Simulating RF MEMS

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Collaborators

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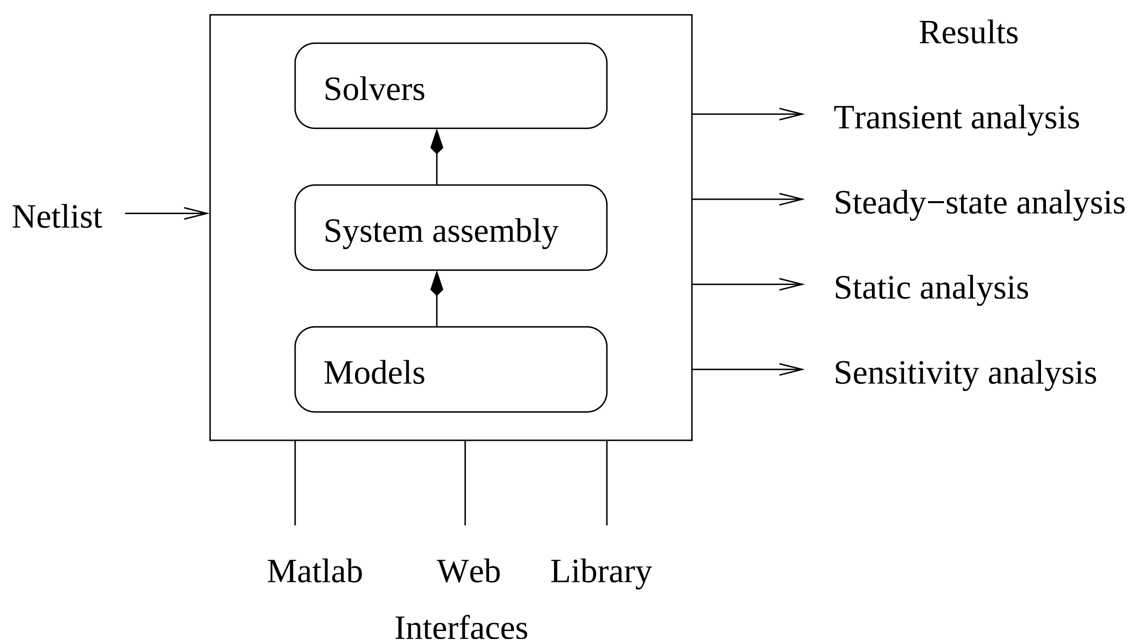
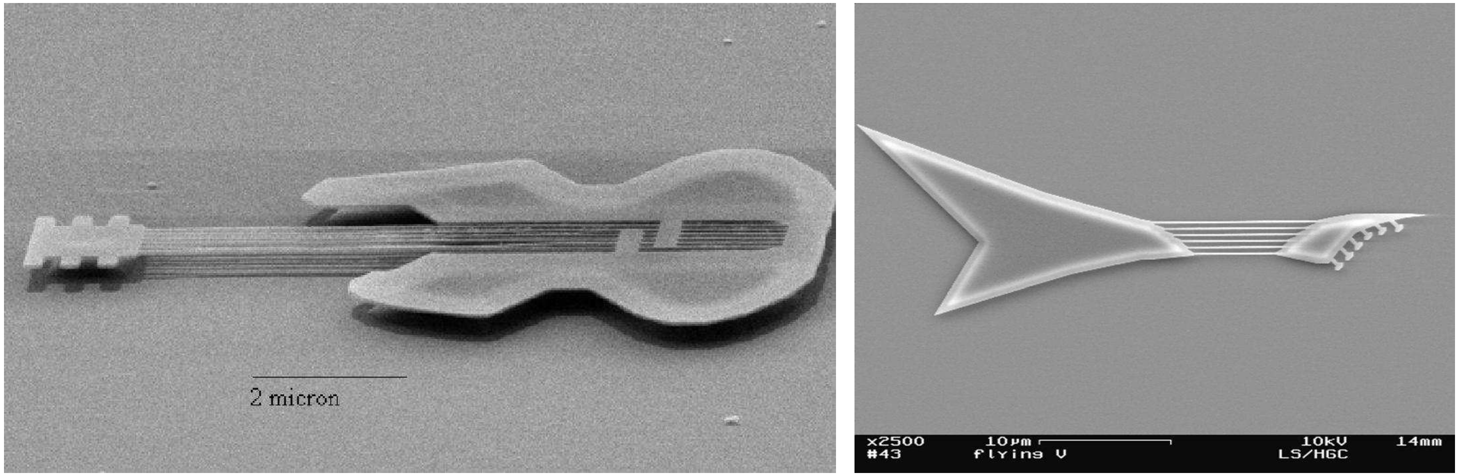
SUGAR

Goal: “Be SPICE to the MEMS world”

- Fast enough for early design stages
- Simple enough to attract users
- Support design, analysis, optimization, synthesis
- Verify models by comparison to measurement



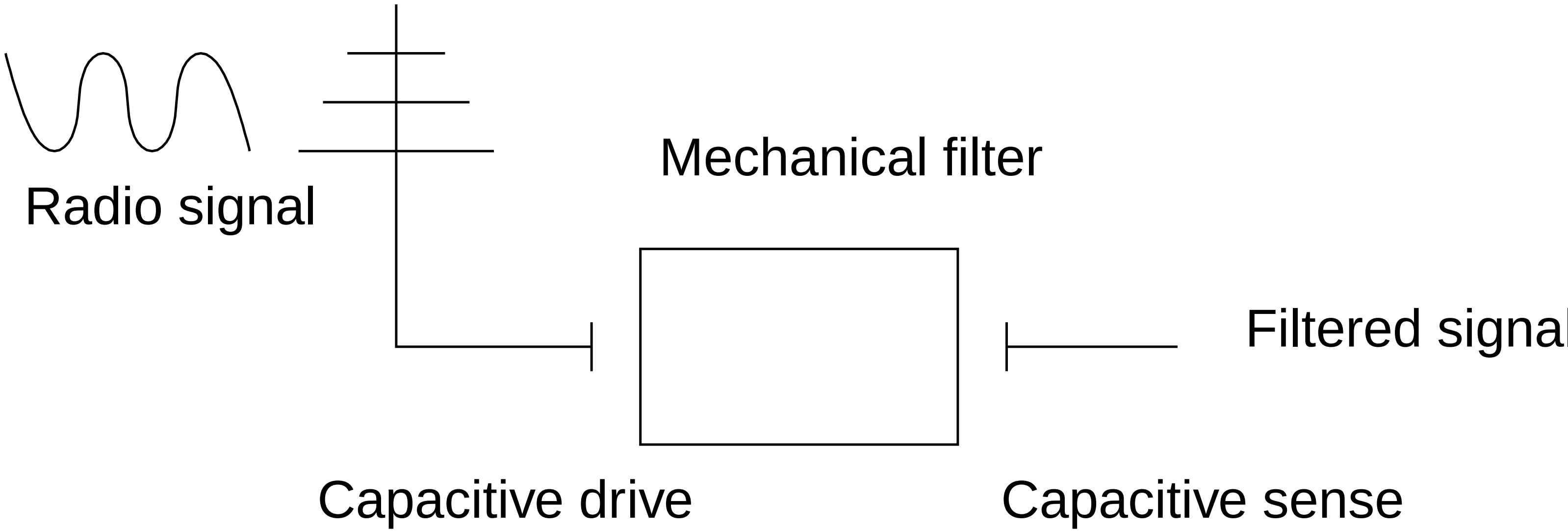
Why RF resonators?



Microguitars from Cornell University (1997 and 2003)

- Frequency references
- Sensing elements
- Filter elements
- Neural networks
- Really high-pitch guitars

Micromechanical filters



- Mechanical high-frequency (high MHz-GHz) filter
- Saves power and cost over electronic filters
- Advantage over piezo-actuated quartz SAW filters
  - Integrated into chip
  - Low power

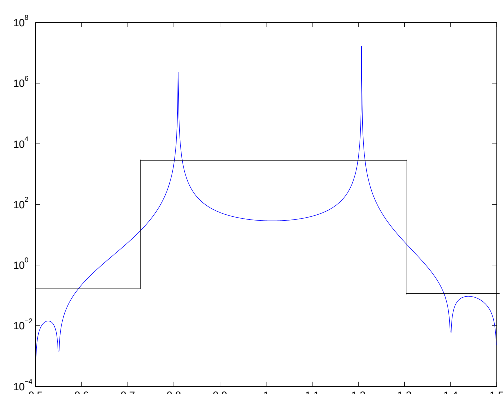
Governing equations: forced response

Time domain:

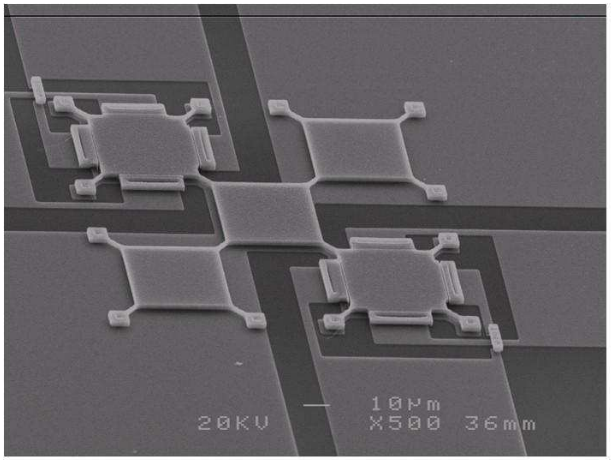
$$\begin{aligned} Mu'' + Cu' + Ku &= P\phi \\ y &= V^T u \end{aligned}$$

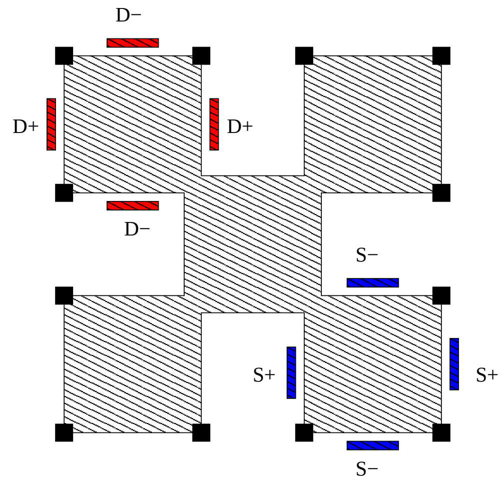
Frequency domain:

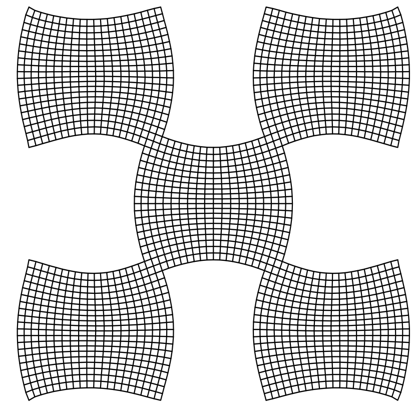
$$\begin{aligned} H(\omega) &= V^T(-\omega^2 M + i\omega C + K)^{-1} P \\ \hat{y} &= H\hat{\phi} \end{aligned}$$



First proposed design: Checkerboard

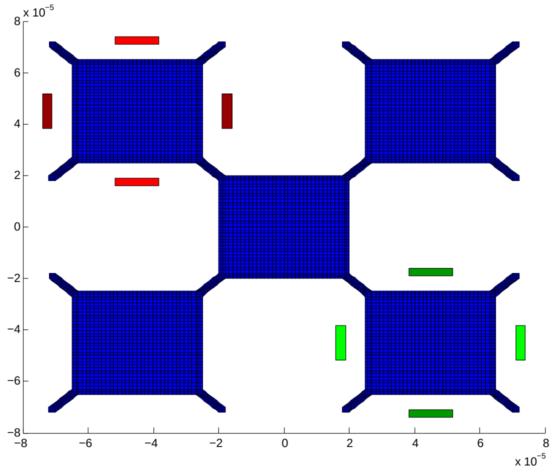


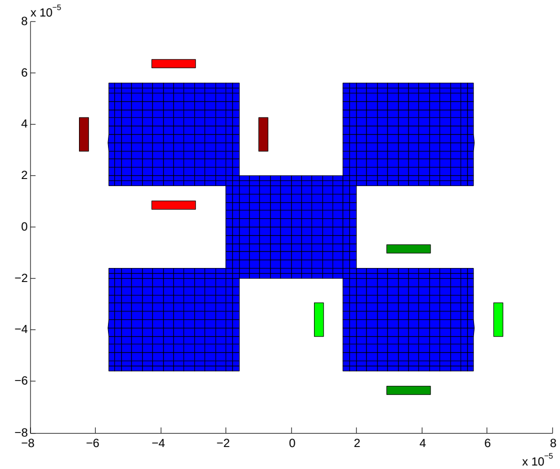




- Array of loosely coupled resonators
- Anchored at outside corners
- Excited at northwest corner
- Sensed at southeast corner
- Surfaces move only a few nanometers

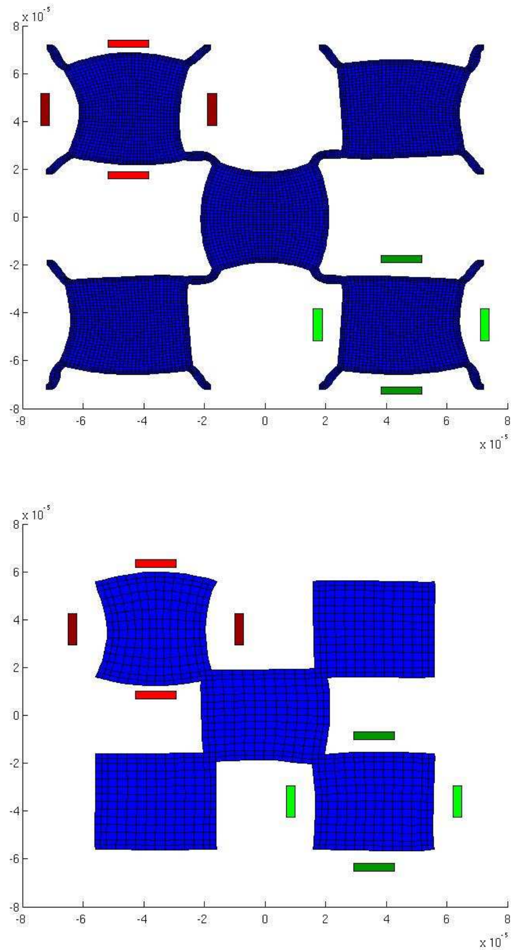
Design questions



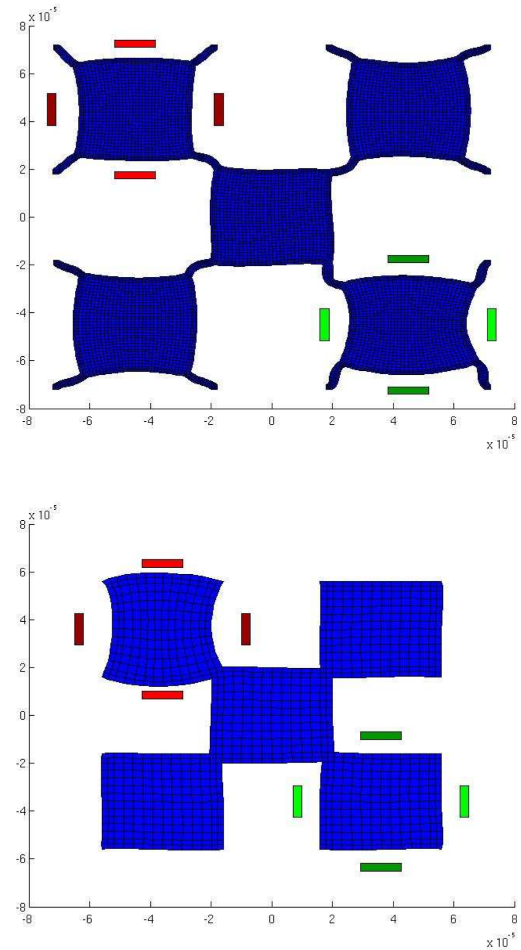


- Where should drive and sense be placed?
- How should the individual resonators be connected?
- How should the system be anchored?
- How many components? What topology?
- What size should the components be?

Checkerboard response

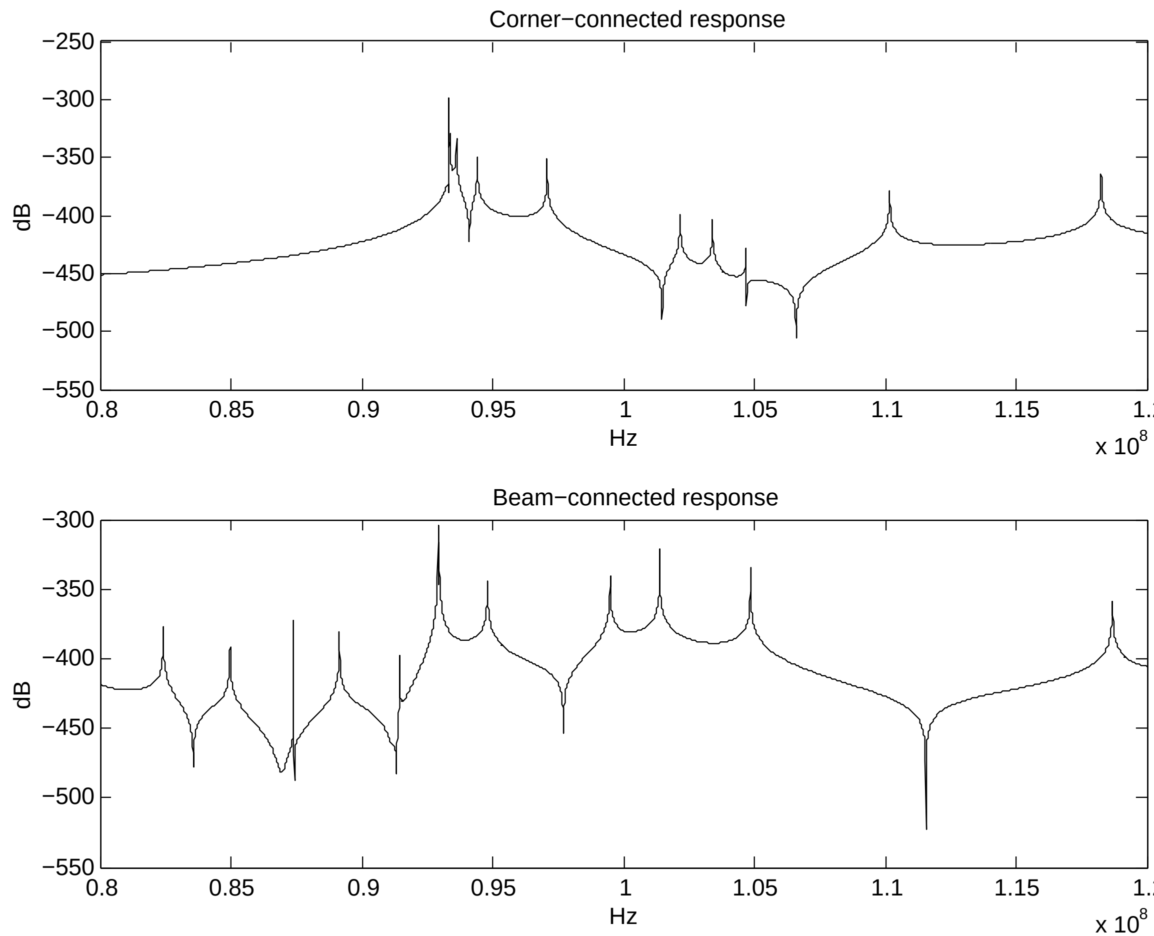


95 MHz



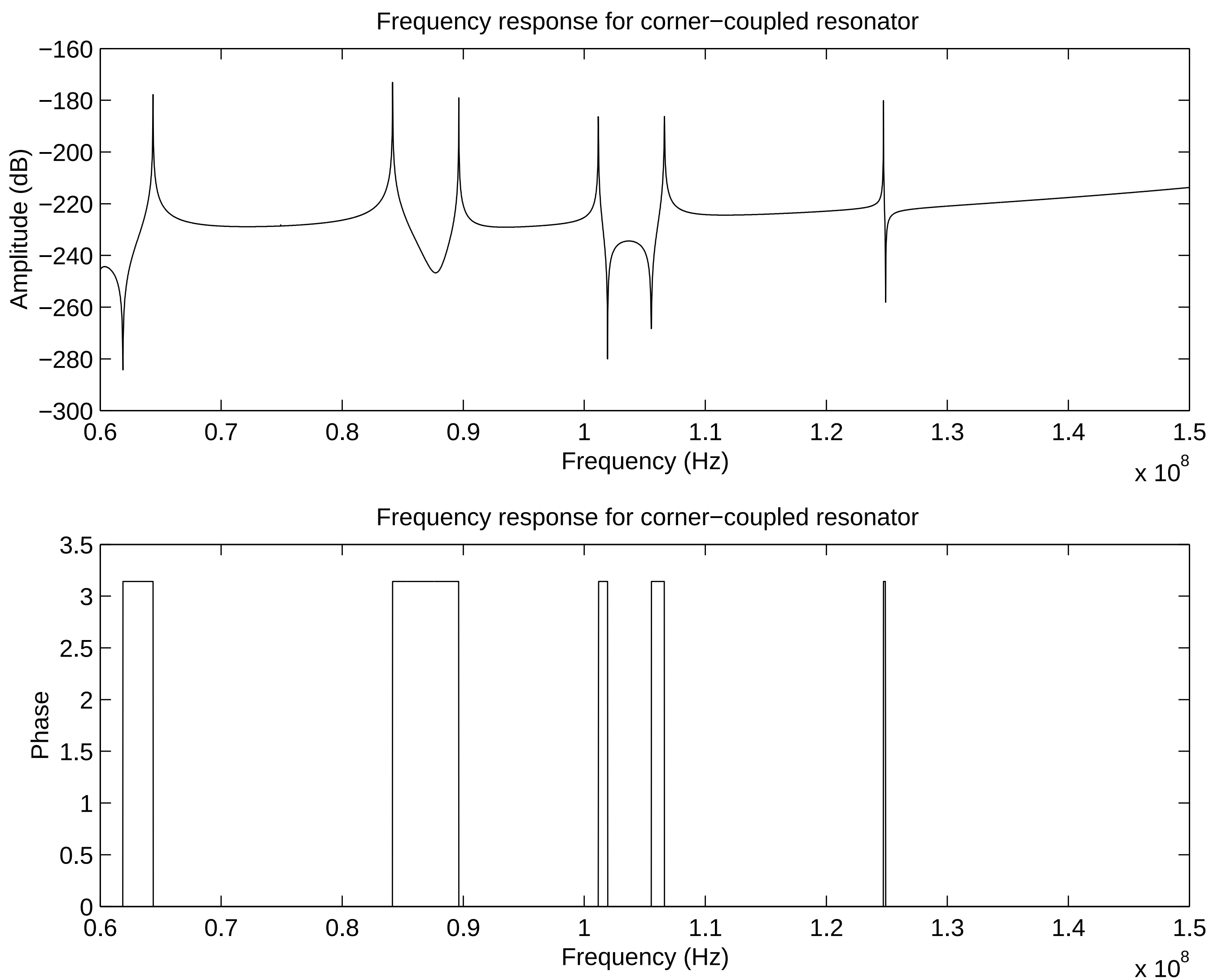
100 MHz

Checkerboard response

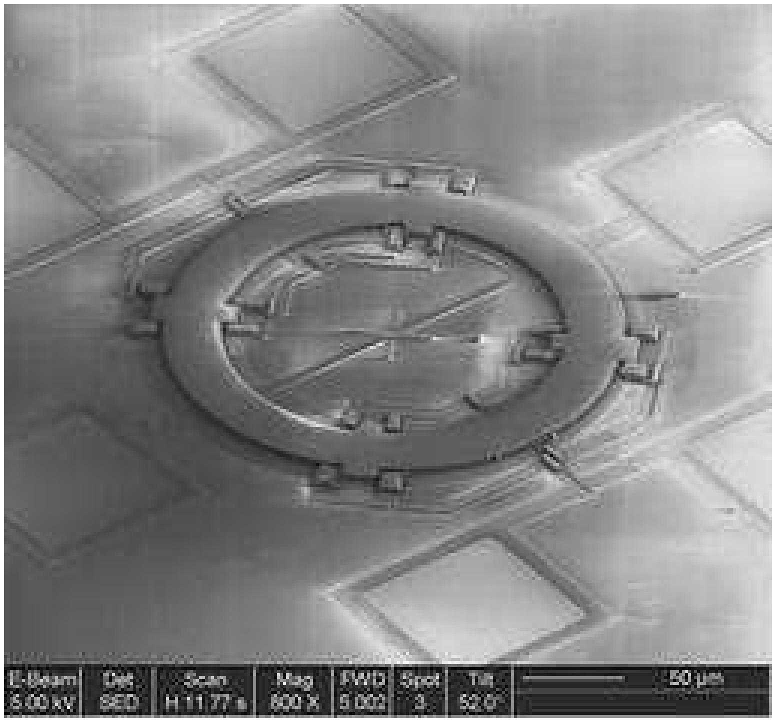


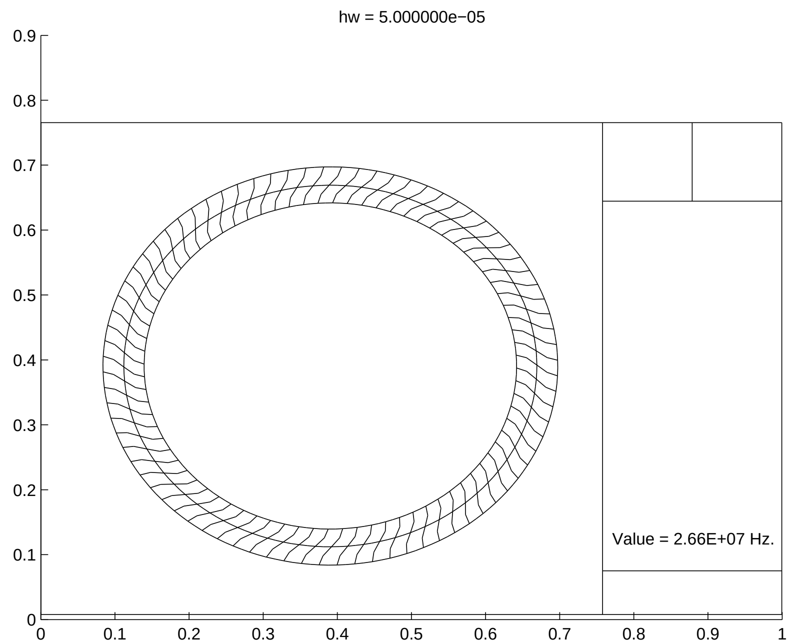
Corner-connected details   Beam-connected details

Checkerboard response: 4-by-4



Shear ring resonator





- Ring is driven in a shearing motion
- Can couple ring to other resonators

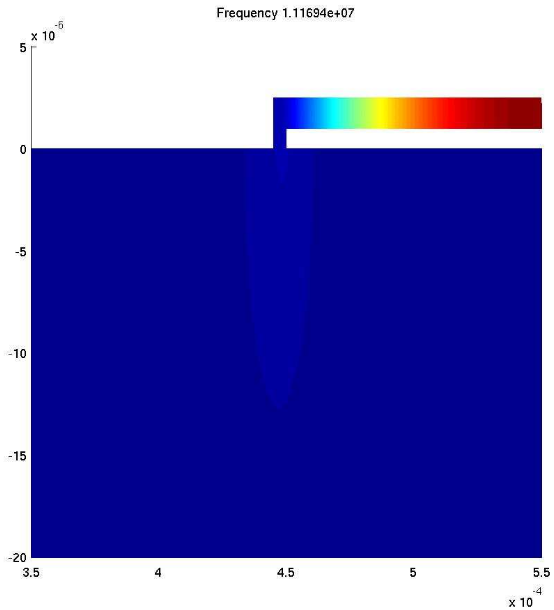
Current questions

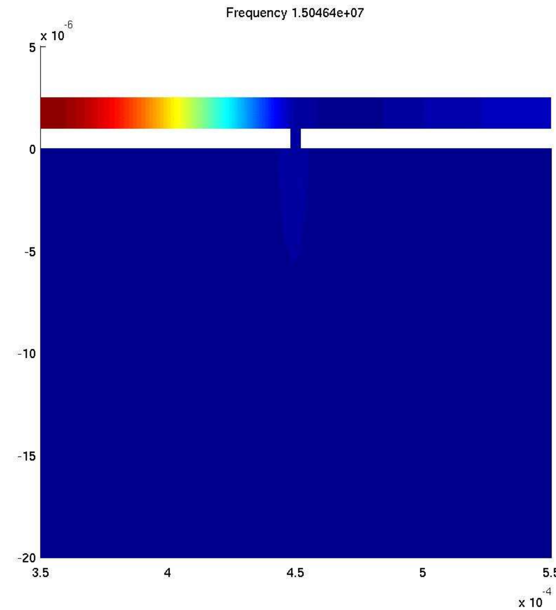
- How do we model damping?
- How do we compute frequency response quickly?
- How do we track dependence on geometry?
- How do we optimize designs?

Energy loss and Q

- Goal: strong output signal and high Q
- Challenge: Model details of energy loss
  - Anchor loss
  - Thermoelastic damping
  - Akheiser damping
  - Air damping
- How are losses affected by fabrication errors (e.g. anchor misalignment)?

Anchor loss

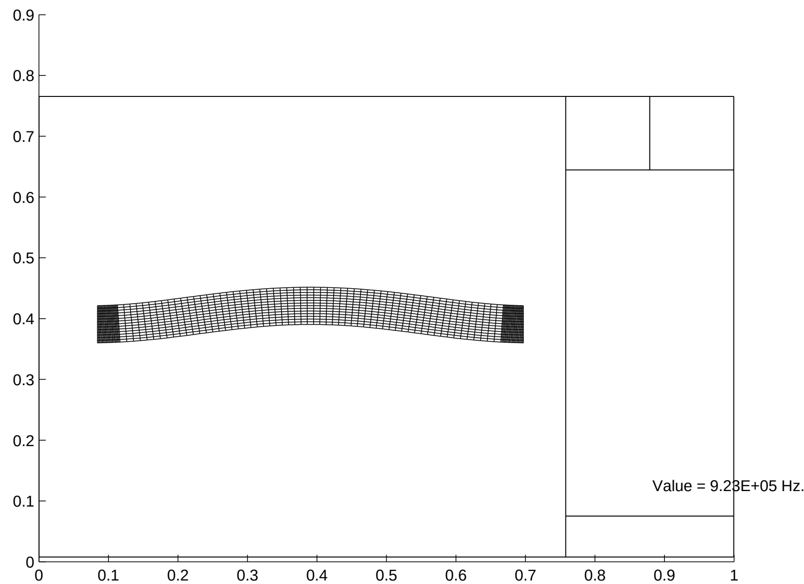


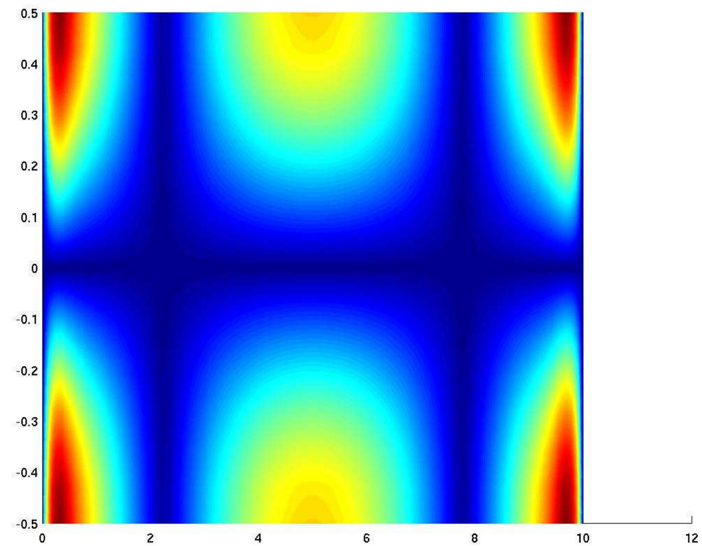


$f_{\text{damp}} \approx 11.5\text{MHz}$ and $Q \approx 50$ $f_{\text{damp}} \approx 15\text{MHz}$ and $Q \approx 160$

- Impose artificial boundary conditions (ABCs)
- Mimic a semi-infinite domain (non-reflecting BC)
- Two main classes: easy + inaccurate, hard + accurate

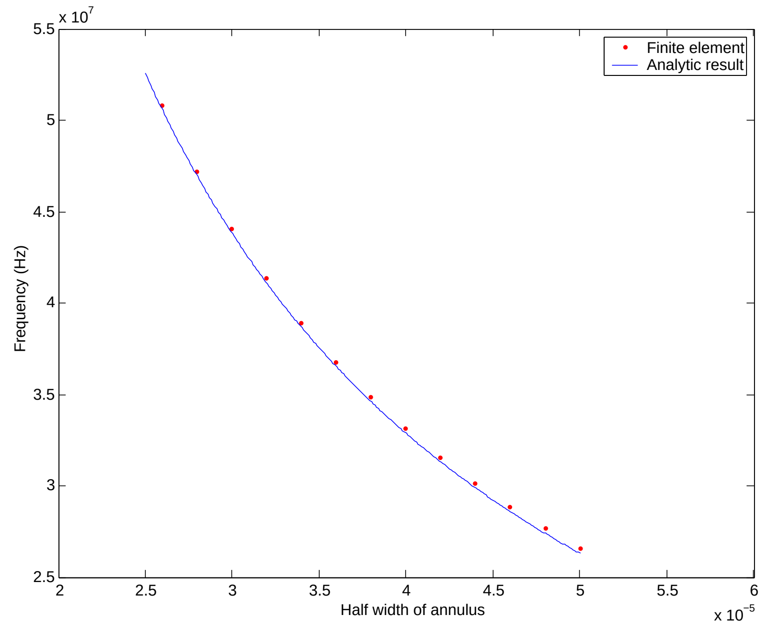
Thermoelastic losses





- Heating coupled to volumetric strain rate
- Diffusion of heat $\Longrightarrow$ irreversible loss
- Zener approximated the effect for beams
- Finite element discretization works more generally
- Accelerate solution with a perturbation method

Mode tracking

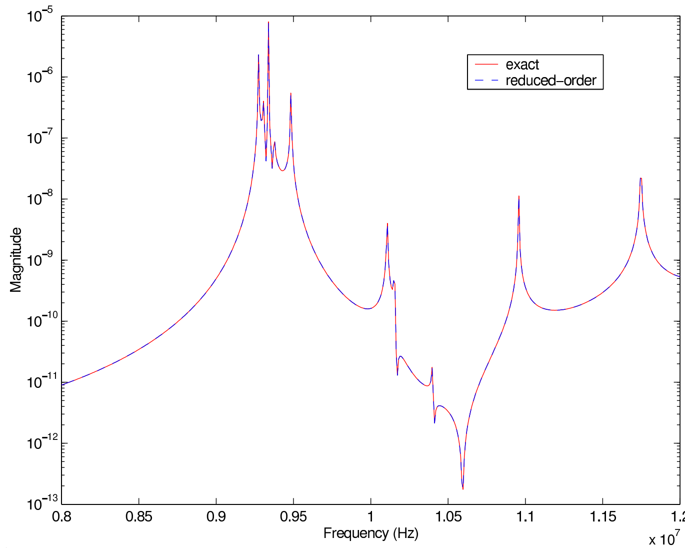


- Differentiate eigenvalue equation $K(s)q(s) = \lambda(s)M(s)q(s)$
- Predictor-corrector iteration
- Convergence criteria, step control based on $|q(s_k)^T q(s_{k+1})|$

Reduction of governing equations

- Typically reduce the problem size while computing.
- Seek the best approximate solution from a family of shapes
- Basis of
  - Finite element methods (infinite-dim $\longrightarrow$ finite)
  - Iterative methods for eigenvalue problems
  - Iterative solvers for linear systems
  - Lumped circuit models (modal mass and stiffness)
- Trick is to choose a good family of approximants

Model reduction



Sun Ultra 10

	Sec	n
ROM:	28	4834
Full:	1474	50

- Approximate with a set of global shape functions
  - Chosen from a Krylov subspace
  - Chosen from analysis of substructures
- Preserve second order system structure

Transfer function optimization

- Choose geometry to make a good bandpass filter
- What is a "good bandpass filter?"
  - $|H(\omega)|$ is big on $[\omega_l, \omega_r]$
  - $|H(\omega)|$ is tiny outside this interval
- How do we optimize?
  - Overton's gradient sampling method
  - Use Byers-Boyd-Balikrishnan algorithm for distance to instability to minimize $|H(\omega)|$ on $[\omega_l, \omega_r]$
  - Small Hamiltonian eigenproblem (with ROM)

Software framework

- Simulations done with FEAPMEX
  - Matlab interface to the FEAP finite element code
  - Provides both FEAP and Matlab capabilities
  - Interface code is publically available

Conclusions

- RF MEMS are an interesting source of computational problems
  - Understanding the physics
  - Applying numerical tools

`http://bsac.berkeley.edu/cadtools/sugar/sugar/`

`http://www.cs.berkeley.edu/~dbindel/feapmex.html`