MEMS Resonator Simulation

T. Koyama, D. Bindel, W. He, E. Quévy
S. Govindjee, J. Demmel, R. Howe

University of California, Berkeley

Resonator Simulation

- High-frequency MEMS resonators (MHz~GHz)

  •Applications as - Small size, low energy consuming frequency references, filters, and sensors

  •Design requires knowledge of

  - Frequency ← Existing Software
  - **Quality factor(Q)** ← ?

$$Q = \frac{\text{Maximum Stored Energy}}{\text{Energy Loss per radian}} \approx \frac{1}{\text{Damping}}$$

HiQLab:Tool for evaluating damping in resonant MEMS

Capabilities

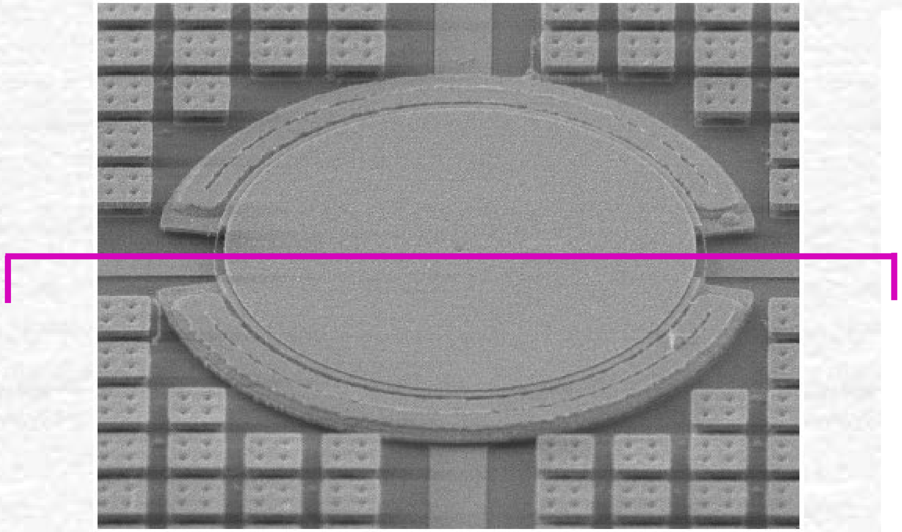
- Finite Element tool
- Dimensions:
  - 1D, 2D, 3D, Axisymmetric
- Analysis:
  - Steady-state/Static
- Elasticity, scalar wave
- Coupled problems:
  - Electromechanical
  - Thermomechanical

Special features

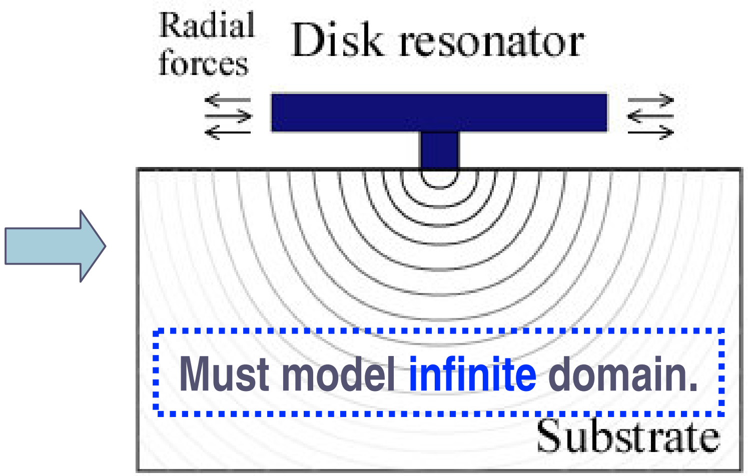
- Damping mechanisms:
  - Anchor loss
  - Thermoelastic damping
- Efficient Algorithms:
  - Eigenfrequency computation
  - Arnoldi based Reduced Order Model (ROM) for transfer function computation
- MATLAB/Lua user interface

Disk resonator (Anchor loss)

- Mechanism: Energy loss from radiating waves escaping into the substrate.



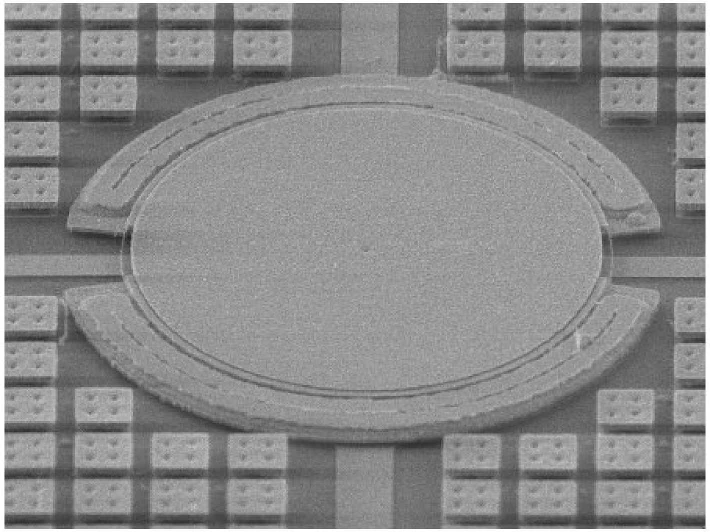
SEM of 41.5 um radius poly-SiGe disk resonator



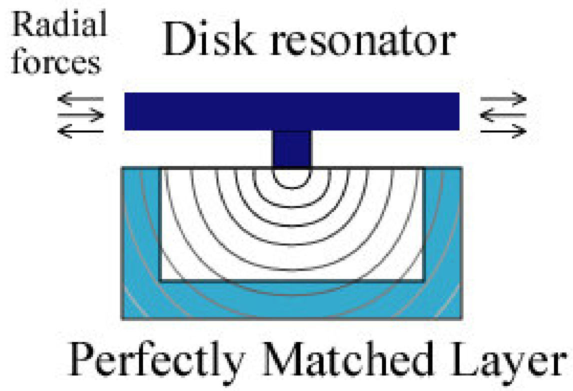
Section of disk resonator

Perfectly Matched Layers (PML)

- Mechanism: Energy loss from radiating waves escaping into the substrate.



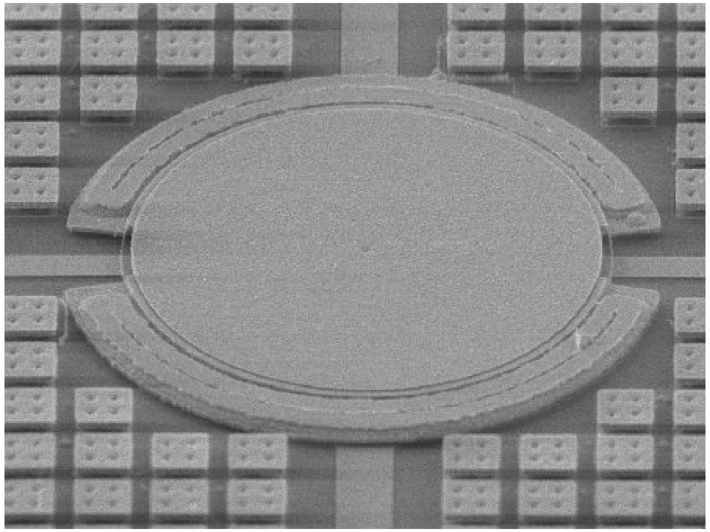
SEM of 41.5 um radius poly-SiGe disk resonator



Outgoing waves are absorbed with zero impedance mismatch at PML boundaries.

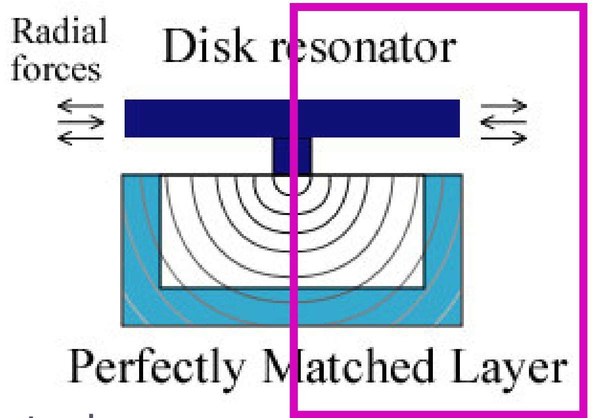
Perfectly Matched Layers (PML)

- Mechanism: Energy loss from radiating waves escaping into the substrate.



SEM of 41.5 um radius poly-SiGe disk resonator

Axisymmetric analysis

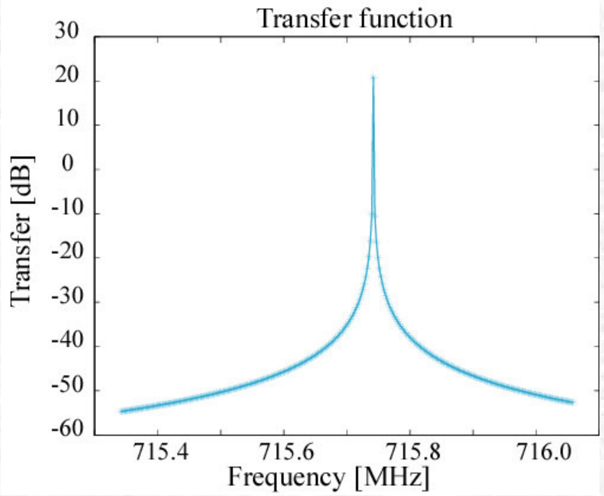


Outgoing waves are absorbed with zero impedance mismatch at PML boundaries.

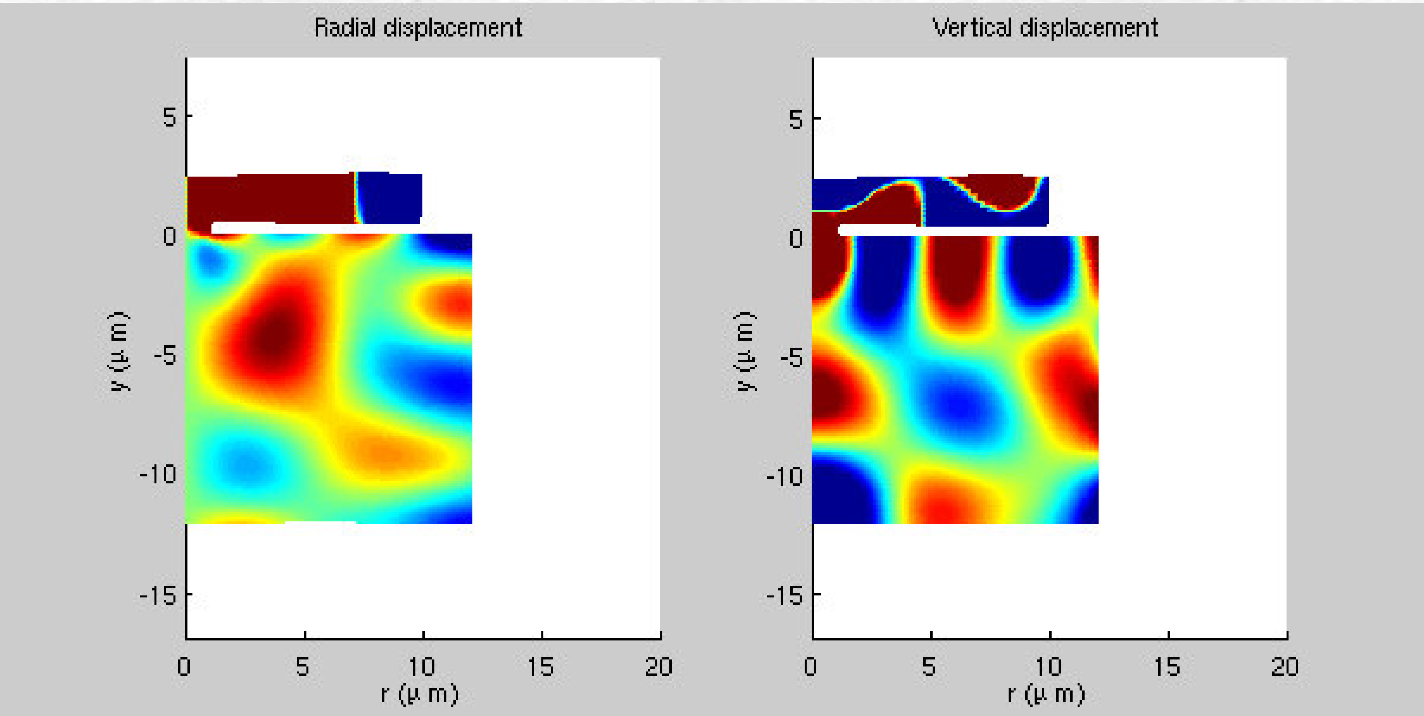
BSAC

Anchor loss simulation

- Without PML



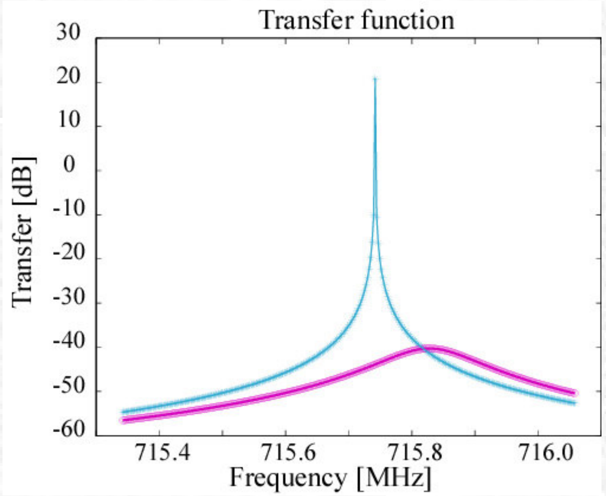
Standing waves are non-physical !

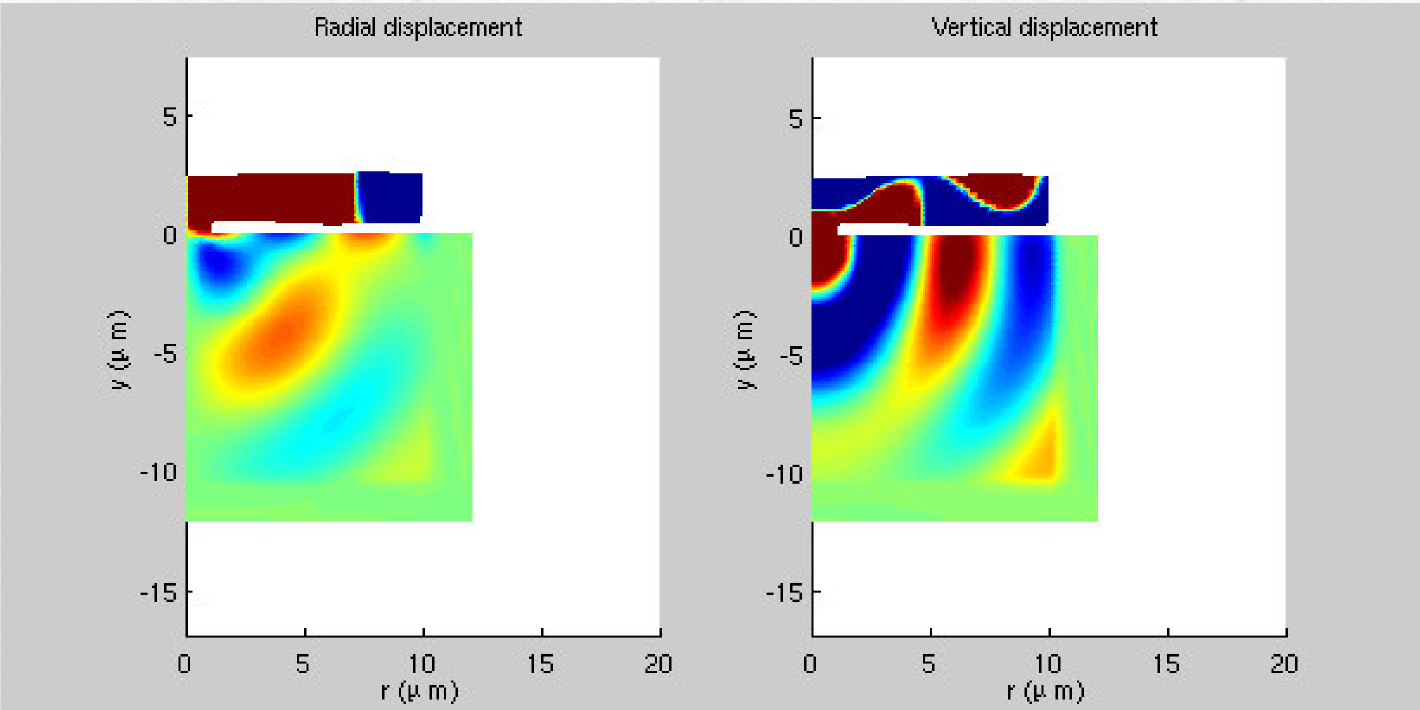


Anchor loss simulation

- WithPML

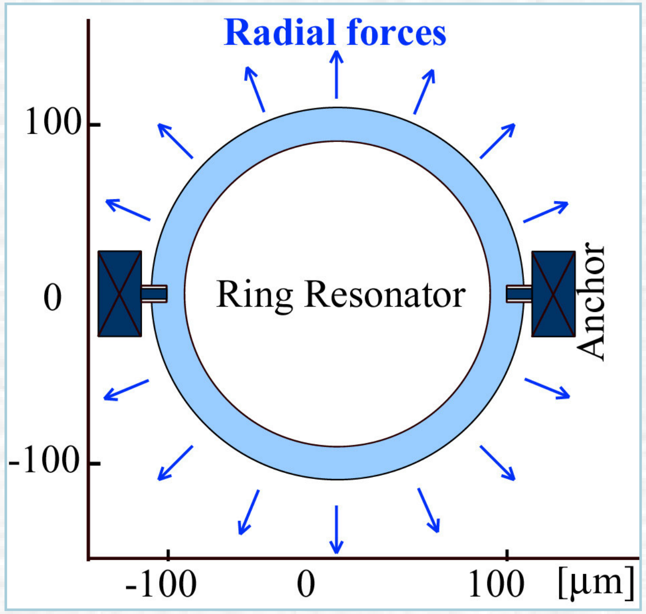
Wave propagation behaviour !
No reflections at boundary !





Ring resonator (Thermoelastic damping)

- Mechanism: Energy loss from coupling of the mechanical and thermal domains



Schematic of ring resonator

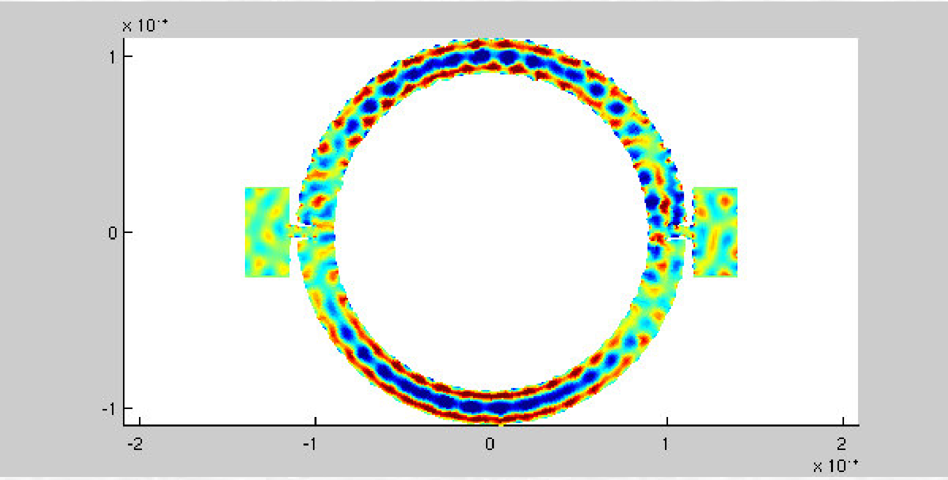
Solve coupled balance of momentum and heat equation

Efficiency of Reduced Order Model

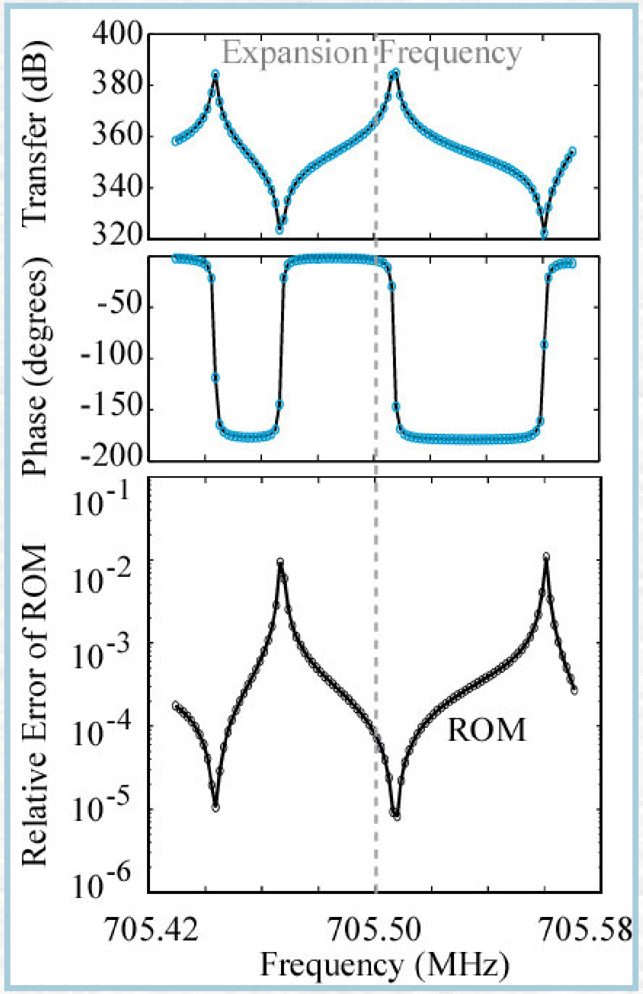
- 2D Plane Stress
- Full
- ROM DOF = 42477
  DOF = 21

100 points
10 Minutes
23 Seconds

Temperature fluctuations



Forced at 705.5[MHz]



Transfer function

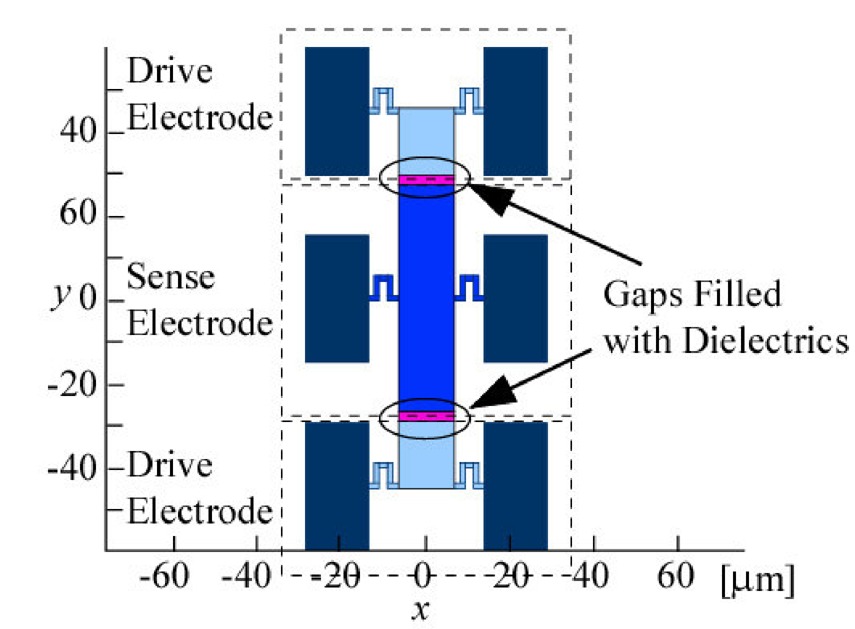
BSAC

Dielectric filled gap resonators

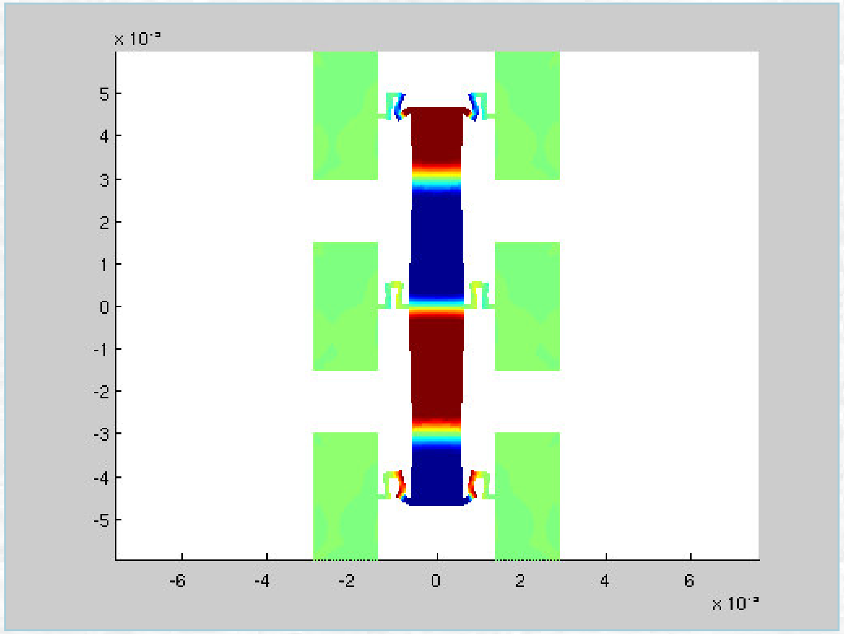
- Idea: Increase electrostatic transduction

for better transduction

Air gap → Fill gap with dielectric material



Schematic of resonator



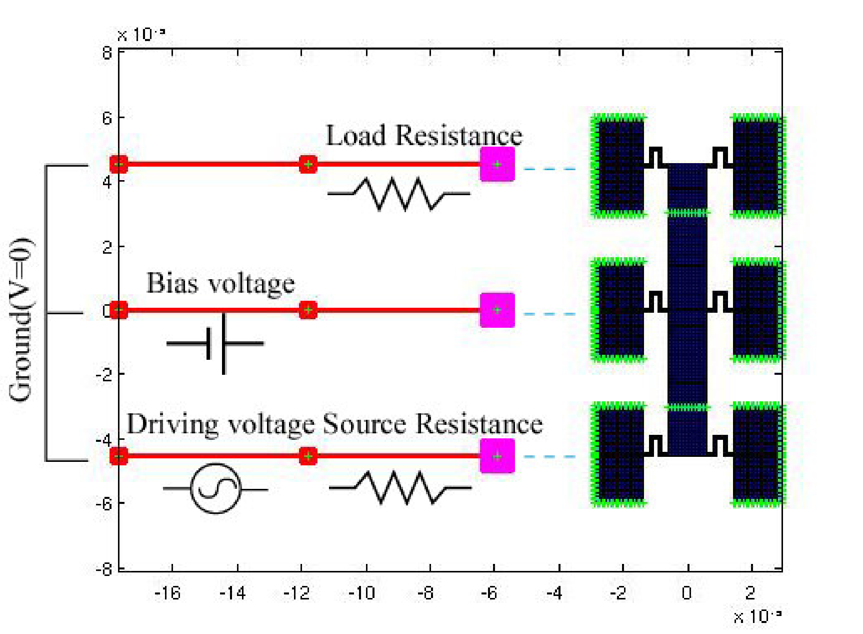
Resonant mode at 140.05[MHz]

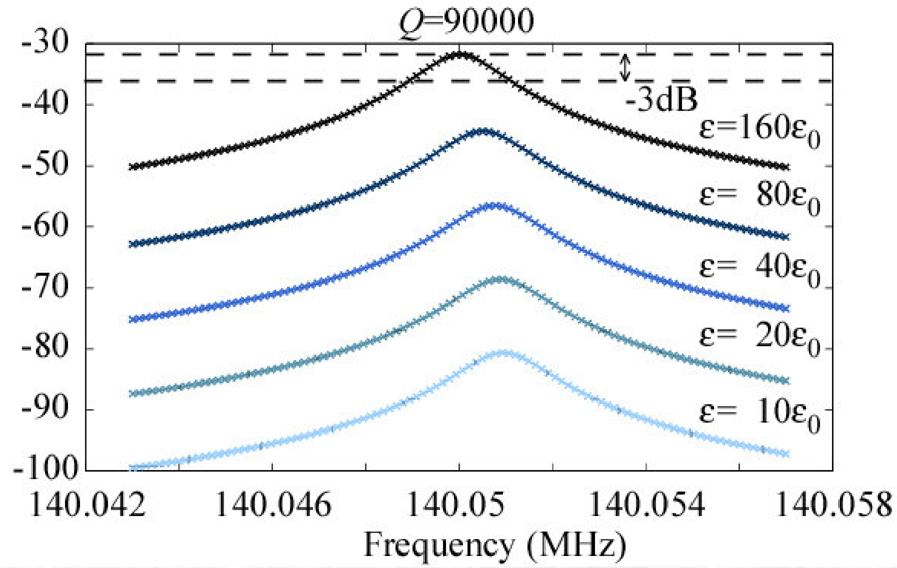
BSAC

Simulation (1): Two port resonator

- Single two port dielectric resonator

Insertion loss decreases with increasing ε





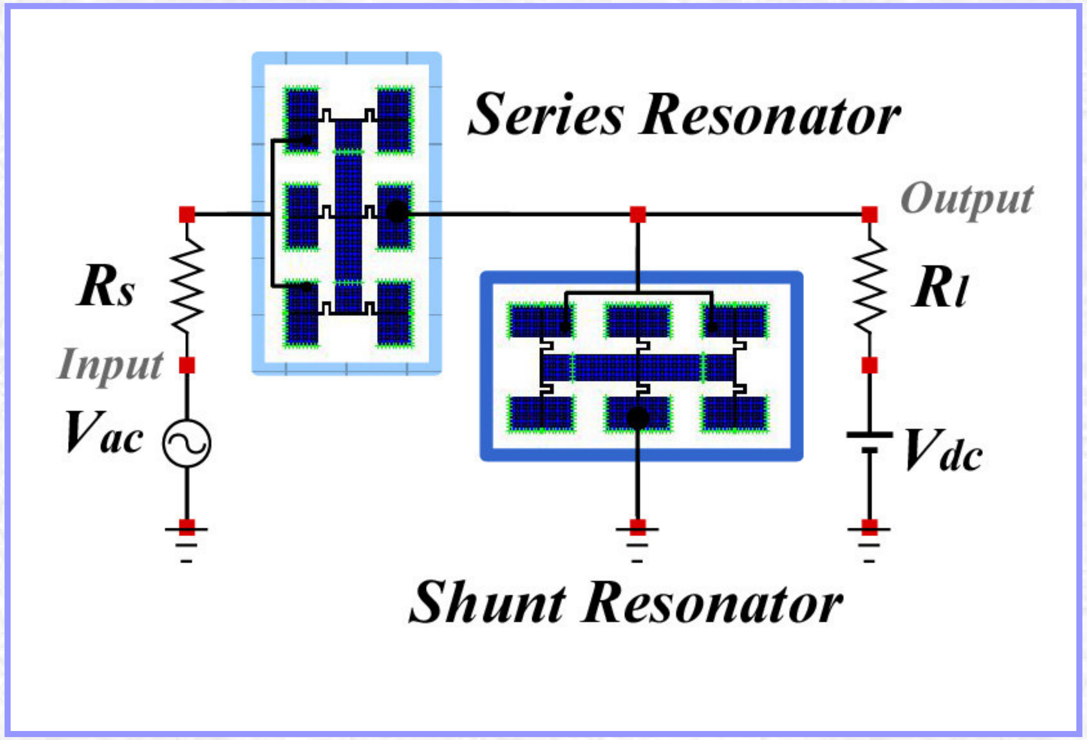
Schematic of surrounding circuitry

Transmission plot varying ε

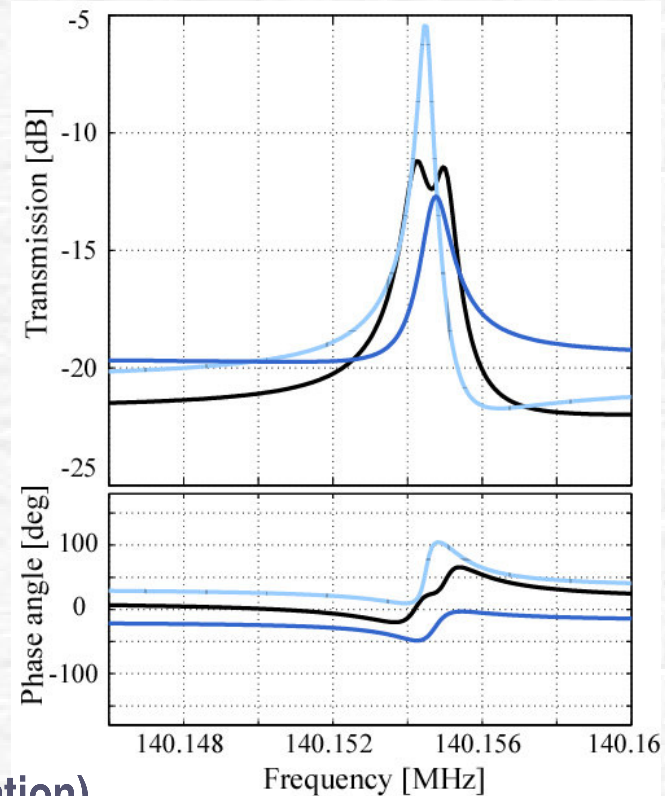
(Anchor loss incorporated)

Simulation (2): Ladder filter

- Electrically coupled resonators



Schematic of ladder configuration **(3.4kΩTermination)**



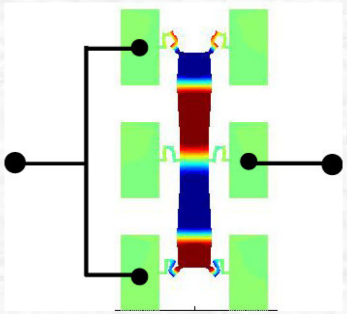
Transmission plot

BSAC

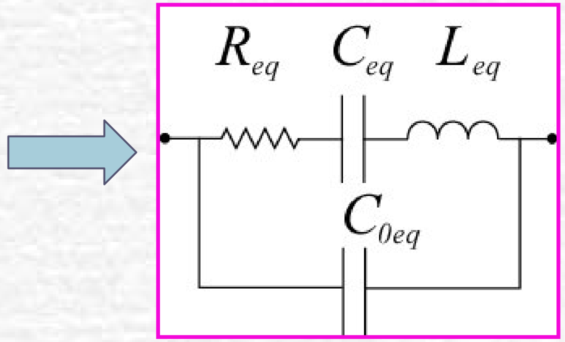
Extracting LRC-C parameters

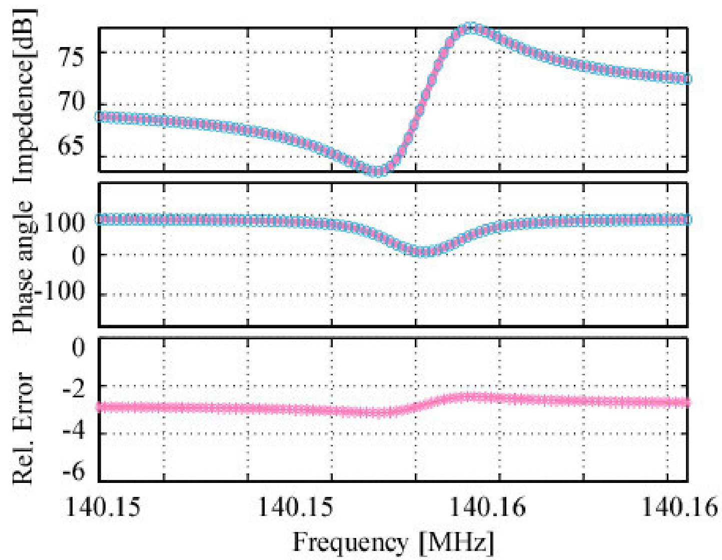
- Equivalent circuit representation

Resonator at specific mode



LRC-C representation





Impedence plot and accuracy of LRC-C representation

L_{eq}= 0.181[H]

R_{eq}= 1.89 [kΩ]

C_{eq}= 0.340[aF]

C_0= 7.13[pF]

V_{dc} = 100 [V]

k = 160 ε_0

f_c = 140.15[MHz]

Enables simple calculations.

Summary

- HiQLab: Resonant MEMS Simulator
  - Simulates Anchor loss / Thermoelastic damping (Simulations have been verified with experiments. "Anchor Loss Simulation in Resonators". MEMS'05).
  - Efficient algorithms for *Q* evaluation which take advantage of underlying structure: Anchor loss / Thermoelastic damping
  - First dielectric drive simulation
- http://www.cs.berkeley.edu/~dbindel/hiqlab
  - Software is freely available
  - Tutorial slides and relevant papers
- Ongoing and future work
  - Resonator optimization for target bandpass filter design
  - Parallel algorithms for solution of larger problems
  - Modeling of other sources of damping