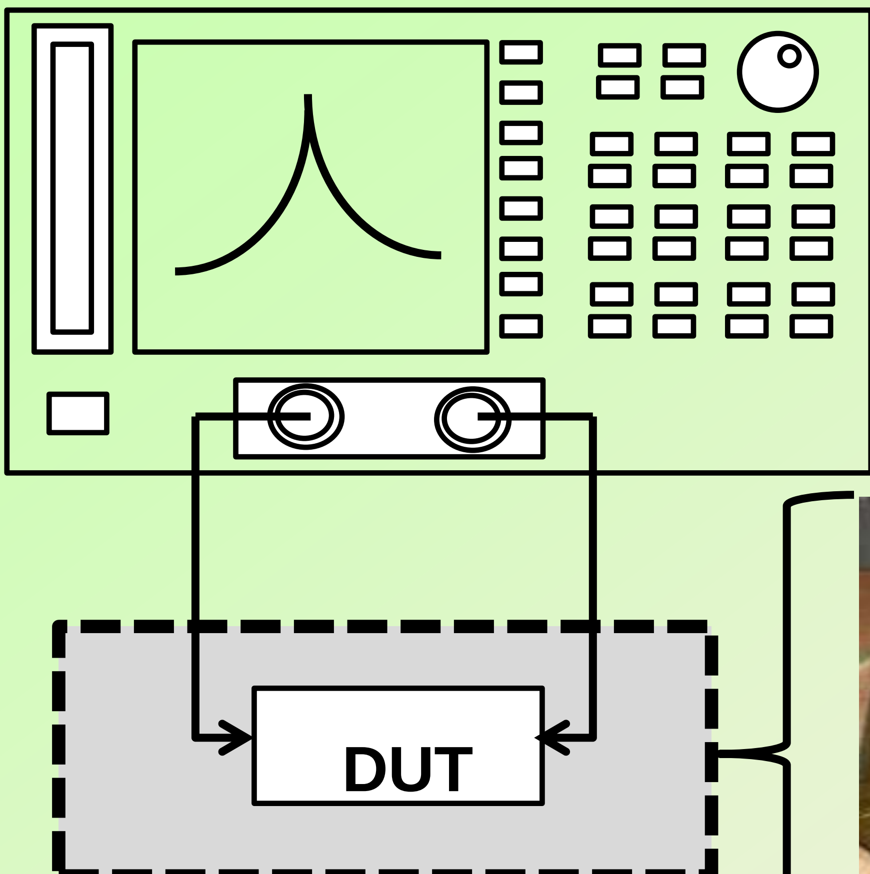


Piezo-on-Silicon Resonators

- **No stiction problems**
- **Mechanically-coupled array of resonators has been successfully fabricated**
- **The inclusion of silicon raise the *Q's* of the devices**

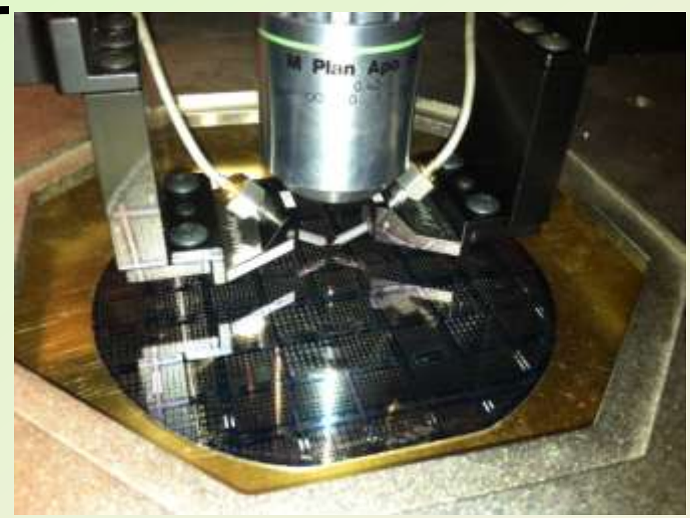
On-Wafer Probing RF Measurement Setup

Vector Network Analyzer



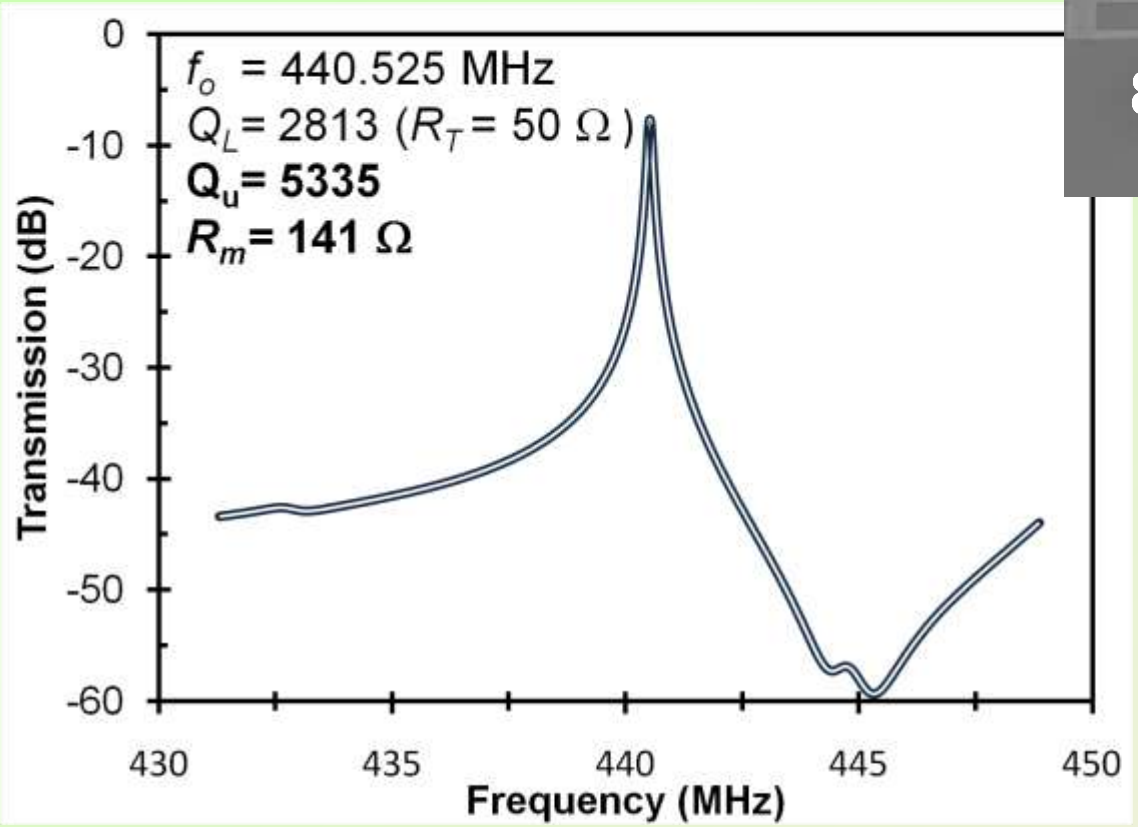
S-Parameters Measurement

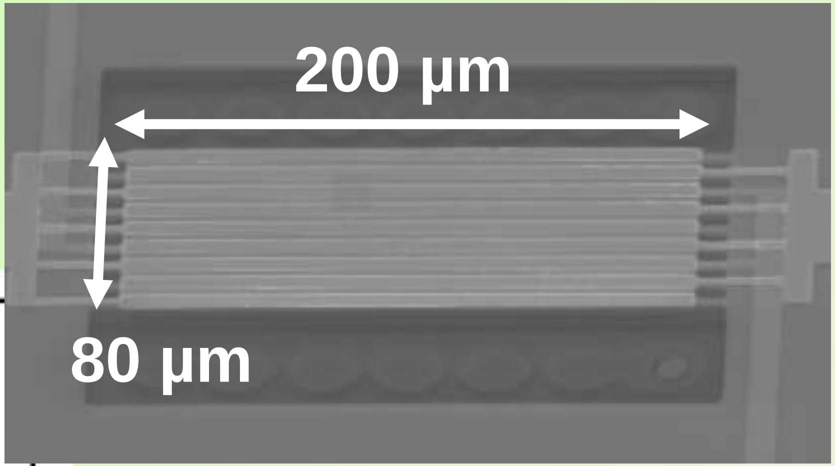
On-Wafer Probing



Piezo-On-Silicon SOI μmechanical Resonators

9th order ZnO-on-SOI rectangular plate resonator

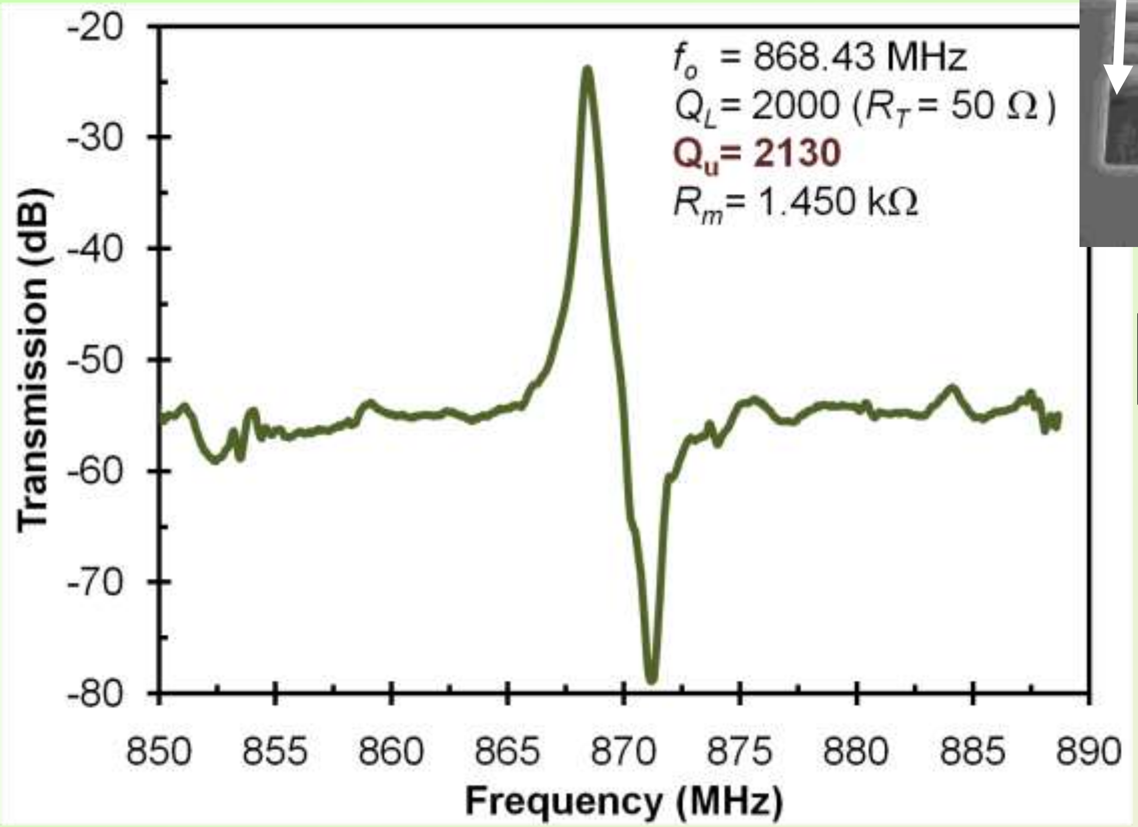


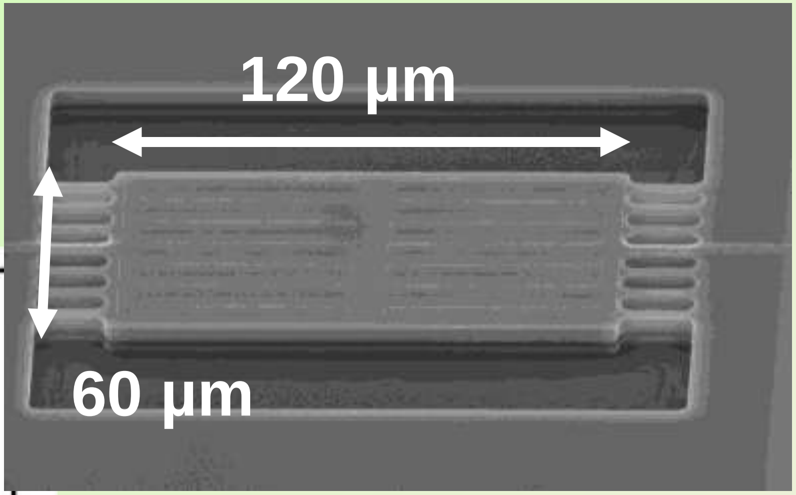


- Low motional resistance
- CAD-definable frequency
- High *Q* (>5,000 unloaded)
- Tiny size (~100 μm)
- IC Monolithic integration

Piezo-On-Silicon SOI μmechanical Resonators

13th order ZnO-on-Silicon rectangular plate resonator





Electrode pitch size

$$\frac{l}{n} = 4.61\mu m$$

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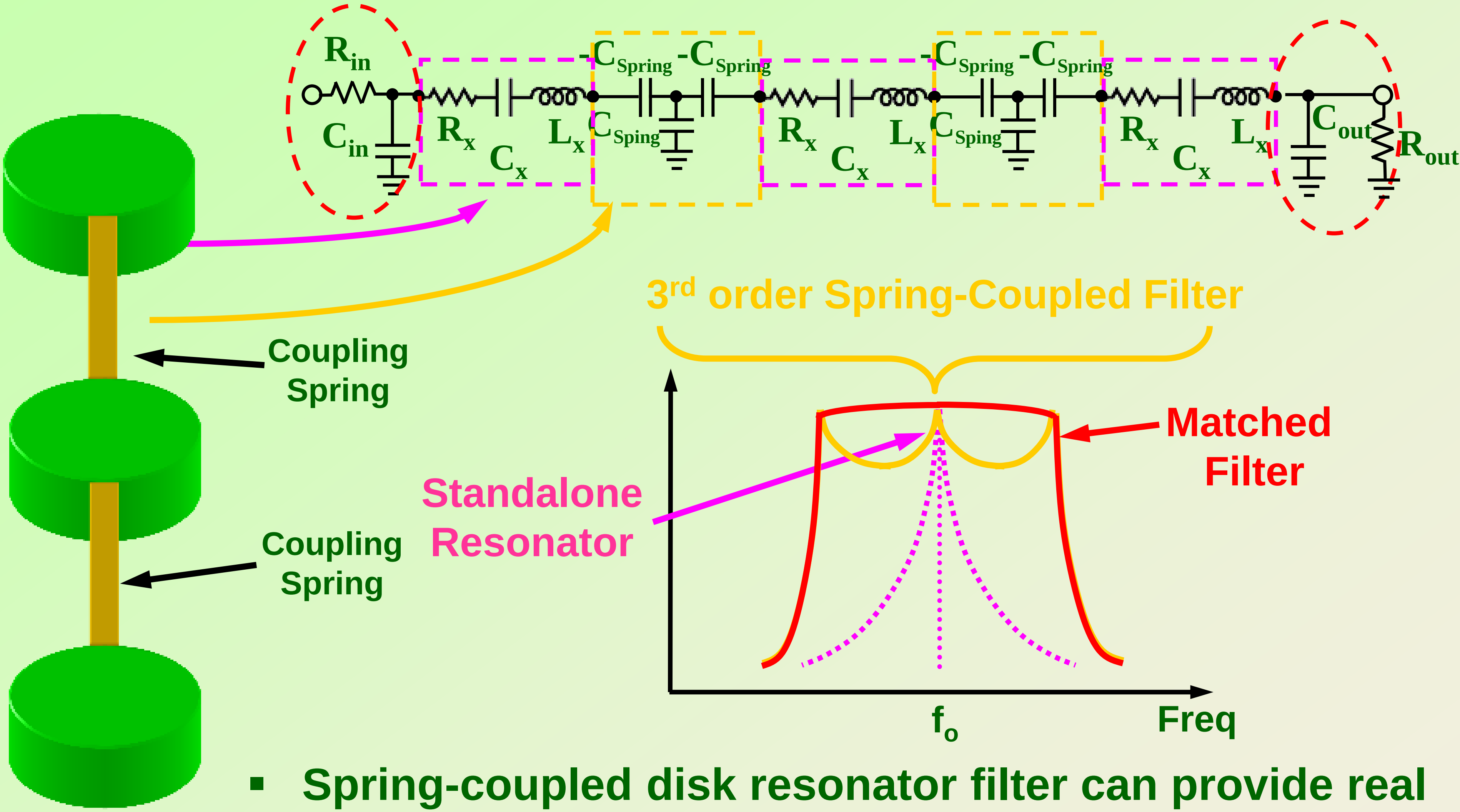
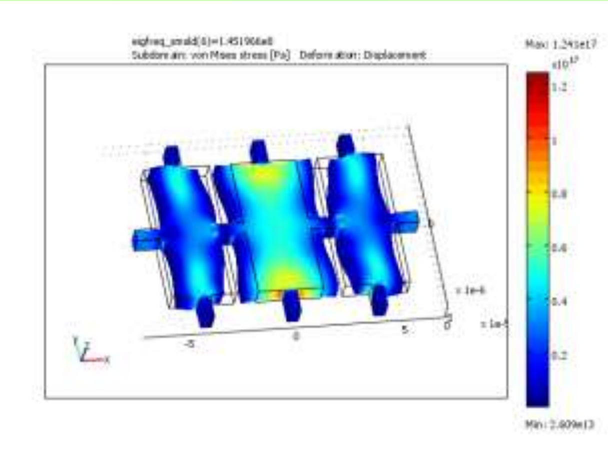
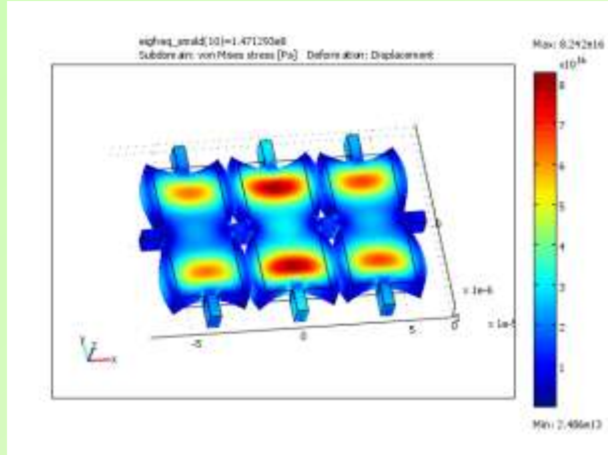
Design of Mechanically-Coupled Resonator Filters

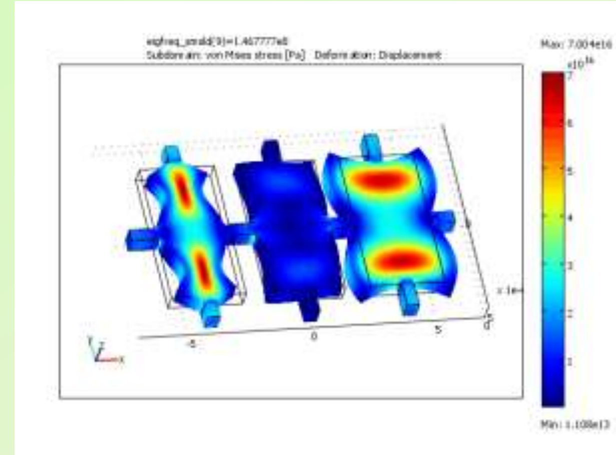


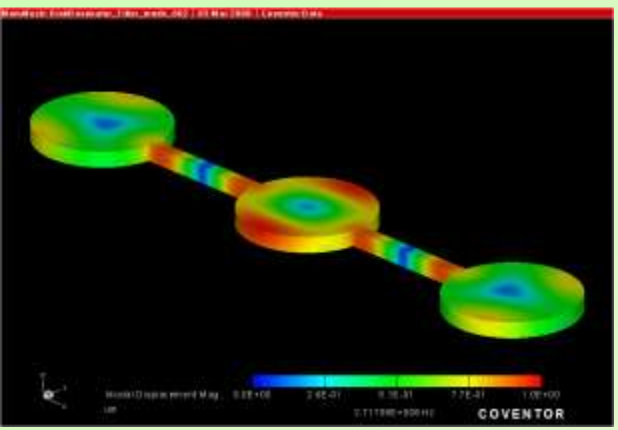
- Spring-coupled disk resonator filter can provide real filter characteristics

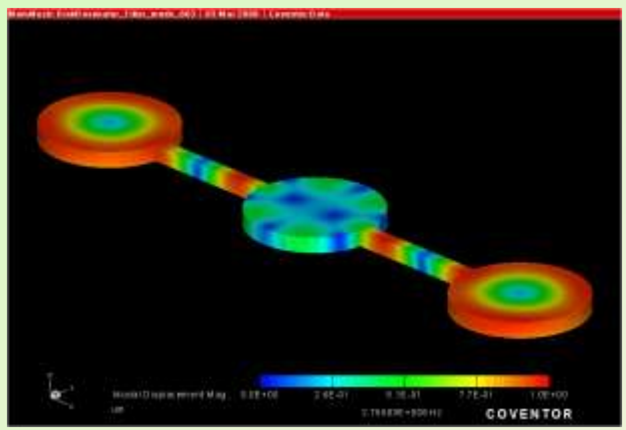
Design of Mechanically-Coupled Resonator Filters

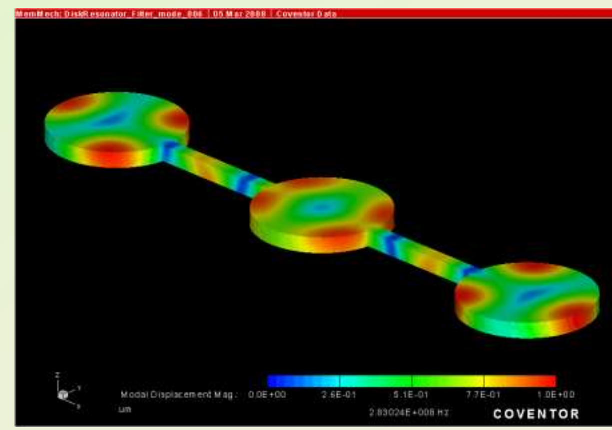








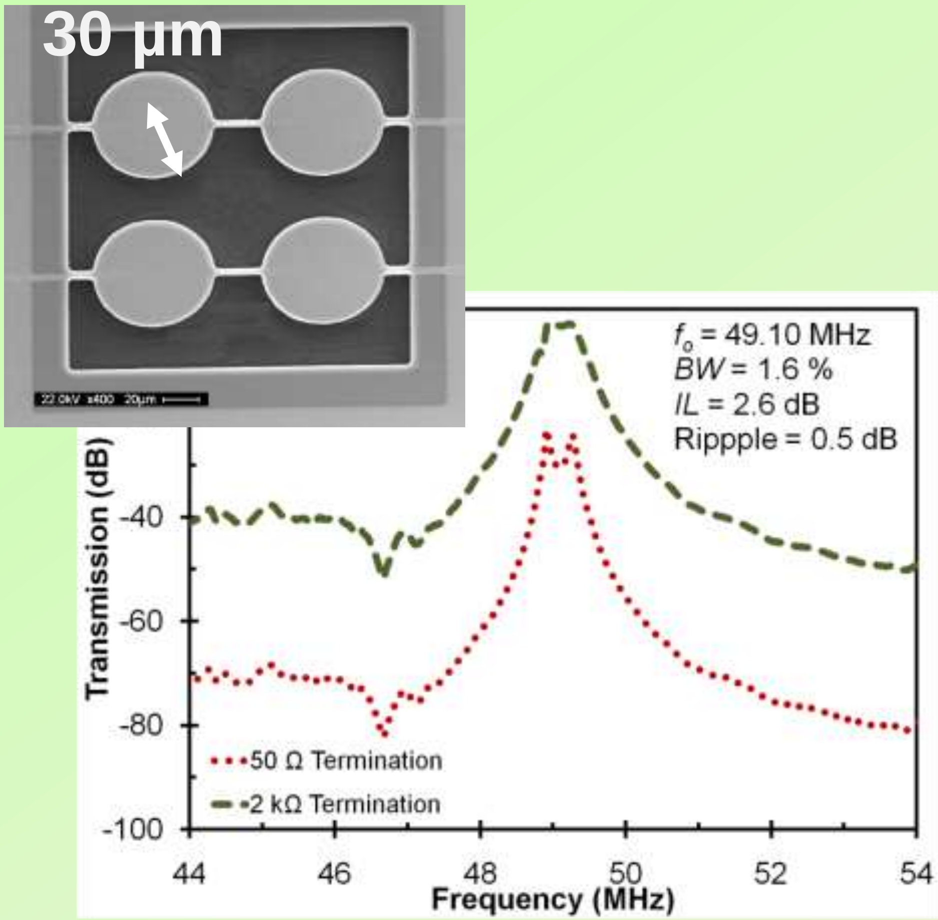


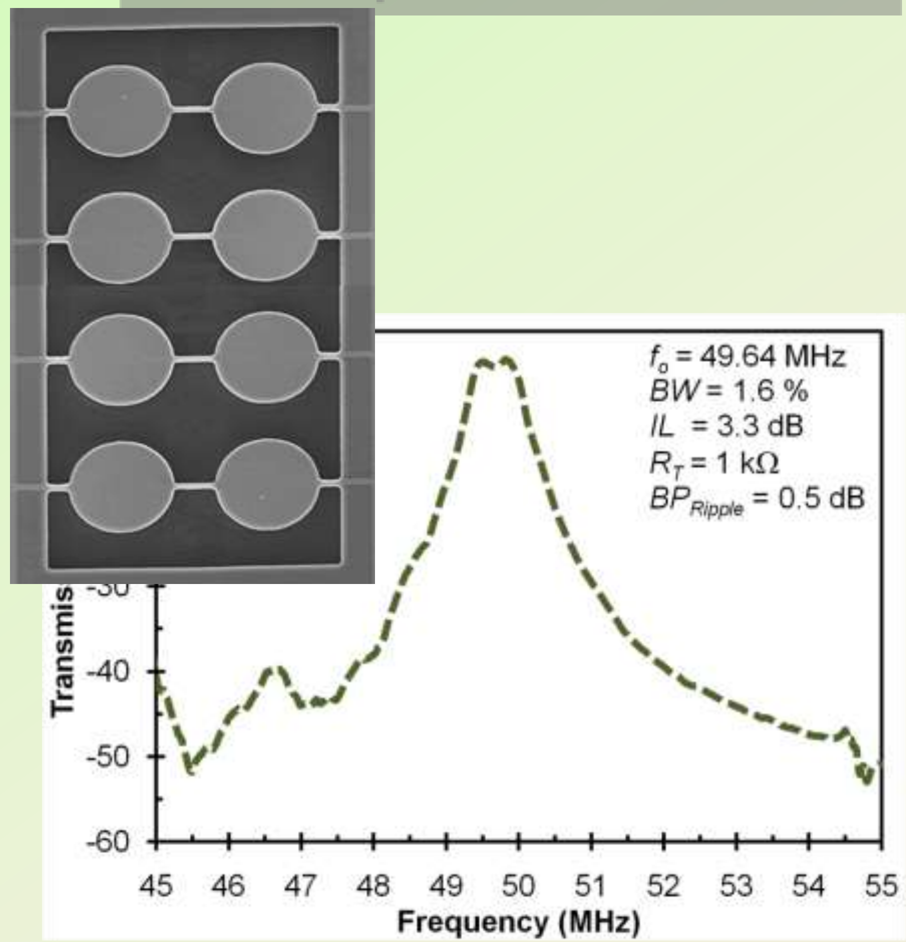


Mechanically-Coupled Filters

Array of 2 × 2 mechanically coupled resonator

Array of 4 × 2 mechanically coupled resonator





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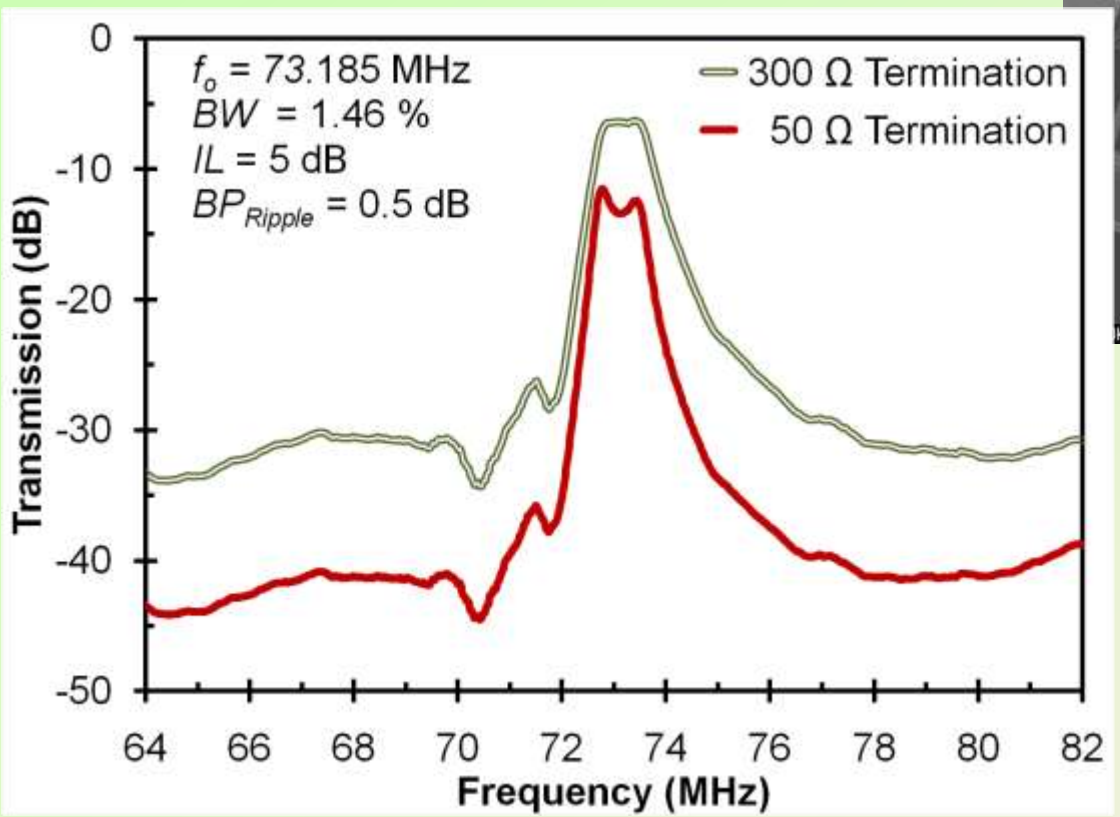
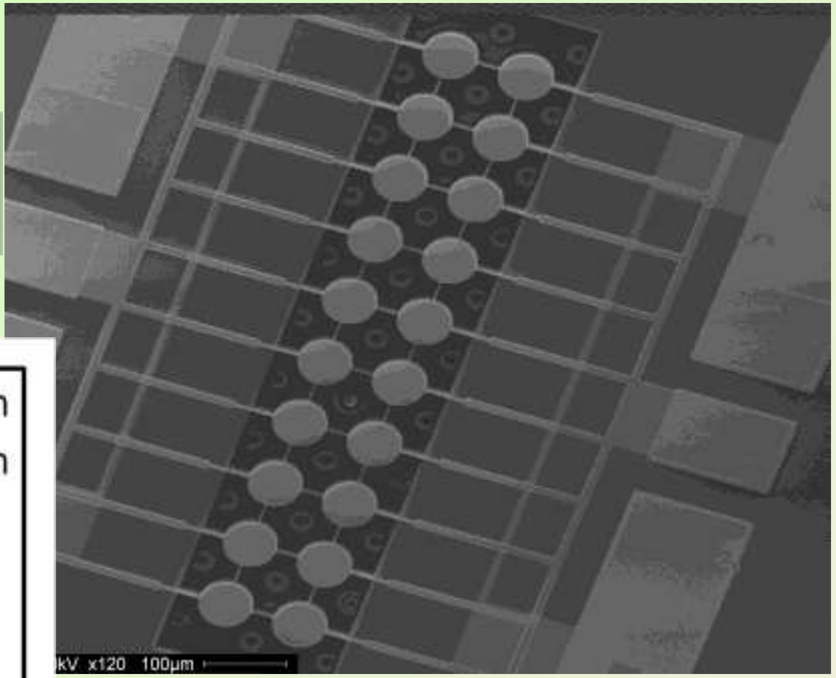
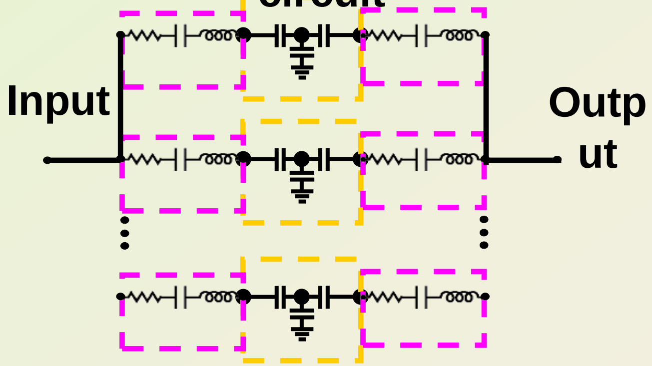
Mechanically-Coupled Filters

Array of 10 × 2 mechanically coupled resonator





Equivalent circuit



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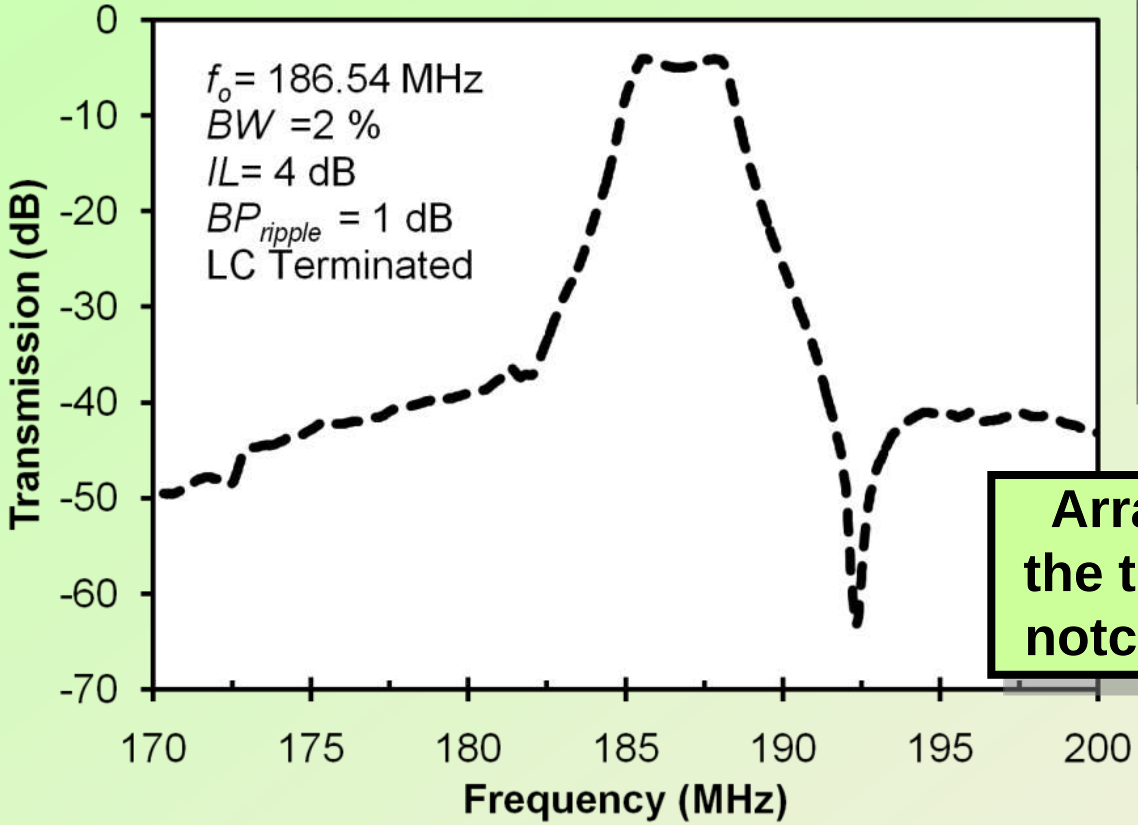
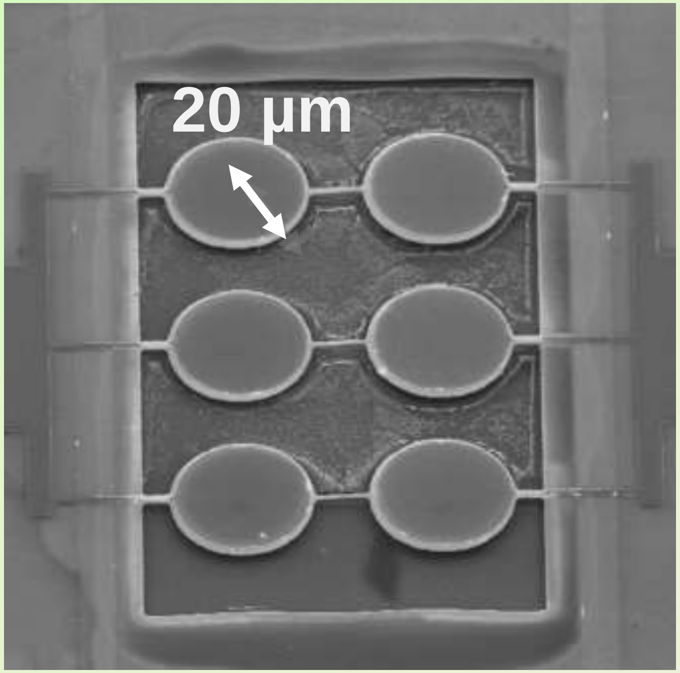
Mechanically-Coupled Filters

Array of 3 × 2 mechanically coupled resonator

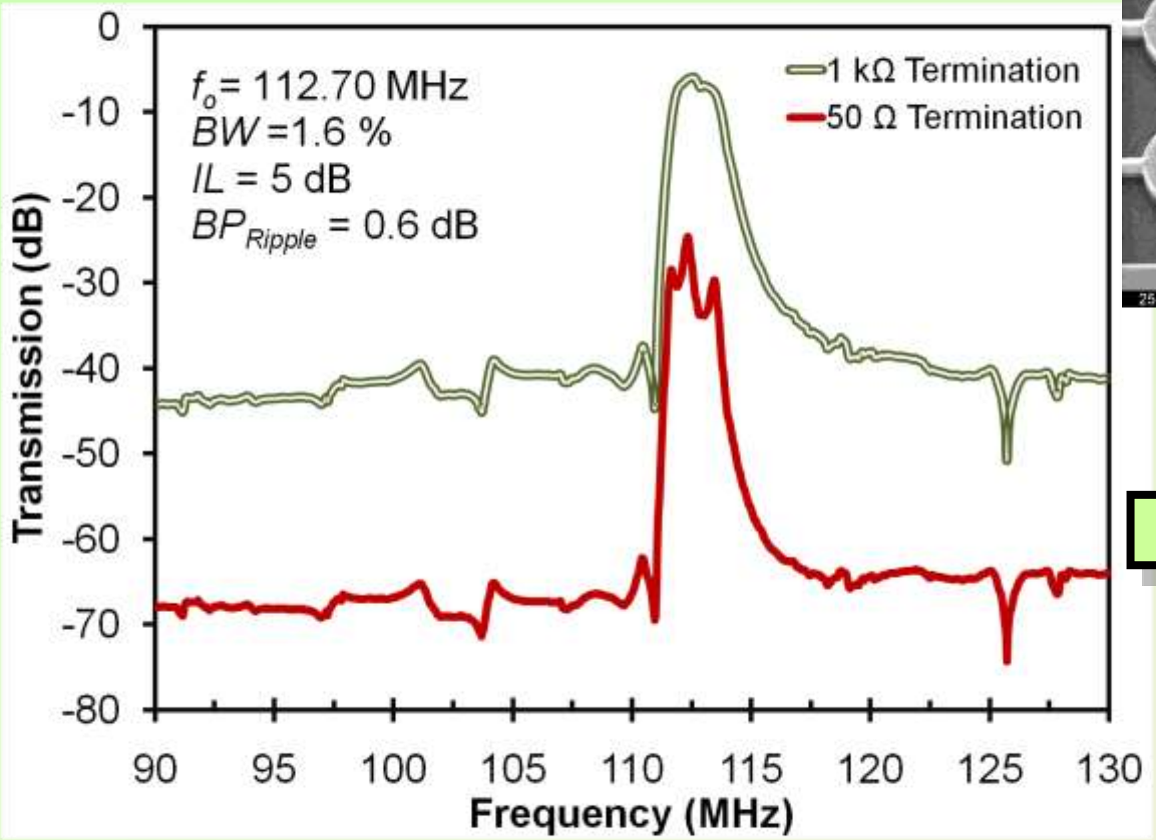


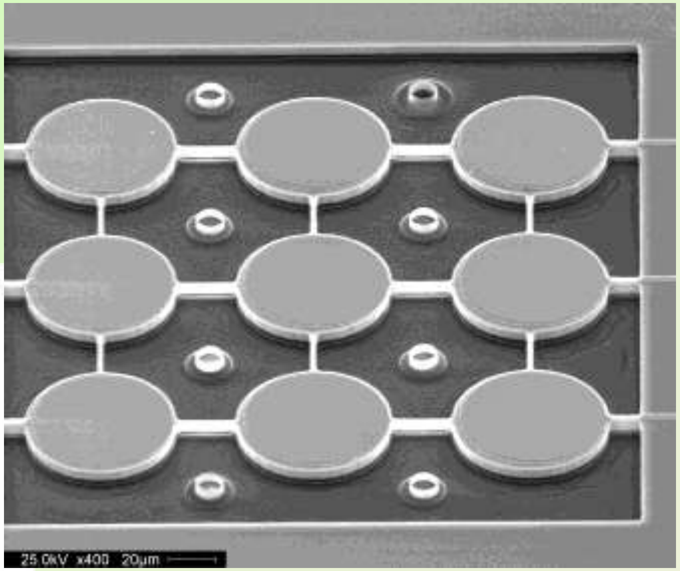


Array scheme → a zero in the transfer function, thus a notch in the freq. spectrum.

Mechanically-Coupled Filters

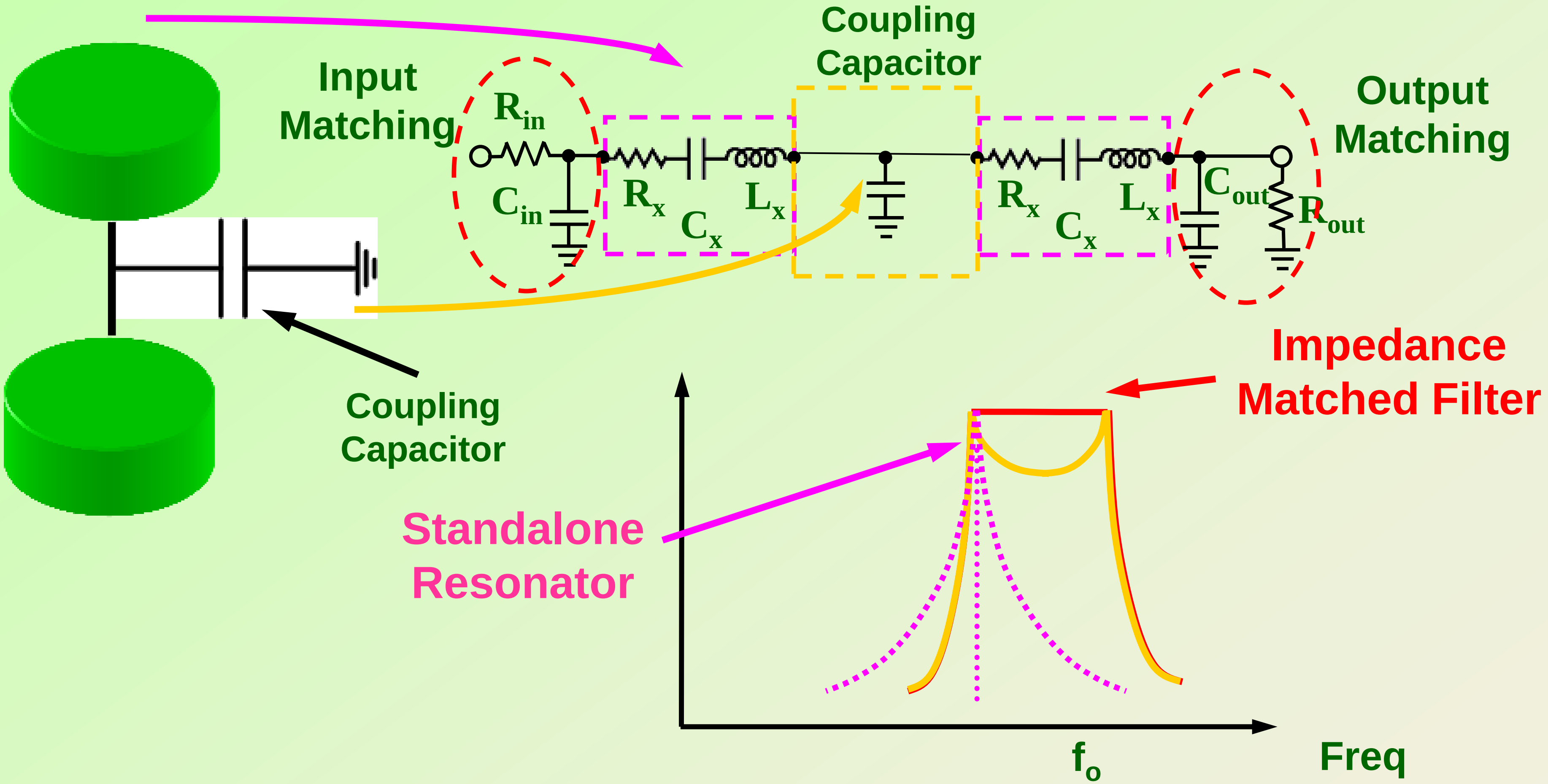
Array of 3 × 3 mechanically coupled resonator





20 dB Shape factor : 1.7

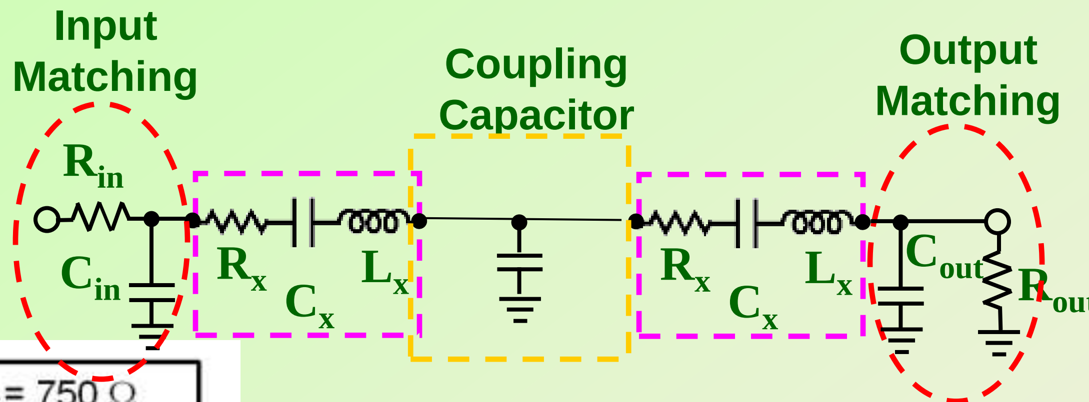
Capacitively-Coupled Filters

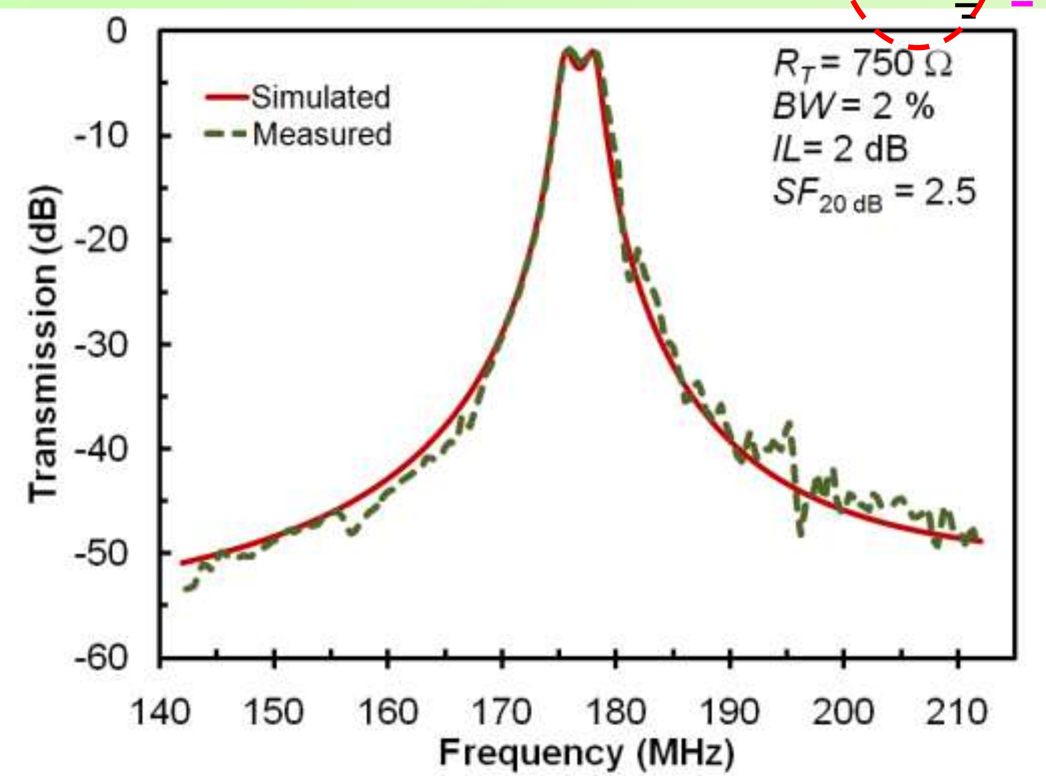


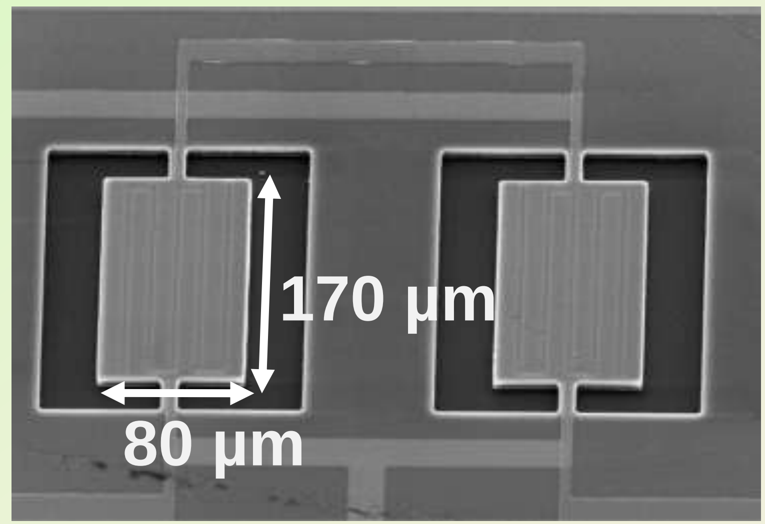
- Capacitively- or electrically-coupled μmechanical resonator filter can provide real filter characteristics

Capacitively-Coupled Filters

2-pole capacitively coupled filter

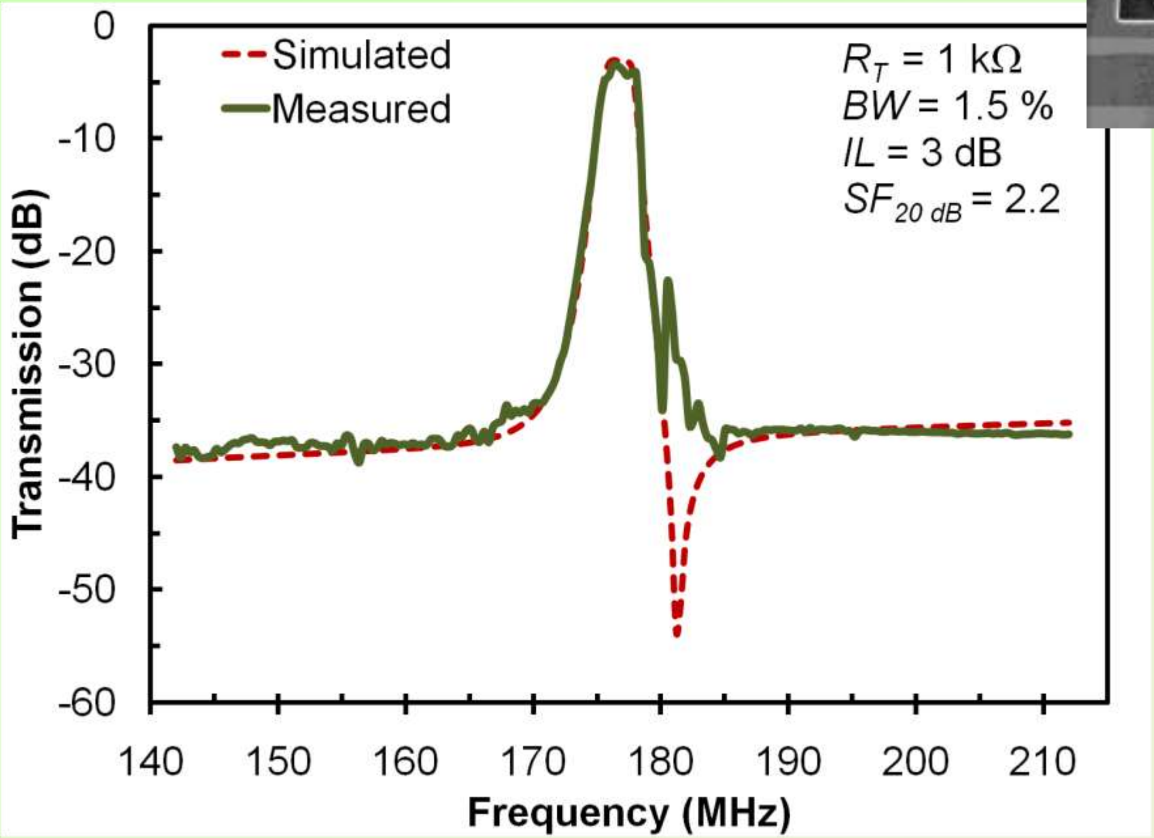


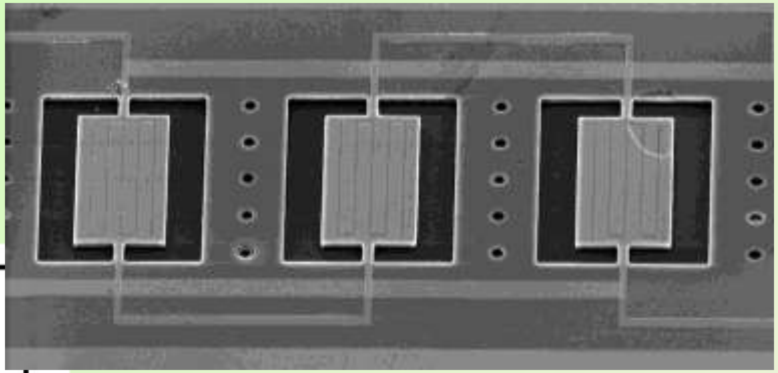




Capacitively-Coupled Filters

3-pole capacitively coupled filter



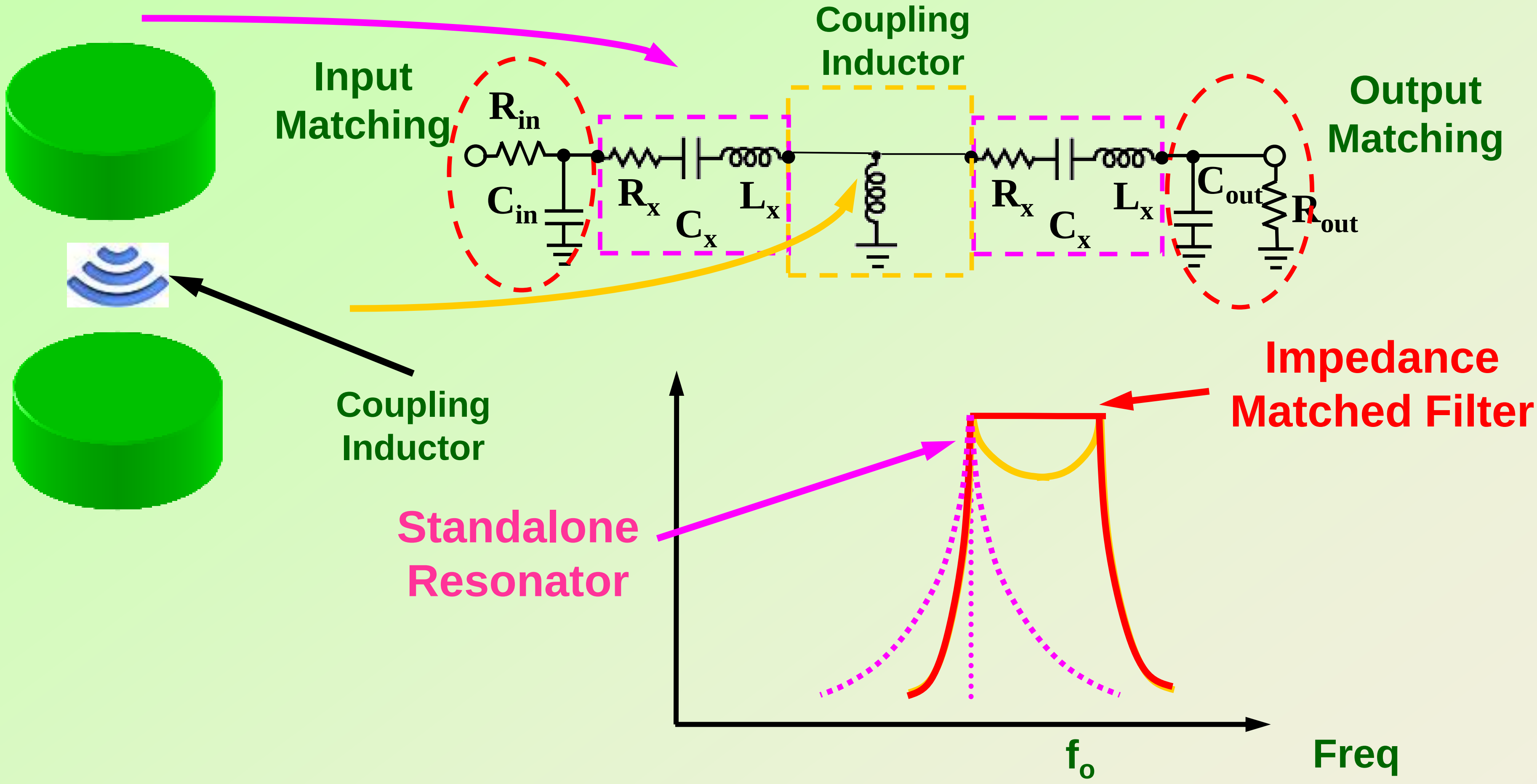


 # Resonators in array ↑

↓

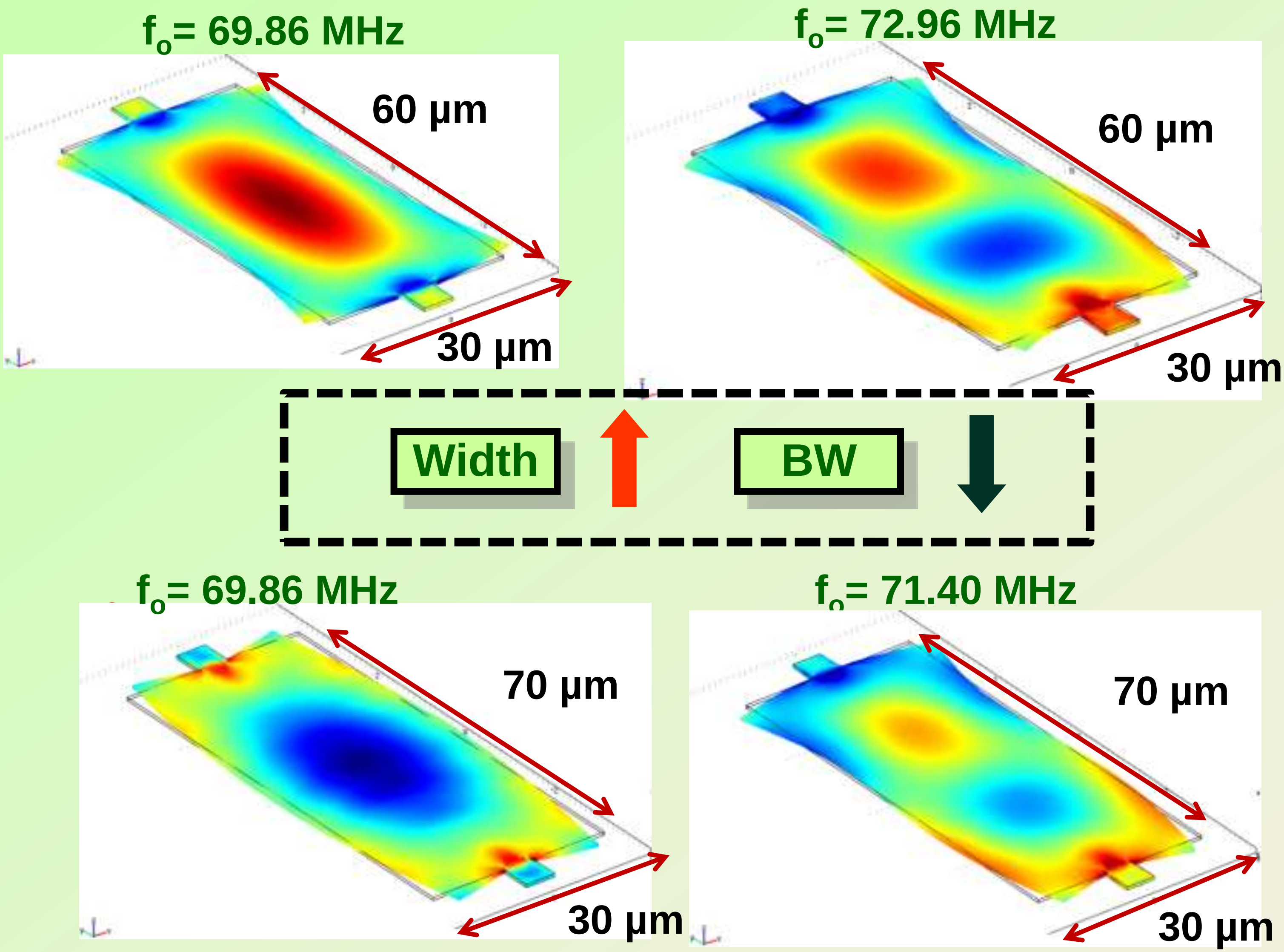
Better shape factor

Acoustically-Coupled Filters



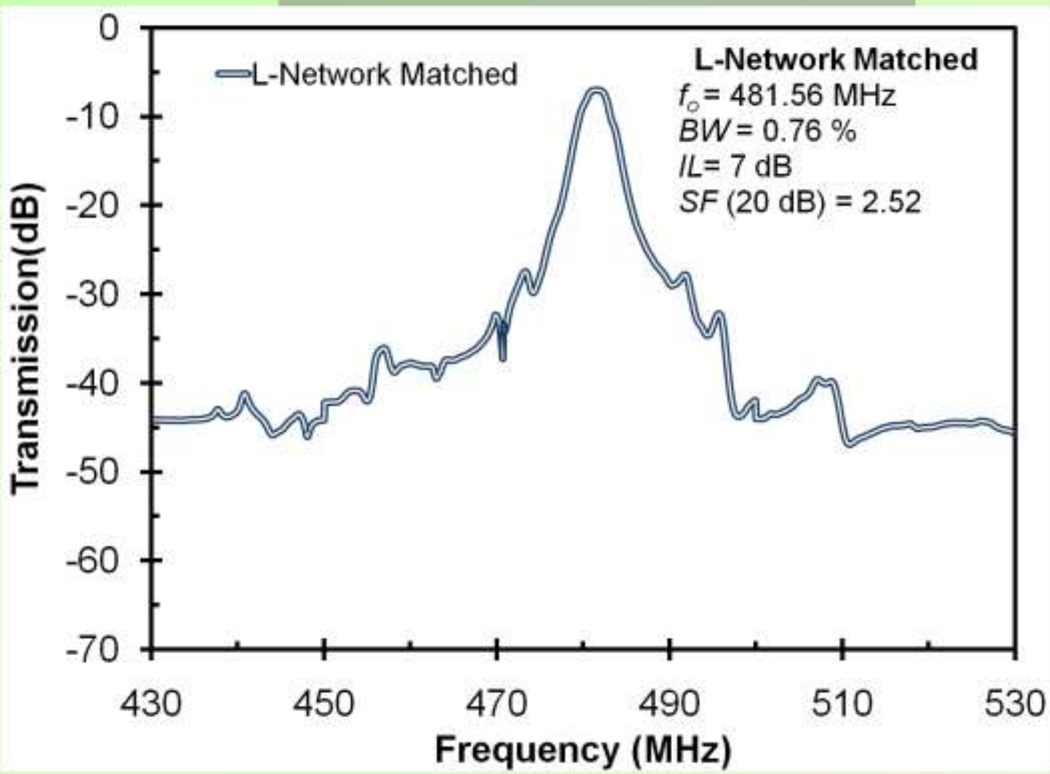
- Acoustically-coupled μmechanical resonator (a single device in two modes) r can provide real filter characteristics

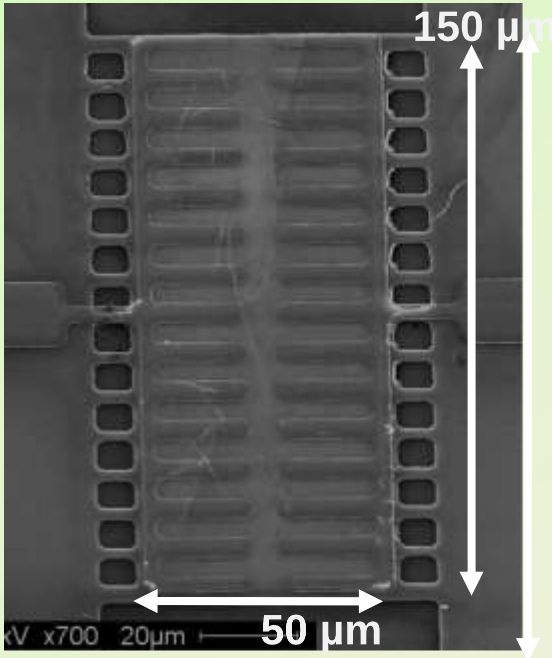
Acoustically-Coupled Filters



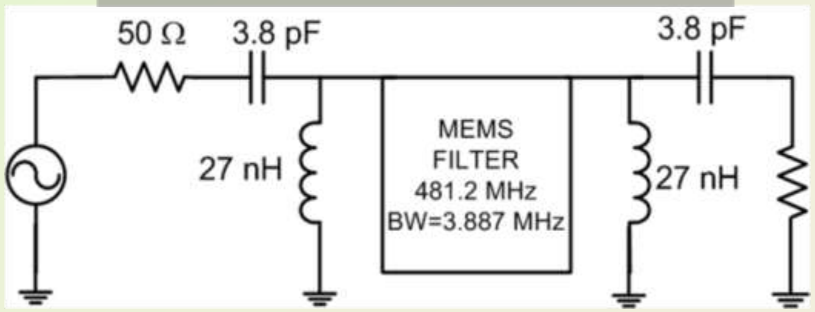
Acoustically-Coupled Filters

Thin-film piezoelectric monolithic filter



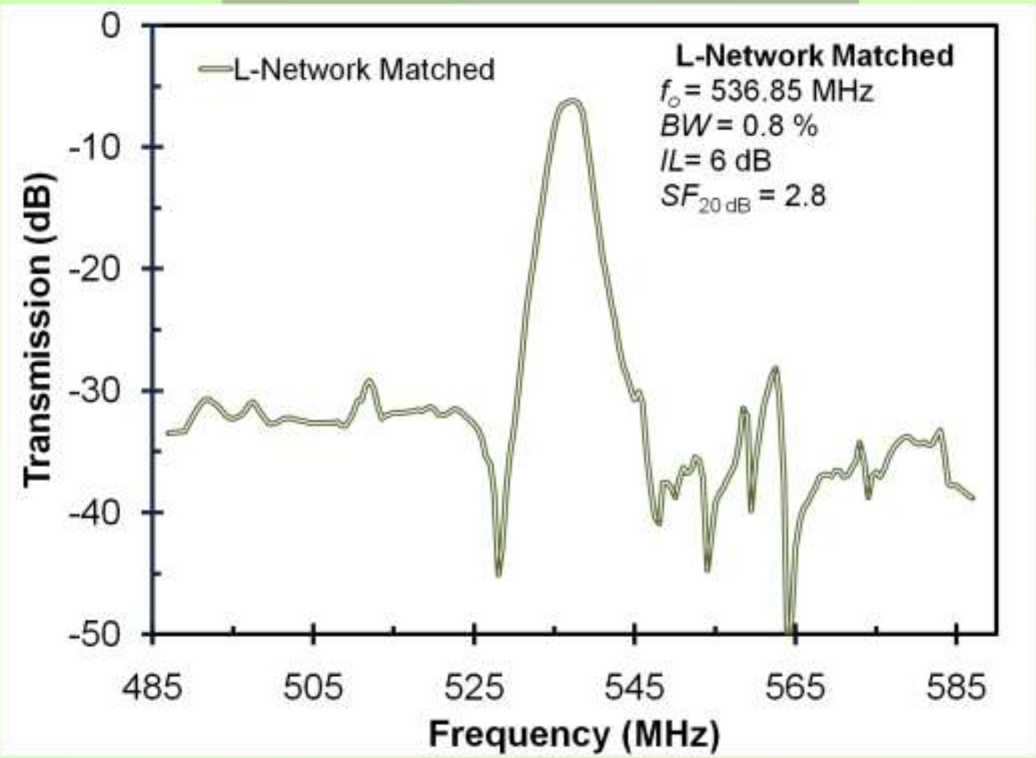


Matching circuit

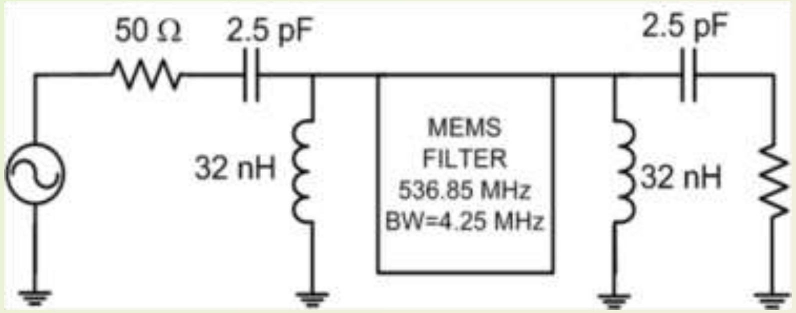


Acoustically-Coupled *Filters*

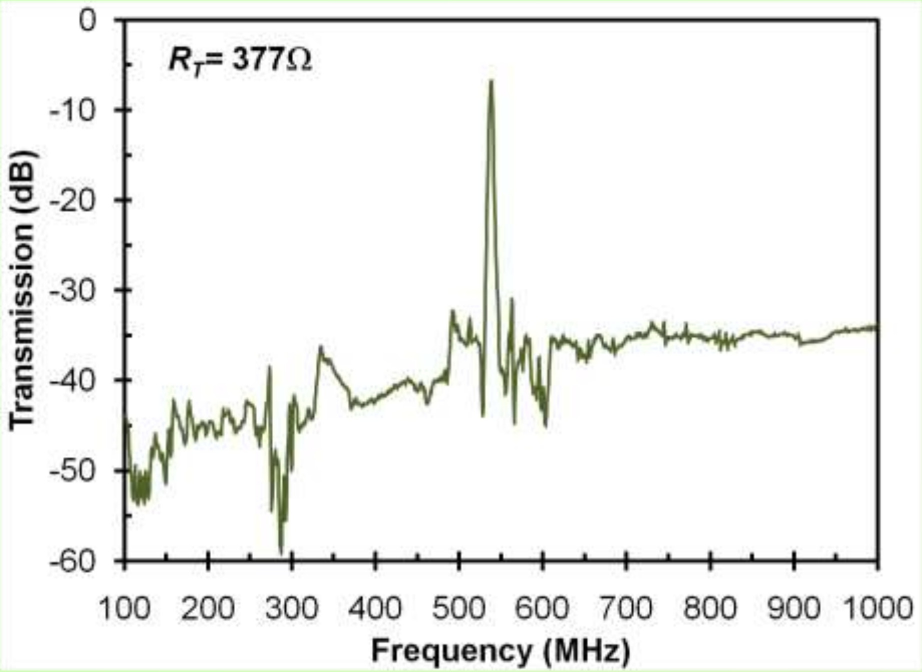
Thin-film piezoelectric monolithic filter



Matching circuit

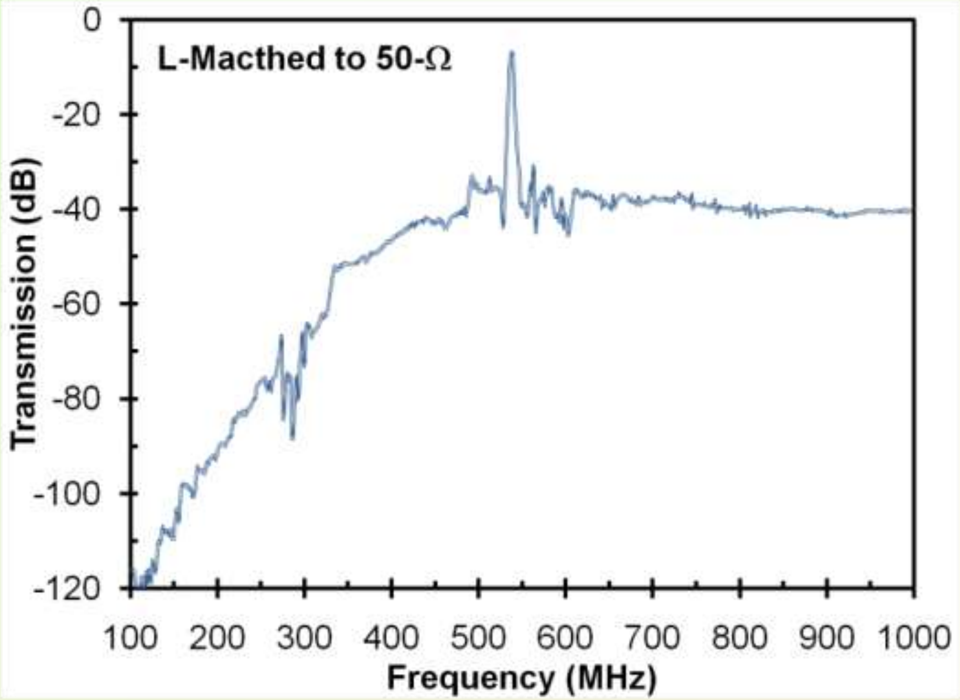


Acoustically-Coupled *Filters*



Terminated with a 377 Ω resistor

Terminated to 50 Ω using a L-matching network



Conclusions

- Successful implementation of bandpass MEMS filters operating in the VHF/UHF bands with performance better than SAW devices by using piezoelectrically-transduced contour-mode resonators.
- Three viable filter design/synthesis strategies were systematically explored (e.g., mechanically, electrically and acoustically coupled filters, etc.).
- Two-pole filters with a bandwidth as narrow as 200 kHz and an insertion loss as low as <2dB have been demonstrated that fulfill the requirements for a variety of wireless applications.
- A robust and high-yield mass-production amenable process for thin-film ZnO-on-SOI resonators and filters have been developed.
- The microfabricated MEMS filters have greatly reduced sizes up to 10-100 times smaller than the commercial devices implemented with SAW resonators operating at the same frequency range.

RF MEMS Transducers Group at USF

Major Research Interests:

- Functional Nanomaterials
- RF/MW/THz NEMS/MEMS Devices
- Micromachined Sensors and Actuators

Current Group Members:

- 12 PhD Students
- 2 M.S. Students
- 4 Undergraduate REU Students
- 1 Post-Doc Fellow

Research Award & Grants (>$5.0M):

- 5 Active Research Grants from NSF
  - ECCS (2), CMMI (1), CHE (1), CBET (1)
- 8 Industrial Research Contracts
  - Draper Lab (2 year project)
  - Raytheon (3 year project)
  - SRI International (Two 3-year projects)
  - Nano CVD Co. (2 year project)
  - Plasma Therm, LLC. (1 year project)
  - Novellus Systems (3 year Project)
  - Modelithics Inc. (multiple year effort)
  - Florida High Tech Corridor

National Science Foundation
WHERE DISCOVERIES BEGIN
Raytheon
DRAPER LABORATORY
FLORIDA high tech Corridor
NanoCVD
nScrypt
Modelithics
ATK
SRI International
AEM, INC.
Plasma-Therm
NOVELLUS

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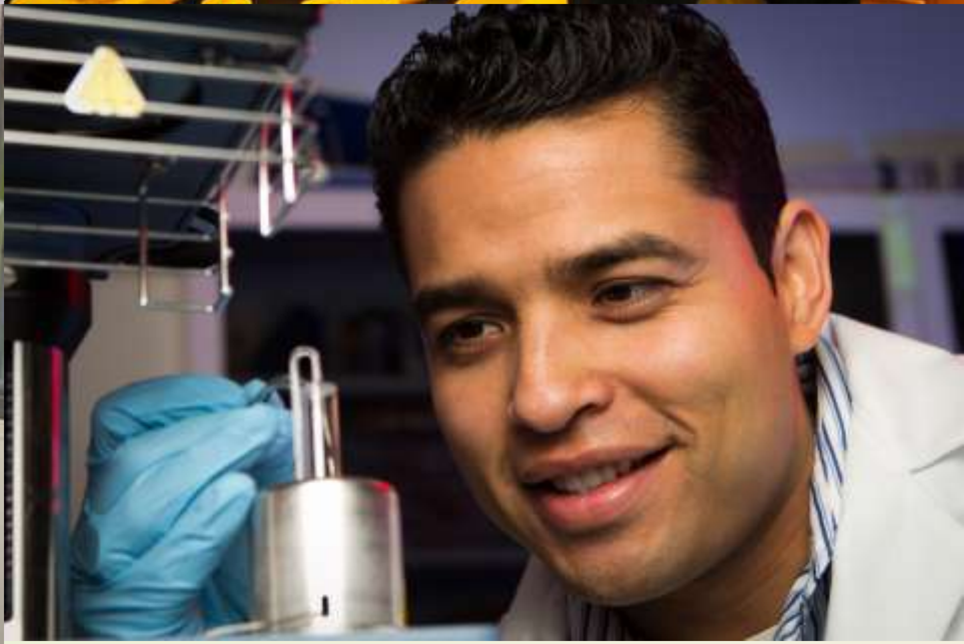
Thanks to My Dedicated Graduate Students



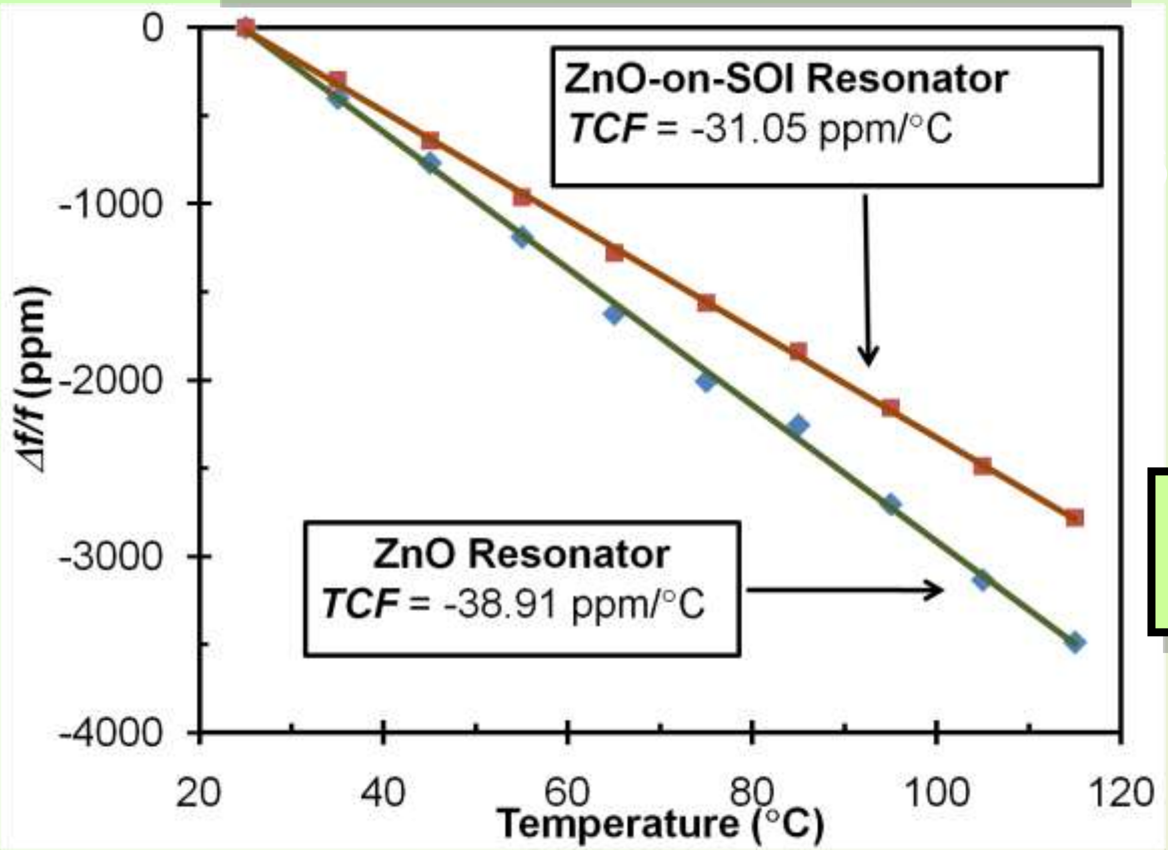



Questions?

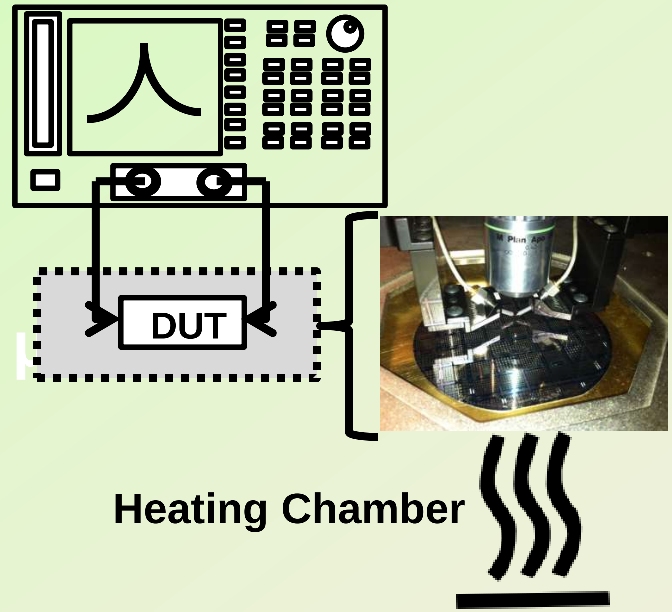
http://transducers.eng.usf.edu

Temperature Coefficient of Micro-Resonators

Temperature Coefficient Frequency



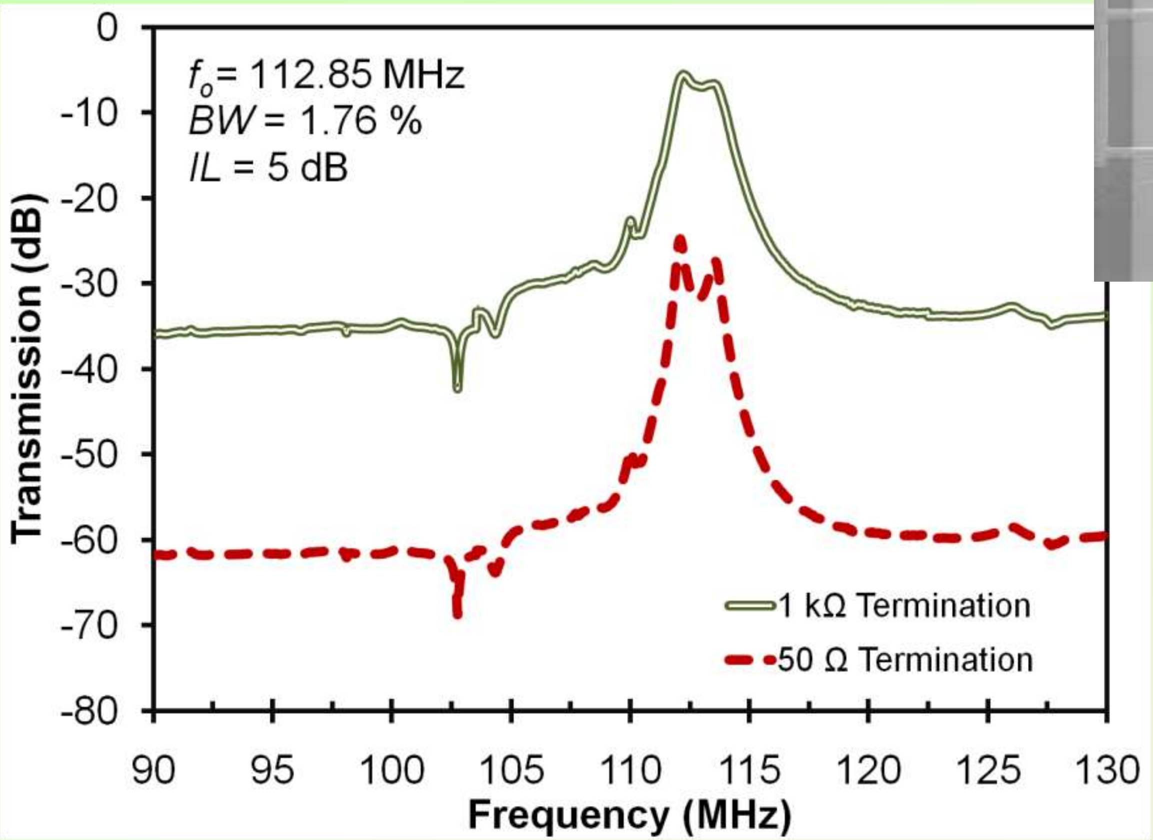
Vector Network Analyzer

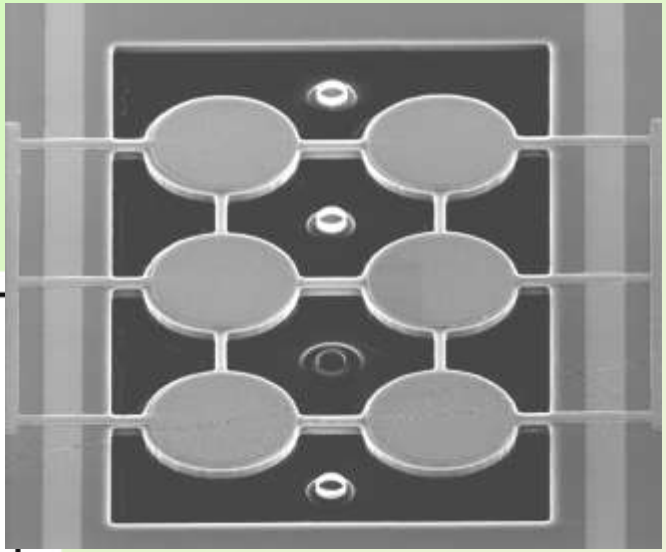


Measurement Setup

Mechanically-Coupled Filter*s*

Array of 3 × 2 mechanically coupled ZnO-on-silicon resonators





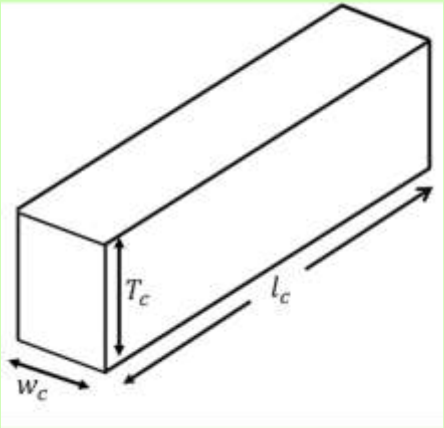
20 µm-radius disk resonators

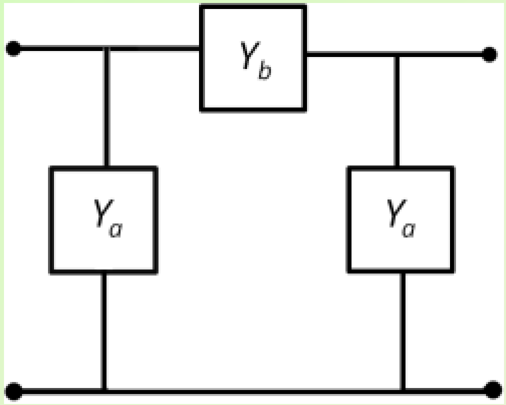
Current State of the Art

Modes of Vibration and Frequency

Mode of Vibration	Frequency Range	Frequency Equation
Flexural -Mode	10 kHz – 10 MHz	$f_o \propto \frac{T}{l^2}\sqrt{\frac{E}{\rho}}$
Contour- Mode	**10 MHz – 10 GHz**	$f_o \propto \frac{1}{2l}\sqrt{\frac{E}{\rho}}$
Thickness- Mode	800 MHz – 20 GHz	$f_o \propto \frac{1}{2T}\sqrt{\frac{E}{\rho}}$
Shear- Mode	800 MHz – 20 GHz	$f_o \propto \frac{T}{l^2}\sqrt{\frac{E}{\rho}}$

Coupling Beam for Mechanically-Coupled Filter





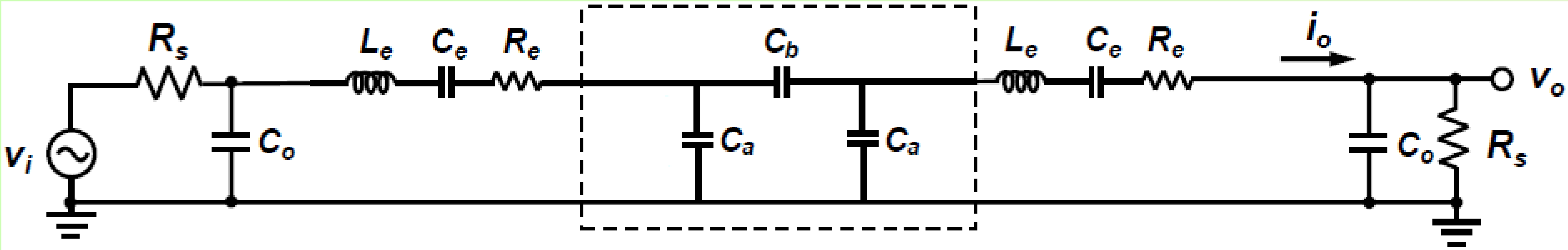
$$Z_0 = \frac{1}{w_c T_c \sqrt{\rho E}}$$

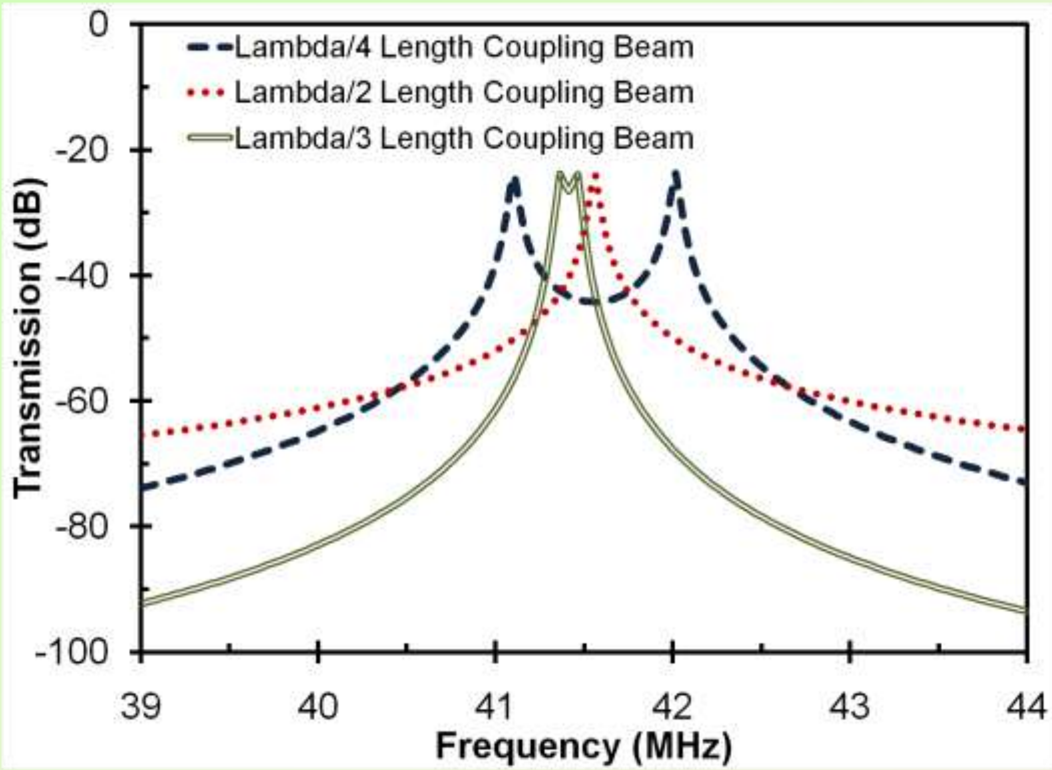
$$\alpha = 2\pi f_0 \sqrt{\frac{\rho}{E}}$$

$$Y_b = \frac{-j}{Z_o \sin \alpha l}$$

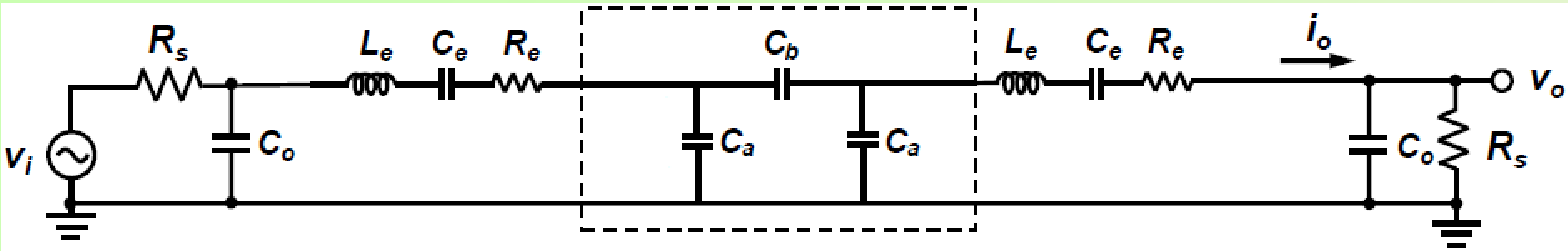
$$Y_a = \frac{-j\, tan(\alpha l/2)}{Z_o}$$

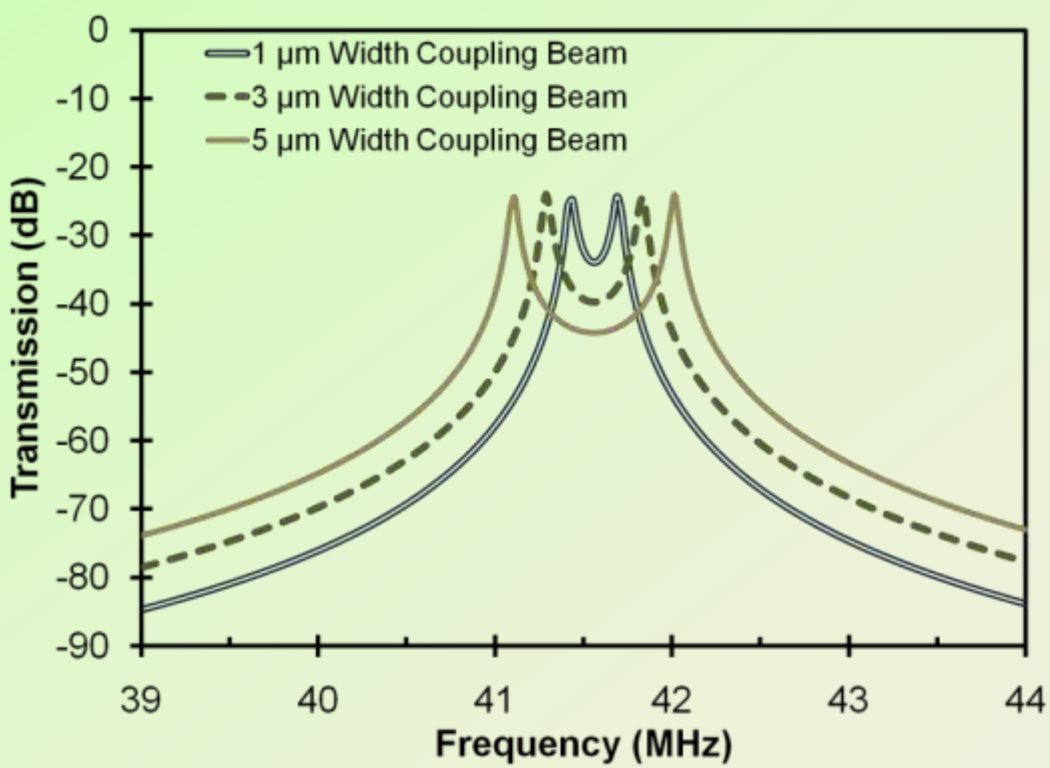
Coupling Beam for Mechanically-Coupled Filter





Coupling Beam for Mechanically-Coupled Filter





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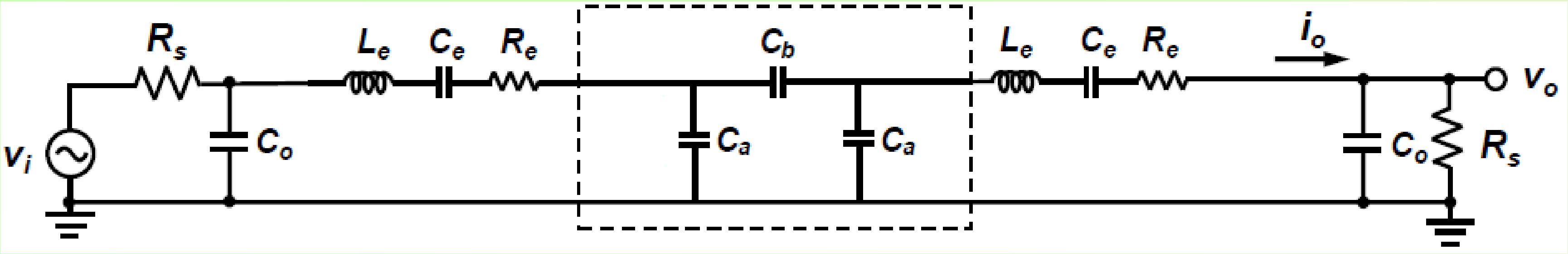
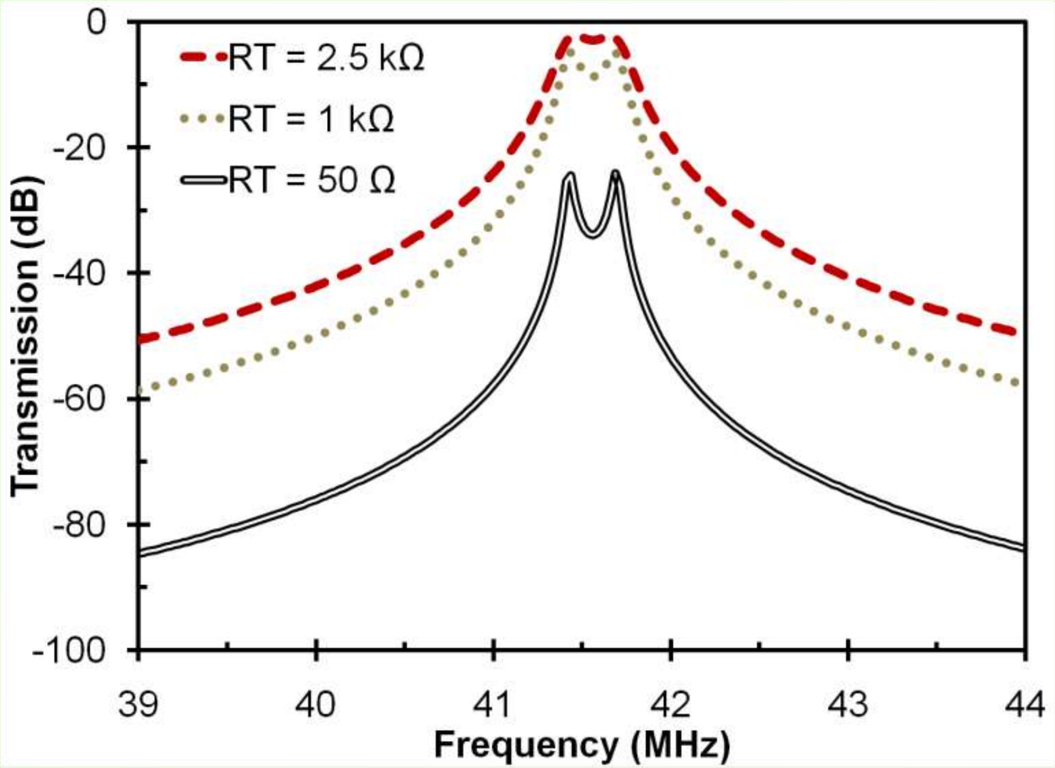
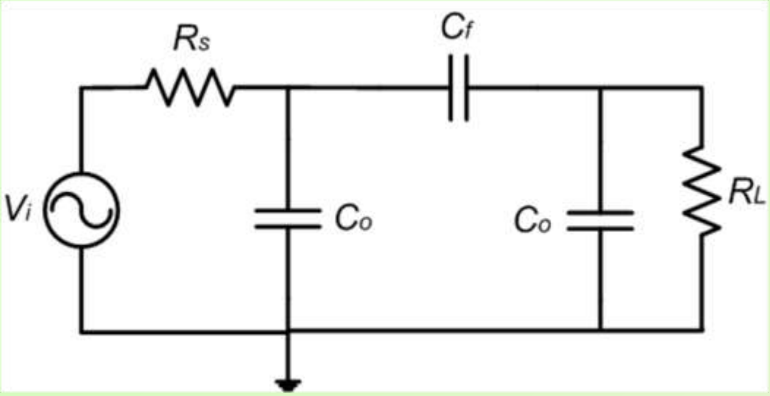
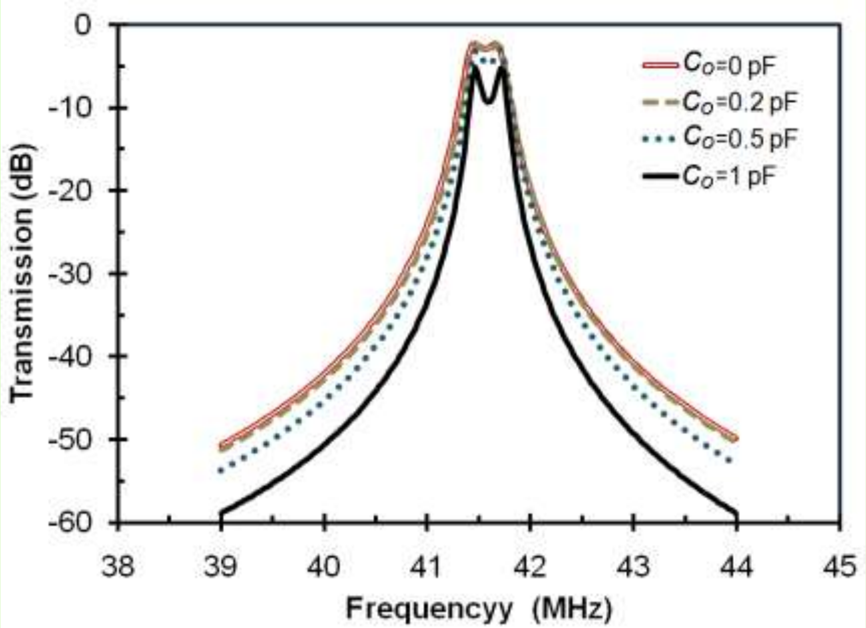
Coupling Beam for Mechanically-Coupled Filter

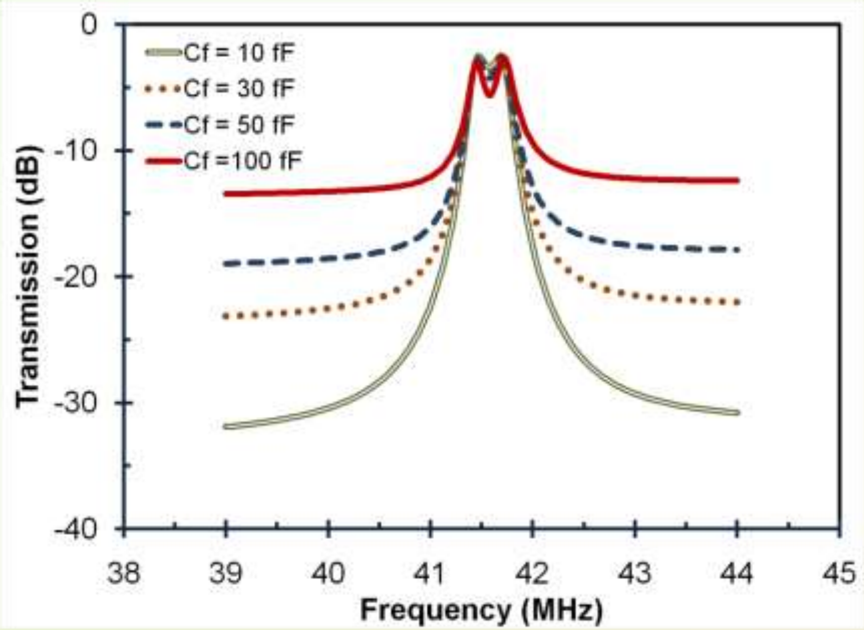




Mechanically-Coupled Filters







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Thickness-Mode Piezoelectric Resonator (2.4-4.8GHz)