Tools for MEMS Simulation

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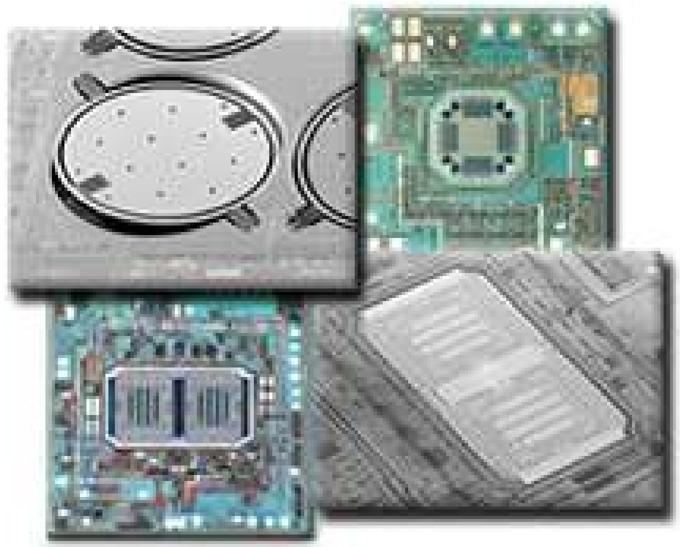
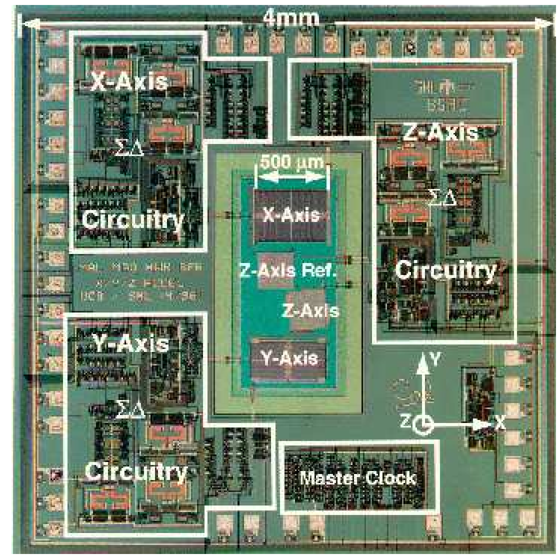
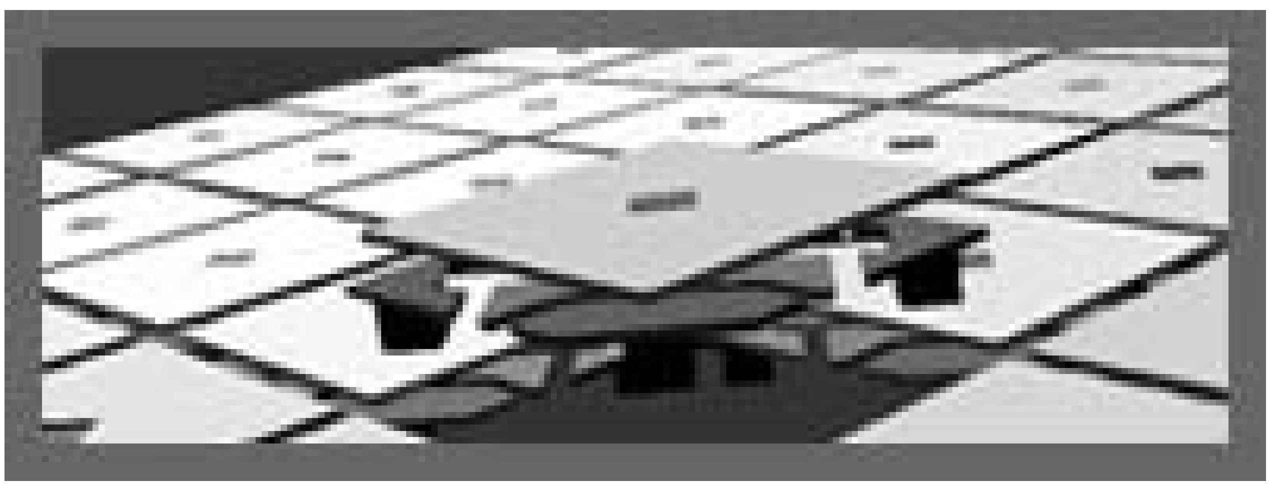
Outline

- Basic MEMS applications and ideas
- The many roles of computation
- Detailed examples: RF elements
  - Checkerboard filter
  - Disk resonator
- Conclusions

What are MEMS?







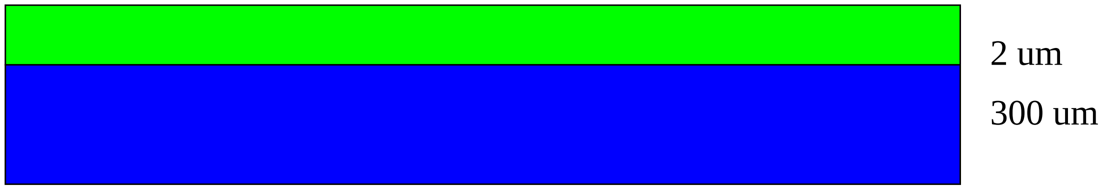
MEMS Basics

- Micro-electro-mechanical systems
  - Chemical, fluid, thermal, optical (MECFTOMS?)
- Applications:
  - Sensors (inertial, chemical, pressure)
  - Ink jet printers, biolab chips
  - RF devices: cell phones, inventory tags, pico radio
  - “Smart dust”
- Use integrated circuit (IC) fabrication technology
- Large surface area / volume ratio
- Still mostly classical (vs. nanosystems)

Fabrication outline

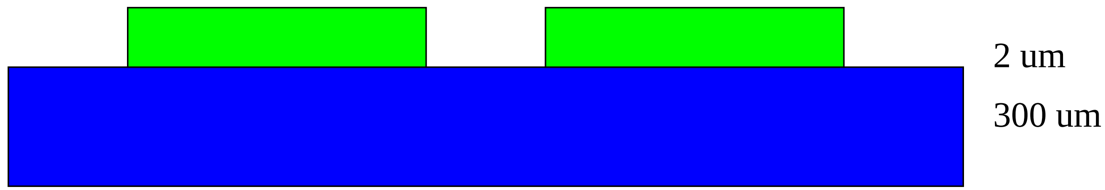
1. Si wafer

Fabrication outline



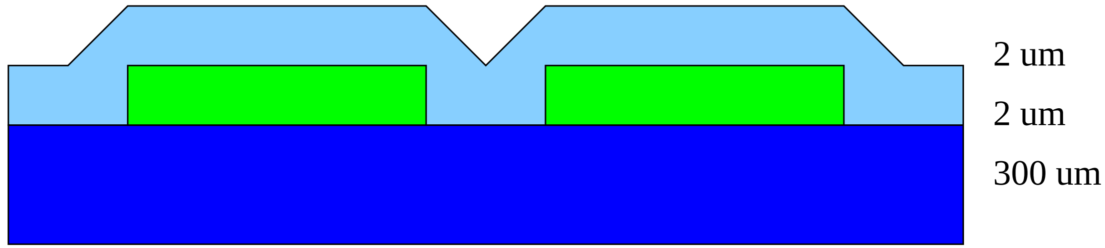
1. Si wafer
2. Deposit 2 microns SiO_2

Fabrication outline



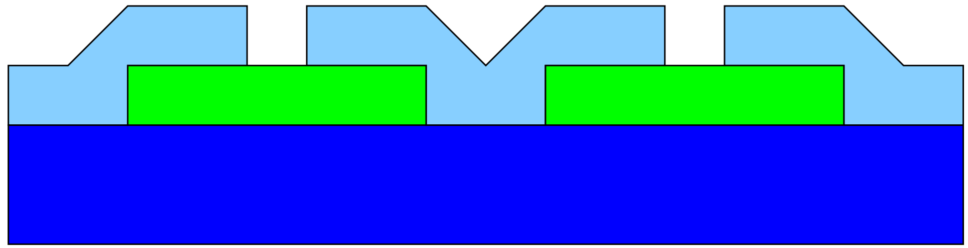
1. Si wafer
2. Deposit 2 microns SiO2
3. Pattern and etch SiO2 layer

Fabrication outline



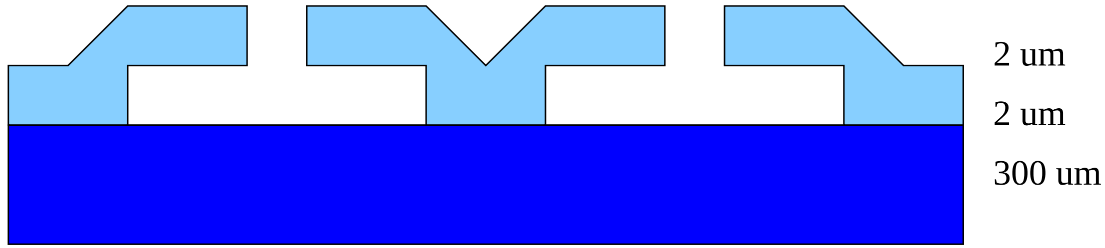
1. Si wafer
2. Deposit 2 microns SiO2
3. Pattern and etch SiO2 layer
4. Deposit 2 microns polycrystalline Si

Fabrication outline



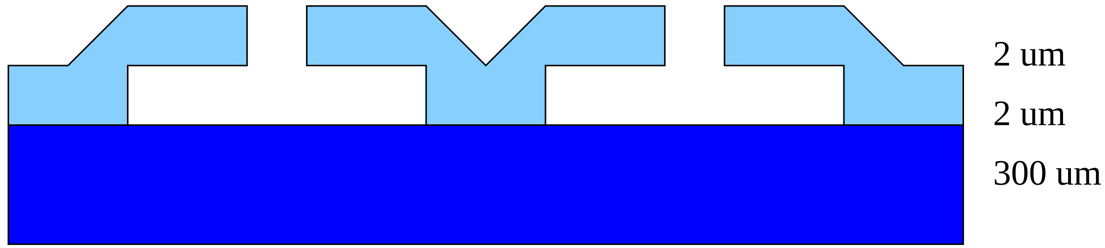
1. Si wafer
2. Deposit 2 microns SiO2
3. Pattern and etch SiO2 layer
4. Deposit 2 microns polycrystalline Si
5. Pattern and etch Si layer

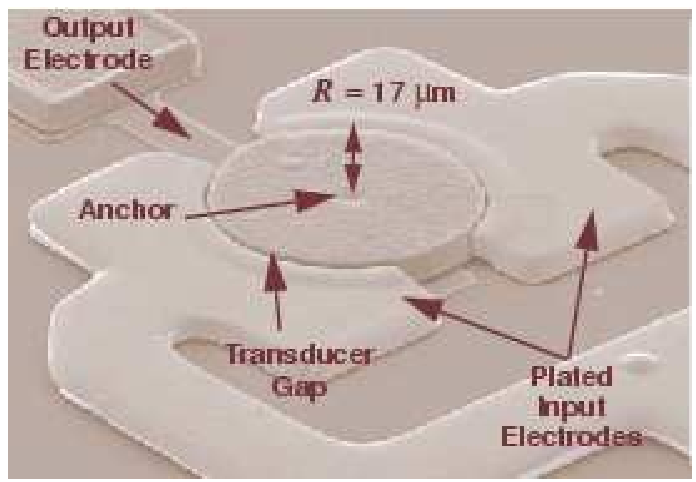
Fabrication outline



1. Si wafer
2. Deposit 2 microns SiO2
3. Pattern and etch SiO2 layer
4. Deposit 2 microns polycrystalline Si
5. Pattern and etch Si layer
6. Release etch remaining SiO2

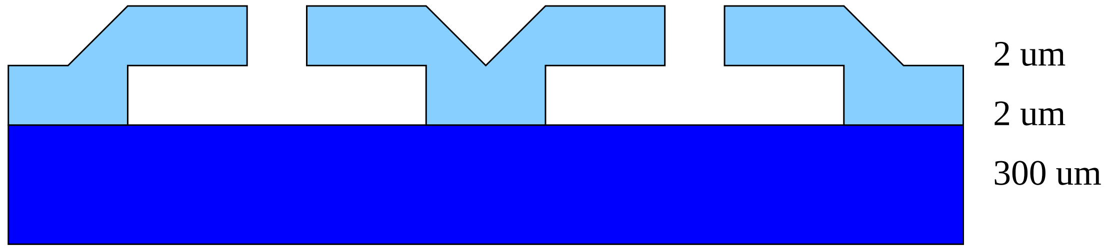
Fabrication result





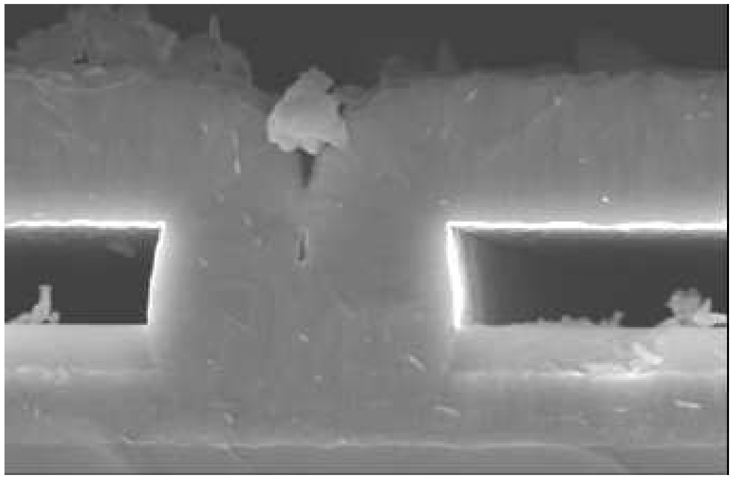
(C. Nguyen, iMEMS 01)

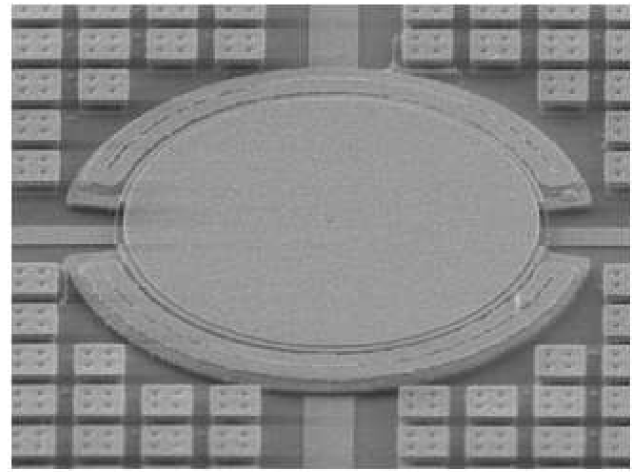
Fabrication characteristics



- Characteristic dimensions: microns
- Geometry is “2.5” dimensional
- Relatively loose fabrication tolerances
- Difficult to characterize

Why simulate?





- "Build and break" is too expensive
  - Wafer processing costs months, thousands of dollars
  - Fabrication is imprecise
  - Days or weeks to take good measurements
- Good experiments need good hypotheses
- Even when device behavior is understood, still need to understand system behavior

From simulation to synthesis

Computer can assist at many levels:

- Fundamental physics
- Detailed device models
- System-level models and macromodels
- Metrology
- Design optimization
- Design synthesis

Research thrusts

- Model development (e.g. new finite elements)
- Numerical algorithms (e.g. model reduction)
- Numerical software engineering (SUGAR, HiQLab)
- Metrology and comparison to measurement
- Optimization and design synthesis

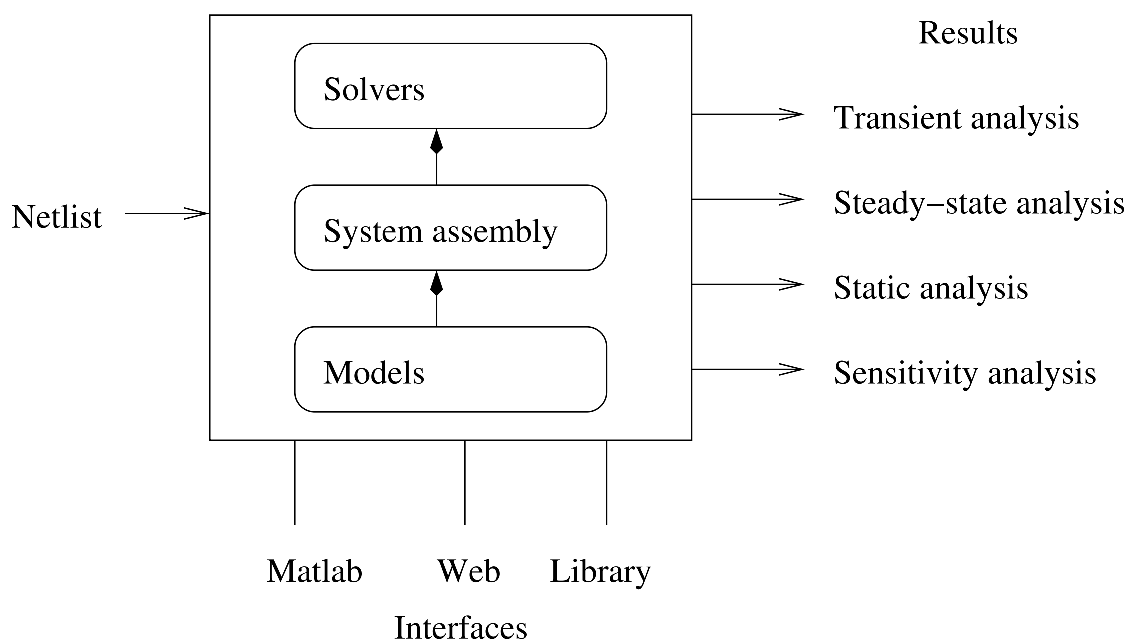
Research group

Faculty		Students	
A. Agogino	(ME)	D. Bindel	(CS)
Z. Bai	(Math,CS,UCD)	J.V. Clark	(AS&T)
J. Demmel	(Math,CS)	C. Cobb	(ME)
S. Govindjee	(CEE)	D. Garmire	(CS)
R. Howe	(EE,ME)	T. Koyama	(CEE)
K.S.J. Pister	(EE)	J. Nie	(Math)
C. Sequin	(CS)	H. Wei	(CEE)
		Y. Zhang	(CEE)

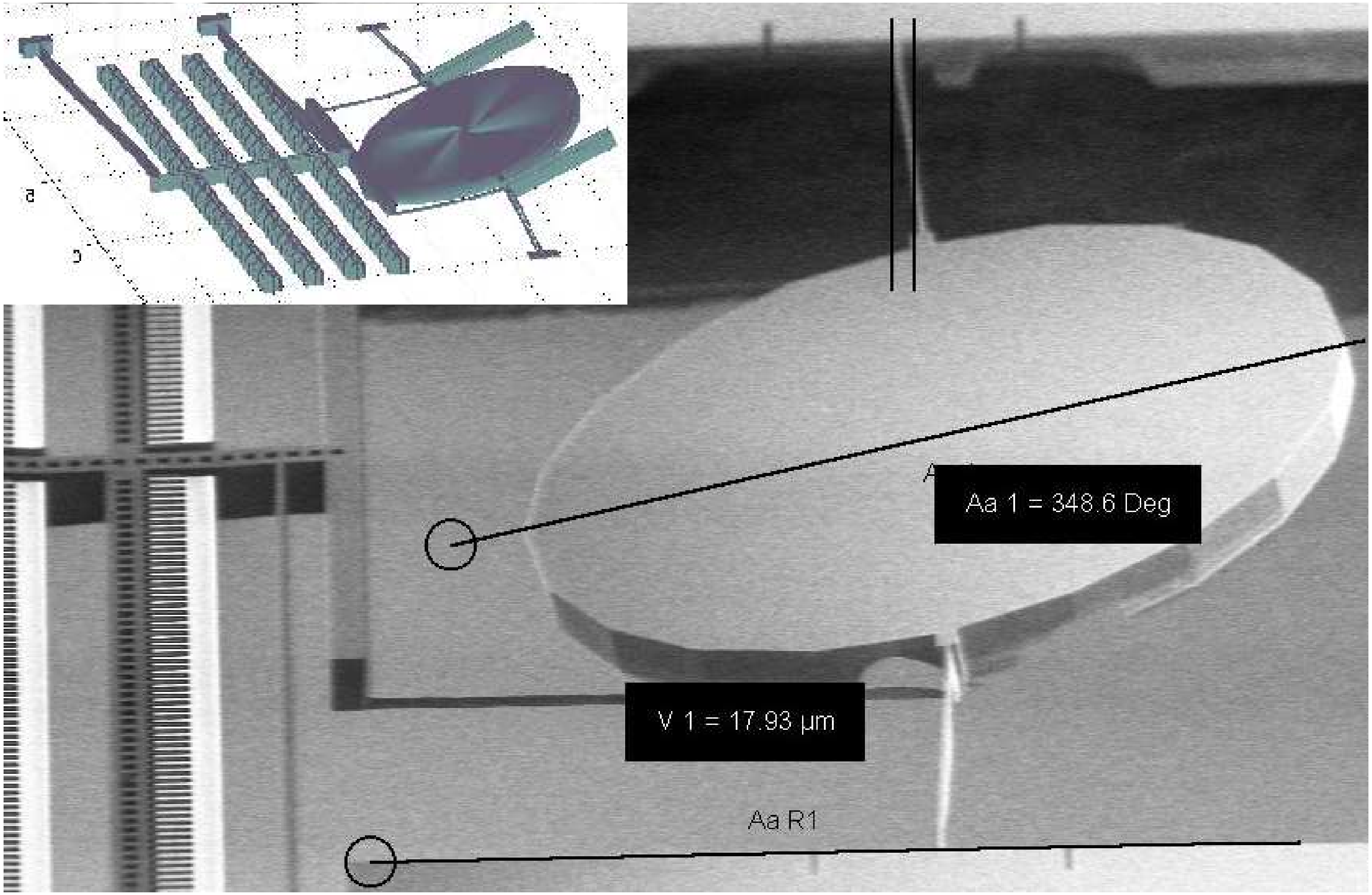
SUGAR

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

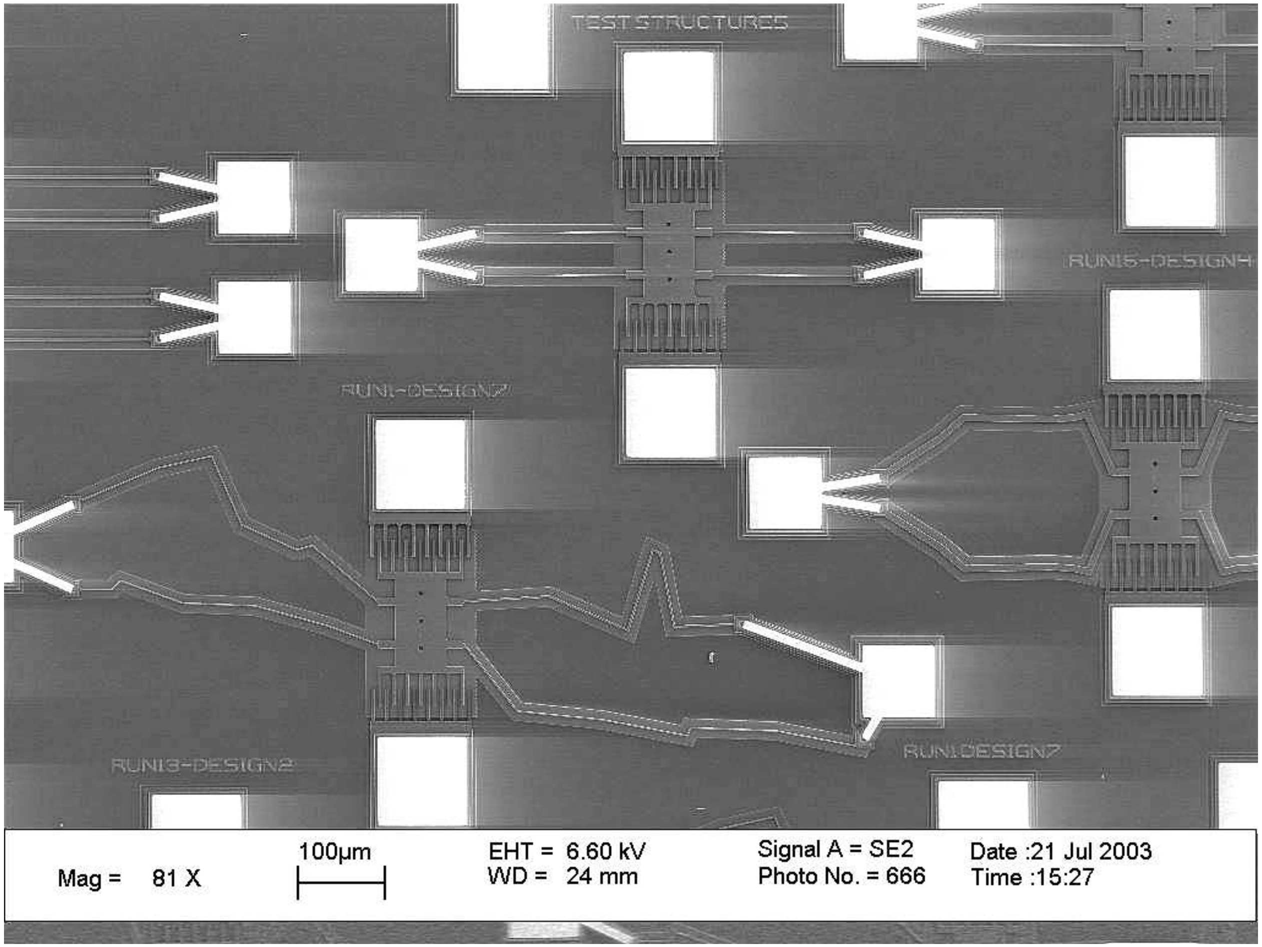


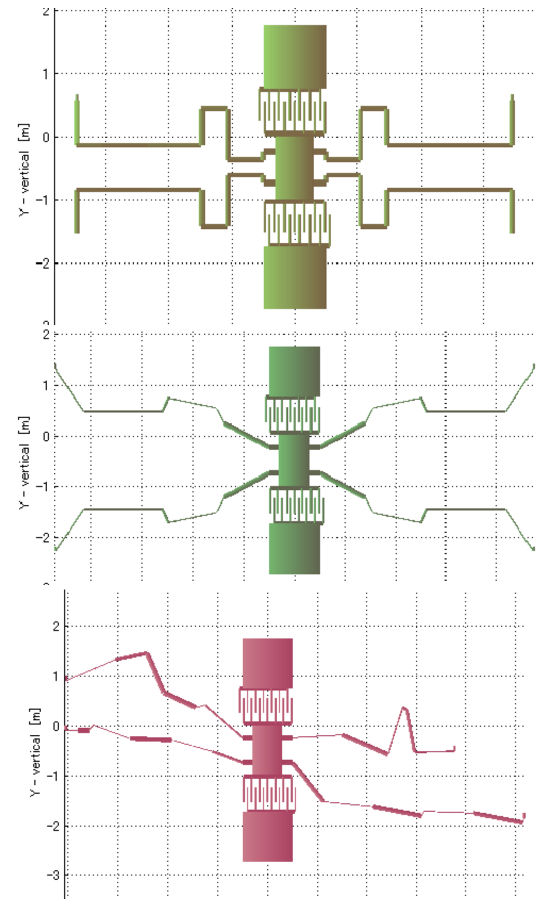
SUGAR: Analysis of a micromirror



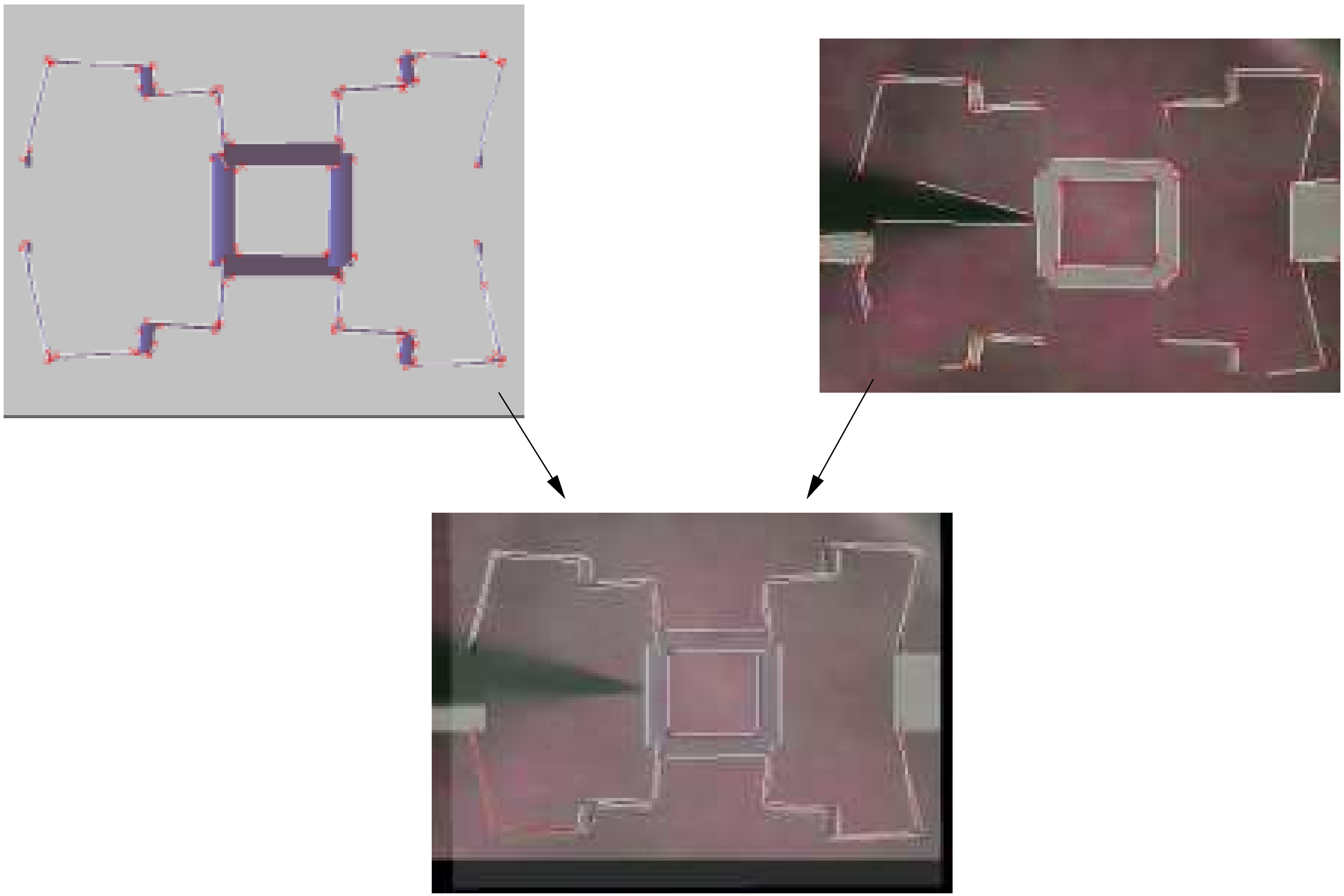
(Mirror design by M. Last)

SUGAR: Design synthesis

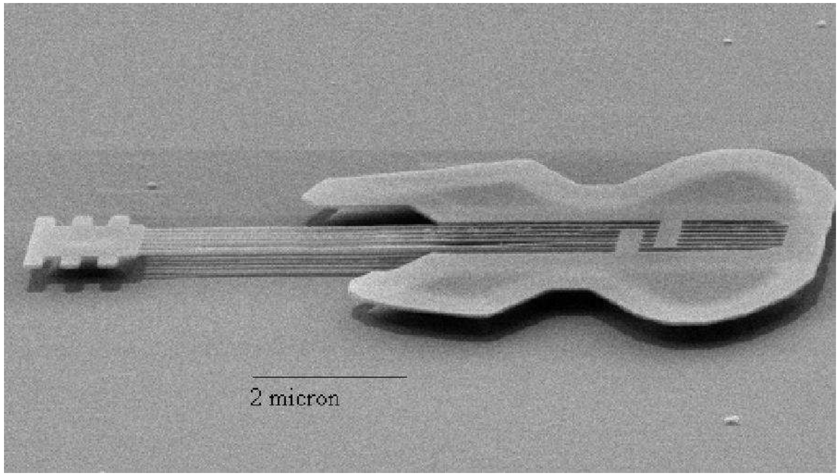


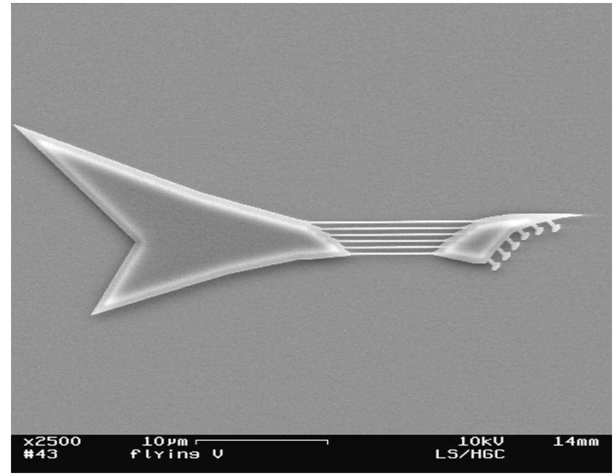


SUGAR: Comparison to measurement



RF resonators

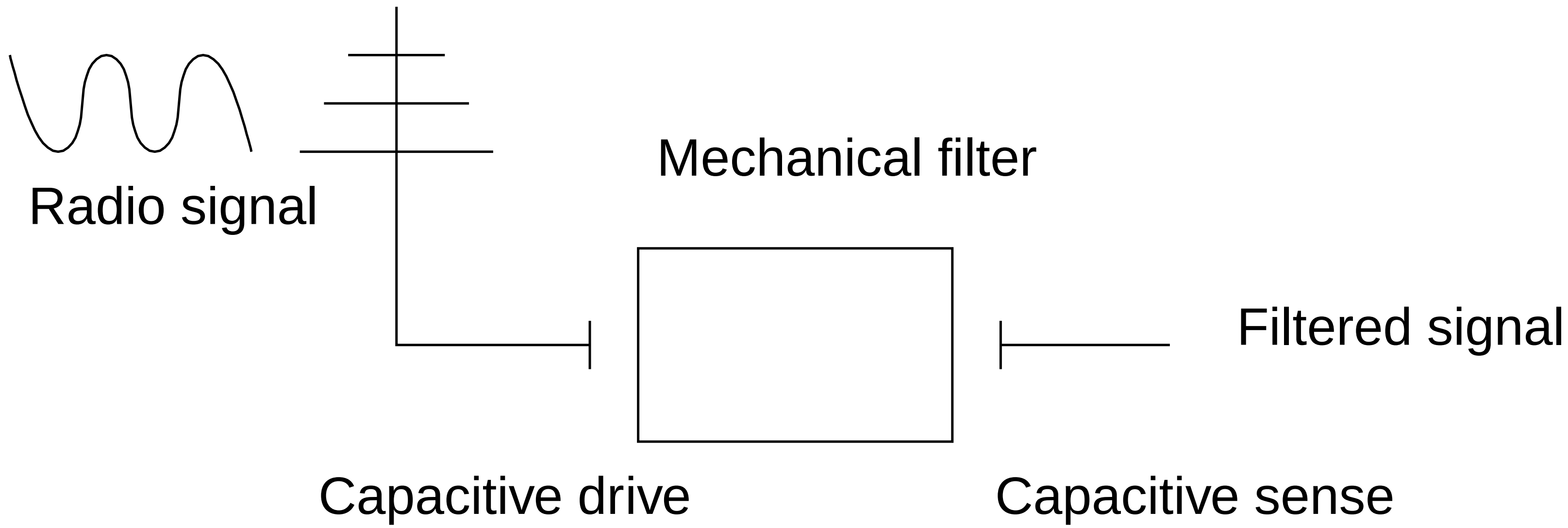




Microguitars from Cornell University (1997 and 2003)

- 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

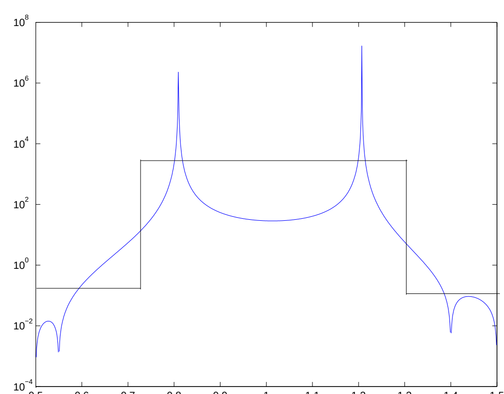
Governing equations

Time domain:

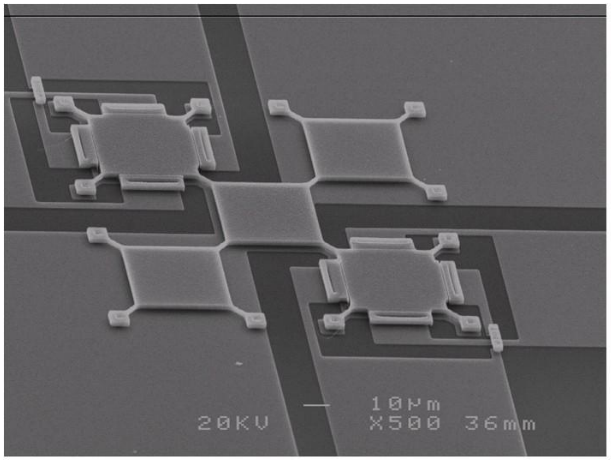
$$
\begin{aligned}
Mu'' + Cu' + Ku &= P\phi \\
y &= V^T u
\end{aligned}
$$

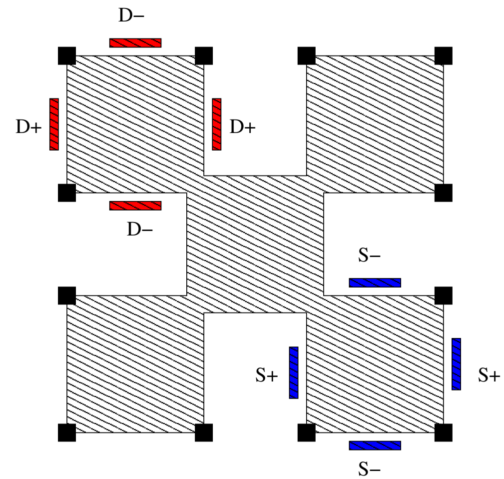
Frequency domain:

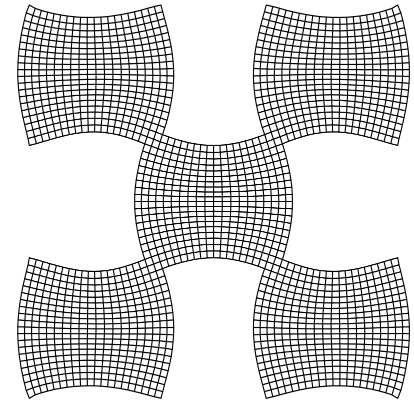
$$
\begin{aligned}
H(\omega) &= V^T(-\omega^2 M + i\omega C + K)^{-1} P \\
\hat{y} &= H\hat{\phi}
\end{aligned}
$$



First proposed design: Checkerboard

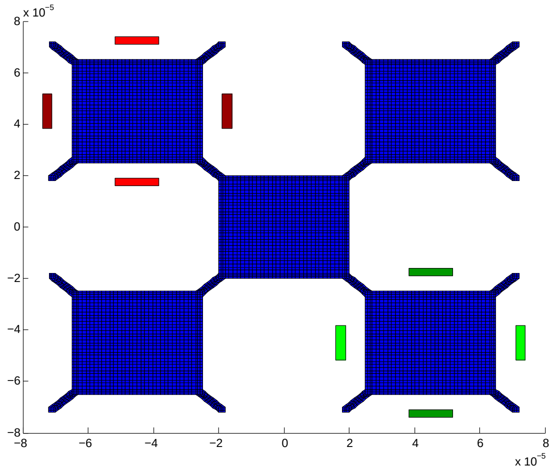


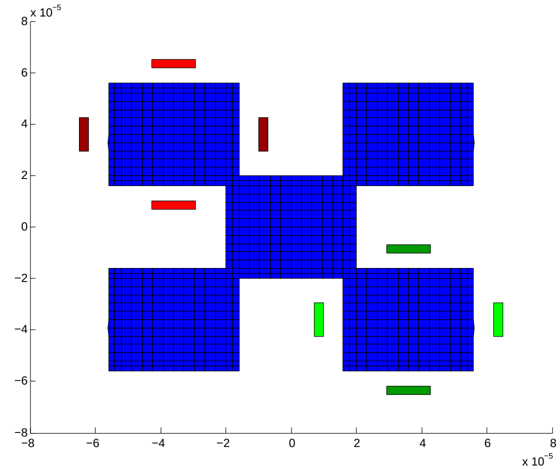




- Array of loosely coupled resonators
- Anchored at outside corners
- Excited at northwest corner
- Sensed at southeast corner
- Surfaces move only a few nanometers

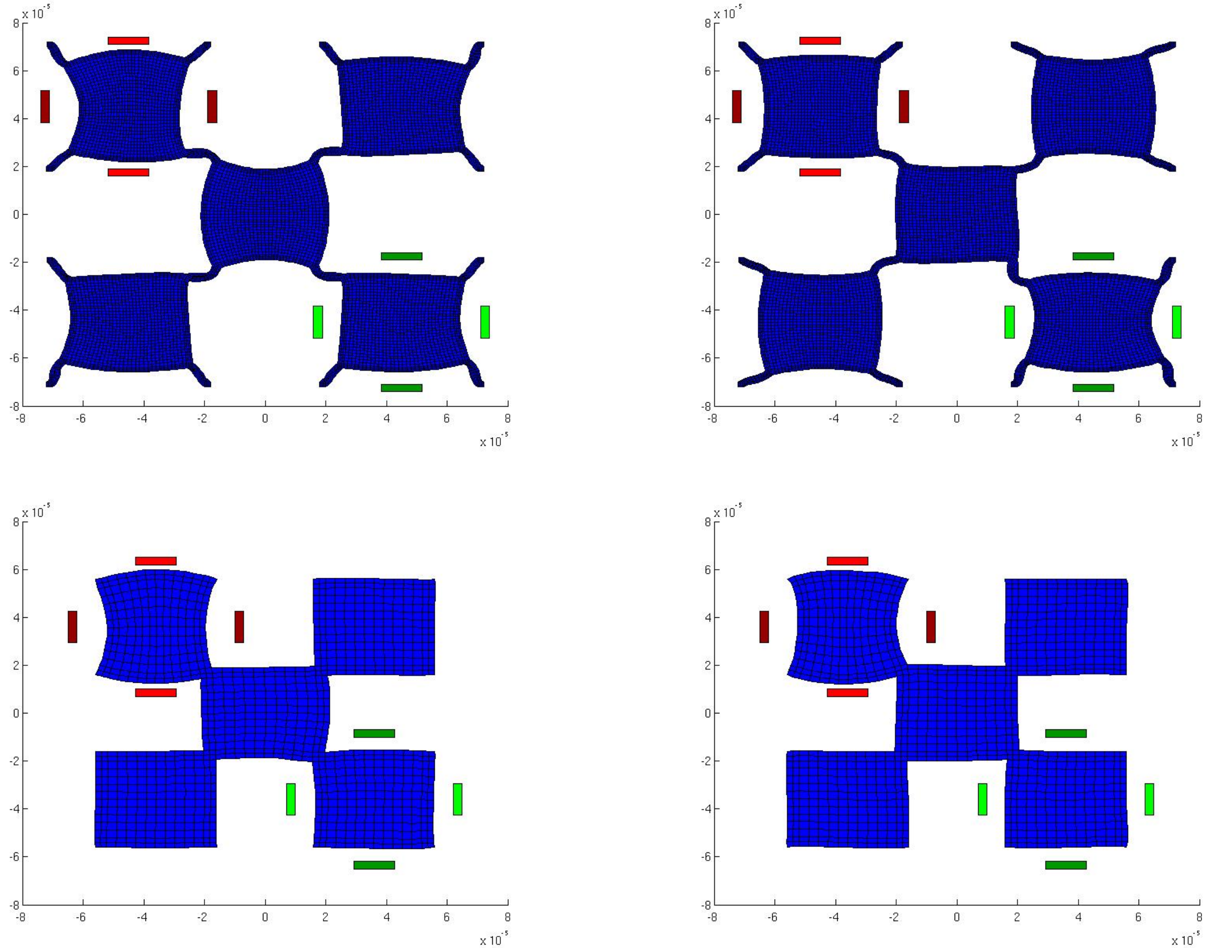
Design questions





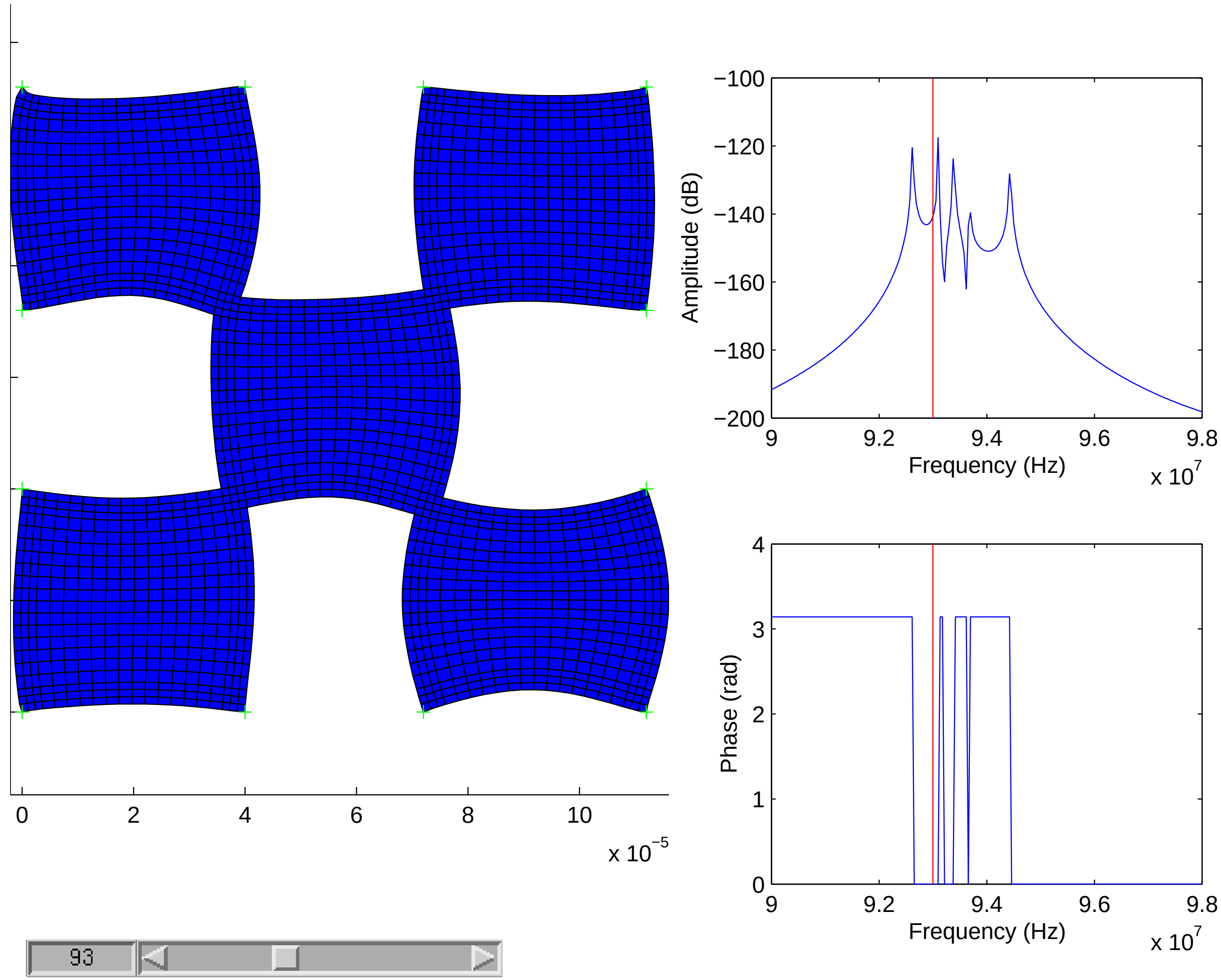
- Where should drive and sense be placed?
- How should the individual resonators be connected?
- How should the system be anchored?
- How many components? What topology?

Checkerboard response

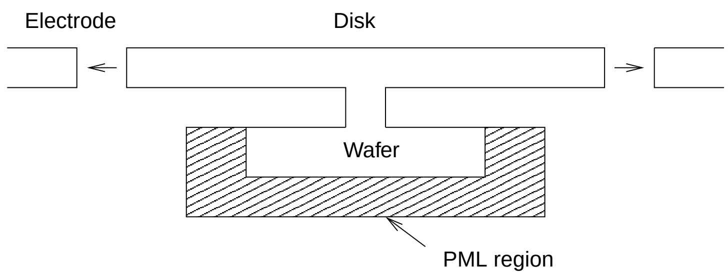


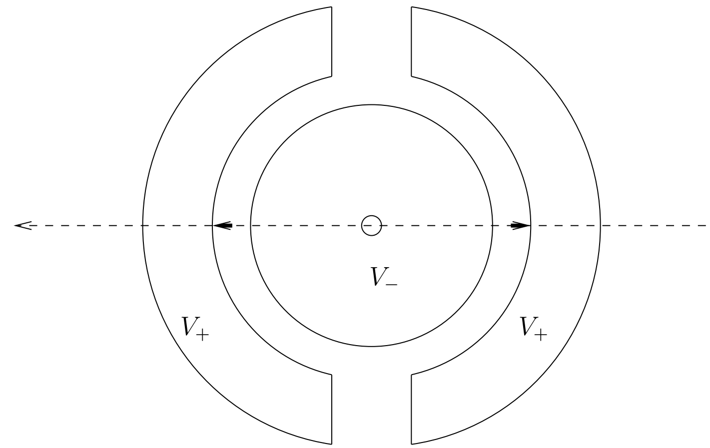
95 MHz 100 MHz

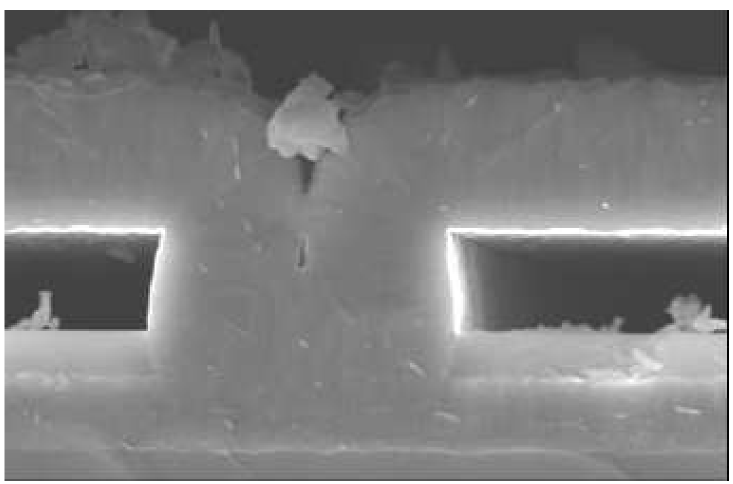
Interactive visualization

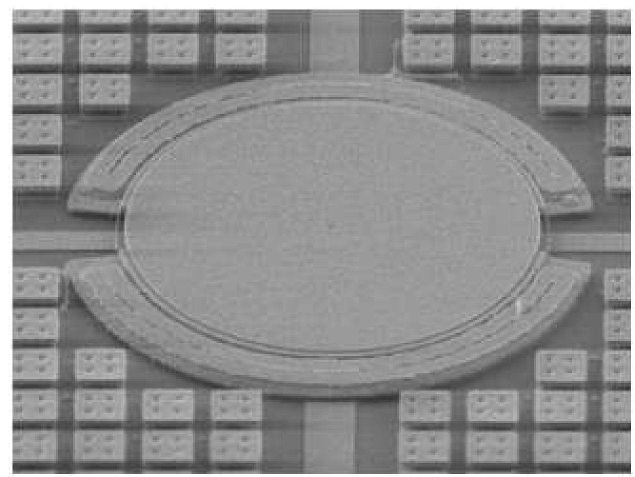


Disk resonator model









SiGe disk resonators built by E. Quévy

Sources of damping

- Fluid damping
  - Air is a viscous fluid ($\mathrm{Re} \ll 1$)
  - Can operate in a vacuum
  - Shown not to dominate in many RF designs
- Anchor loss
  - Elastic waves radiate from structure
- Thermoelastic damping
  - Volume changes induce temperature change
  - Diffusion of heat leads to mechanical loss
- Material losses (catch-all)
  - Low intrinsic losses in silicon, diamond, germanium
  - Terrible material losses in metals

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Substrate model

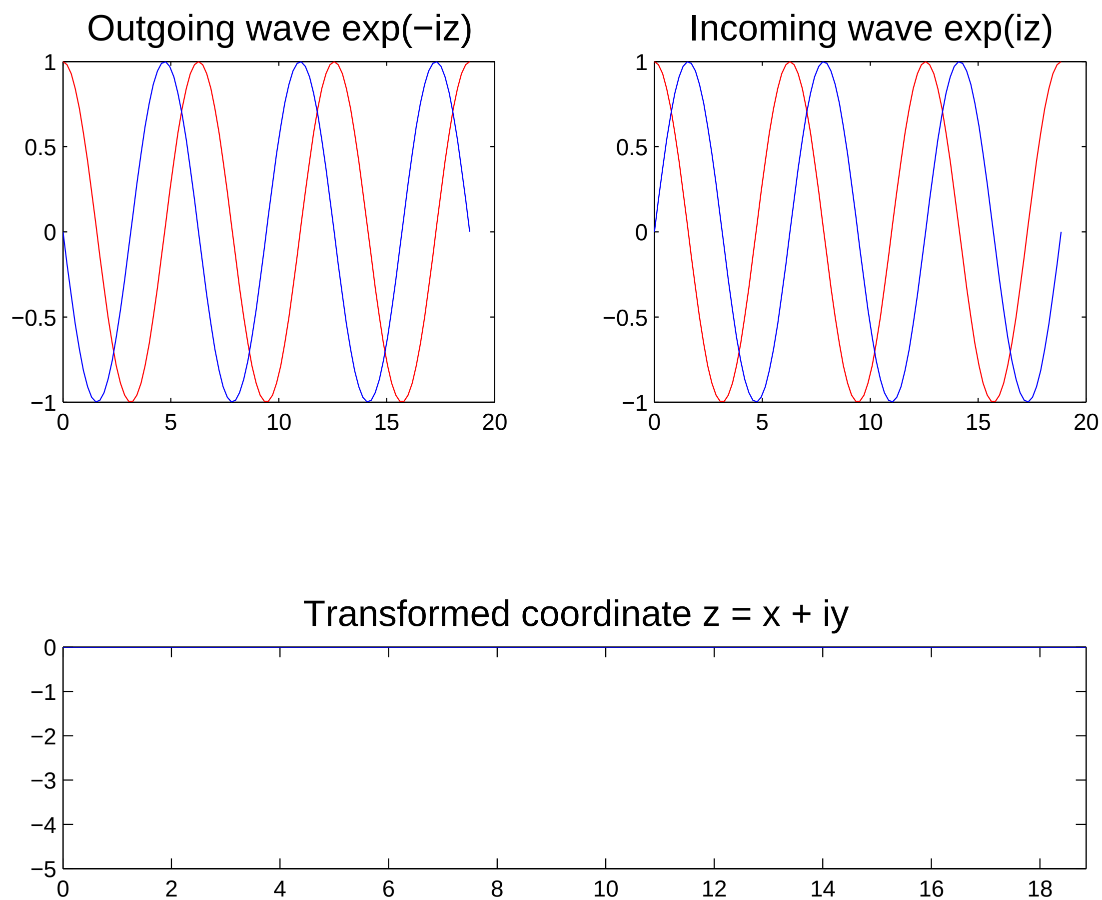
Goal: Understand energy loss in this resonator

- Dominant loss is elastic radiation from anchor.
- Disk resonator is much smaller than substrate
- Very little energy leaving the post is reflected back
  - Substrate is semi-infinite from disk's perspective
- Possible semi-infinite models
  - Matched asymptotic modes
  - Dirichlet-to-Neumann maps
  - Boundary dampers
  - Perfectly matched layers

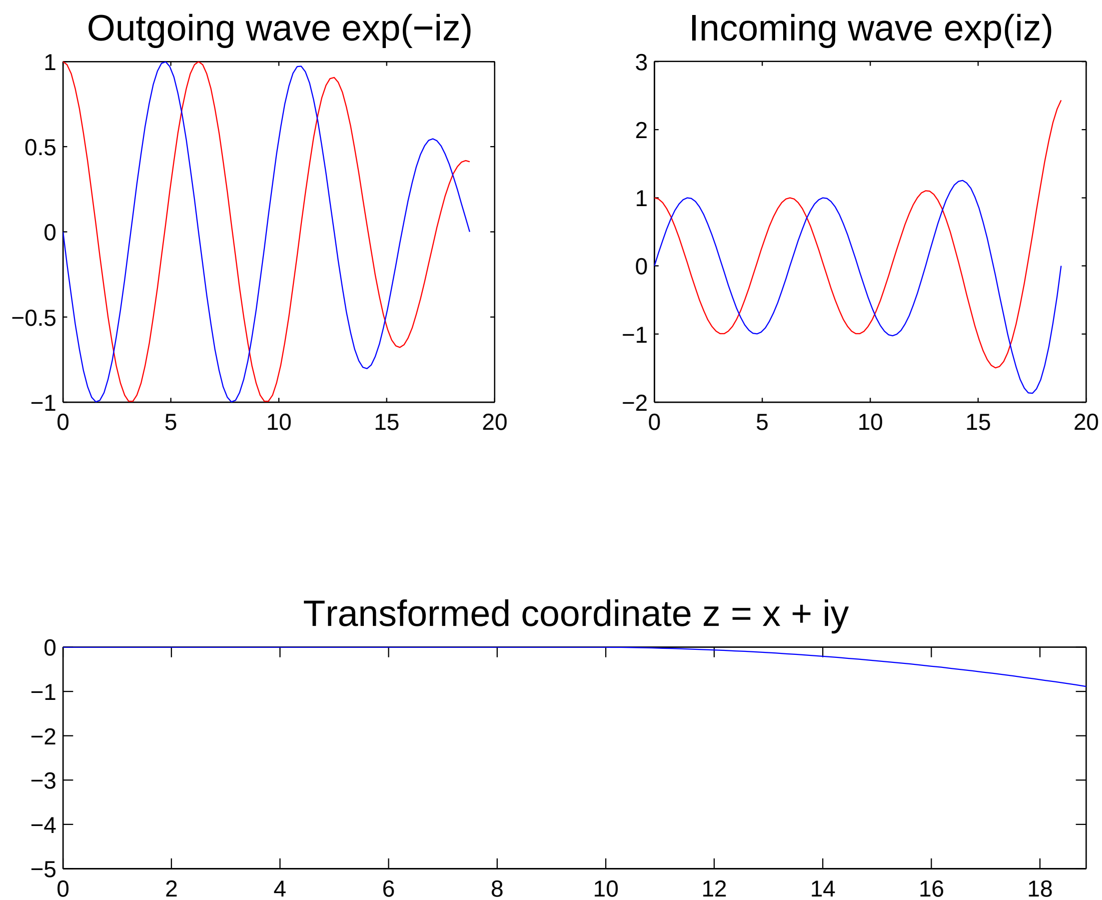
Perfectly matched layers

- Apply a complex coordinate transformation
- Generates a non-physical absorbing layer
- No impedance mismatch between the computational domain and the absorbing layer
- Idea works with general linear wave equations
  - First applied to Maxwell's equations (Berengér 95)
  - Similar idea introduced earlier in quantum mechanics (*exterior complex scaling*, Simon 79)

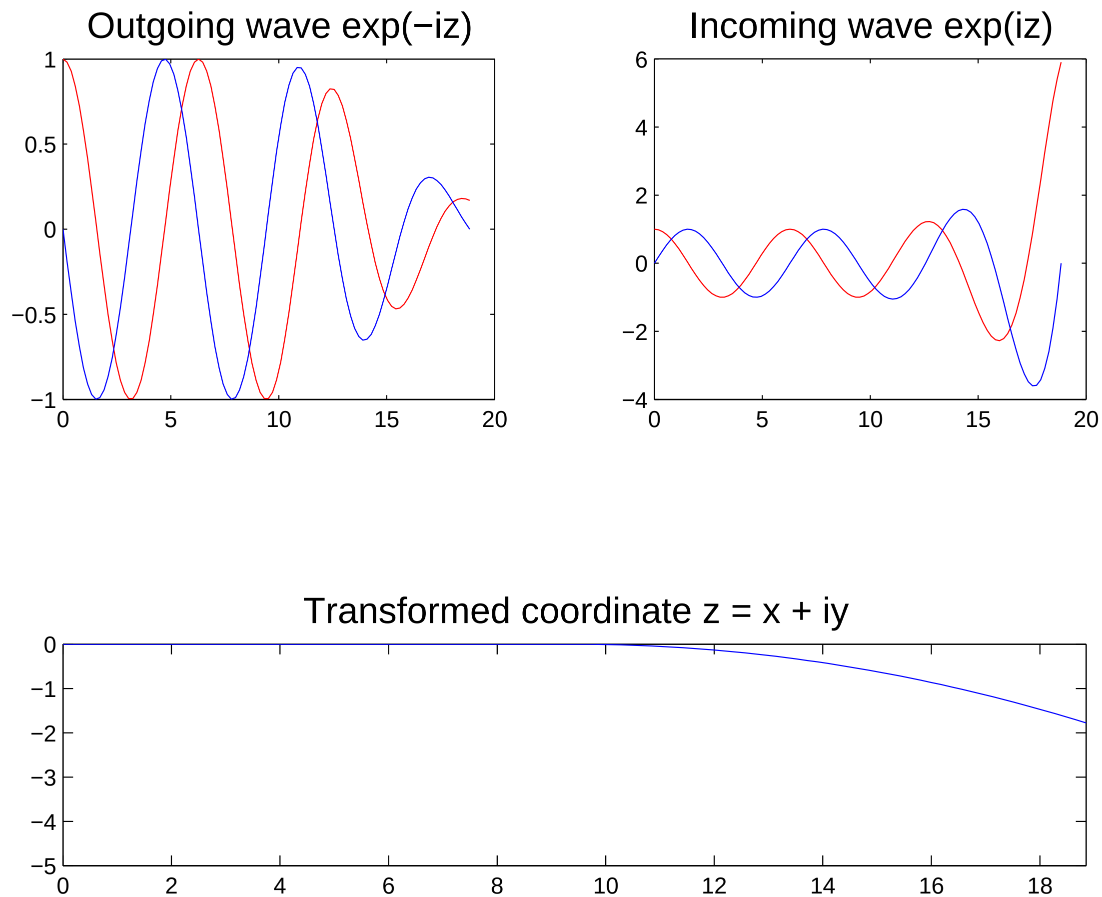
Scalar wave example



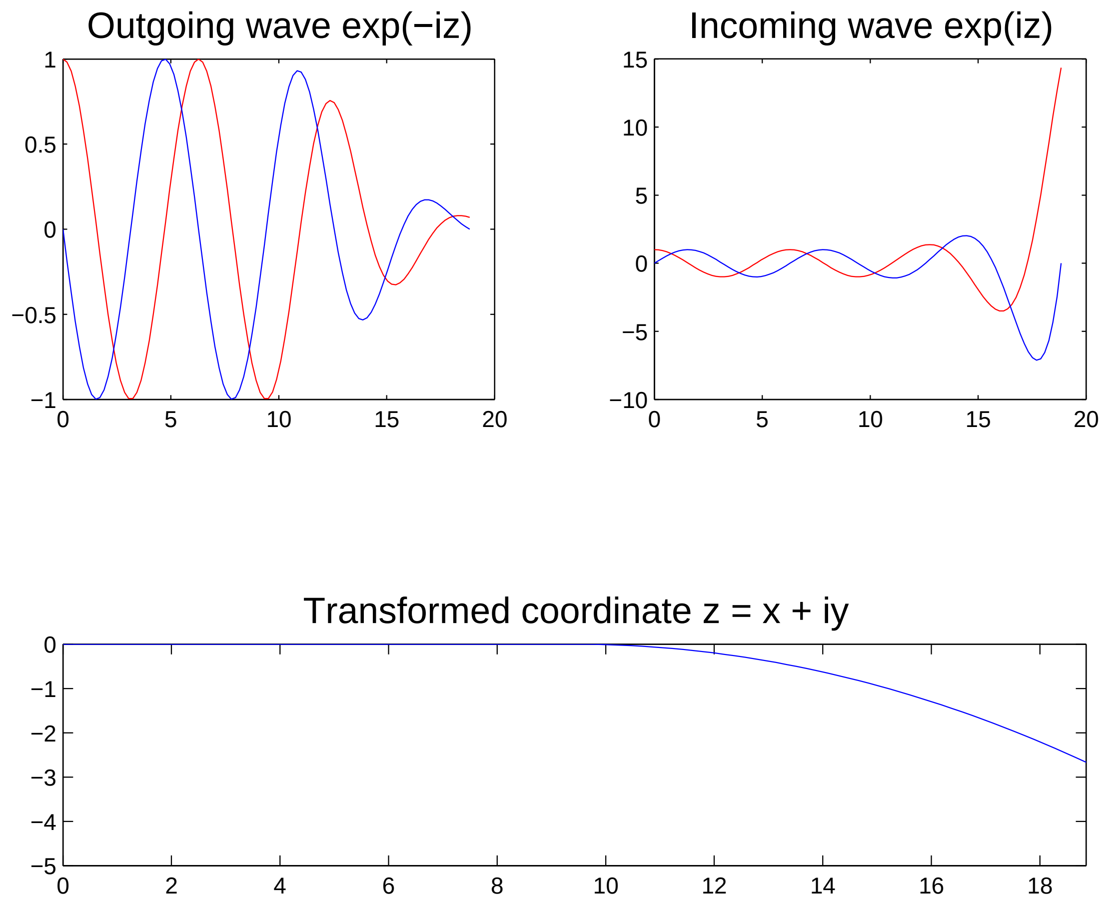
Scalar wave example



Scalar wave example



Scalar wave example



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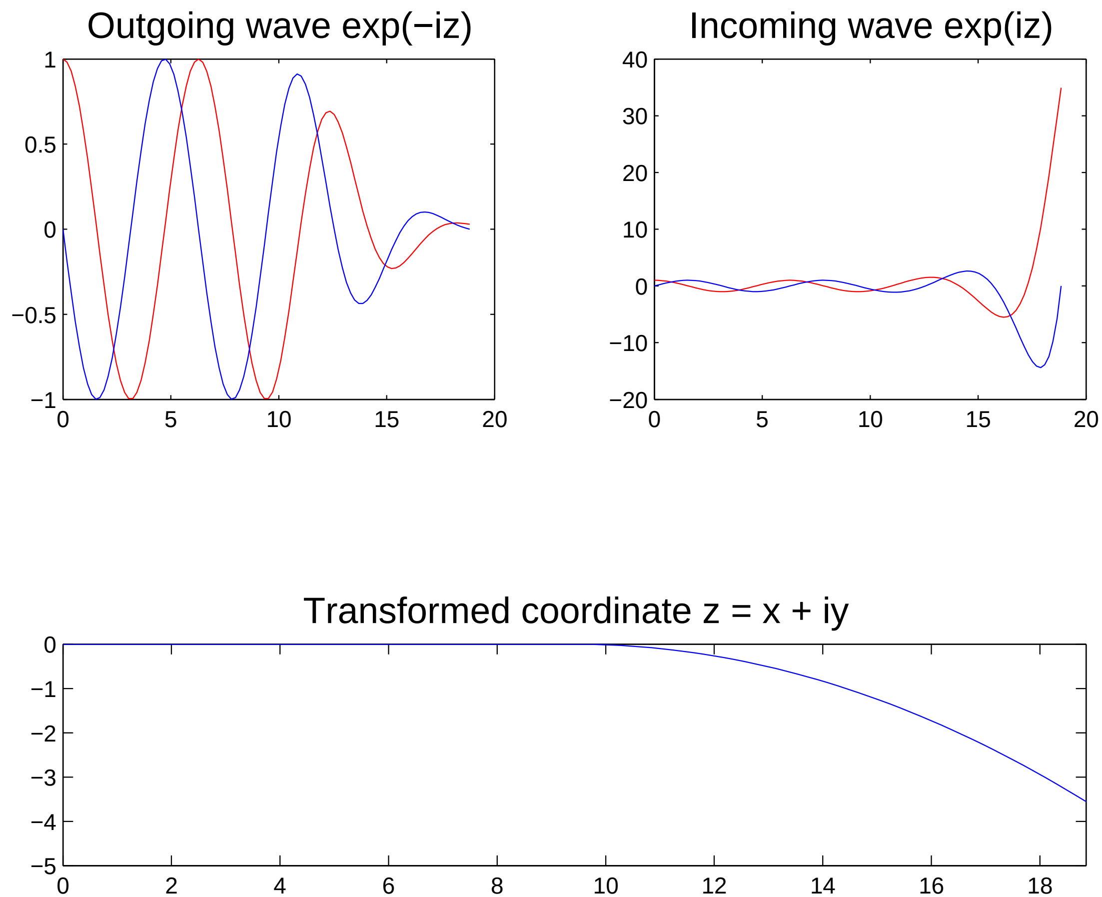

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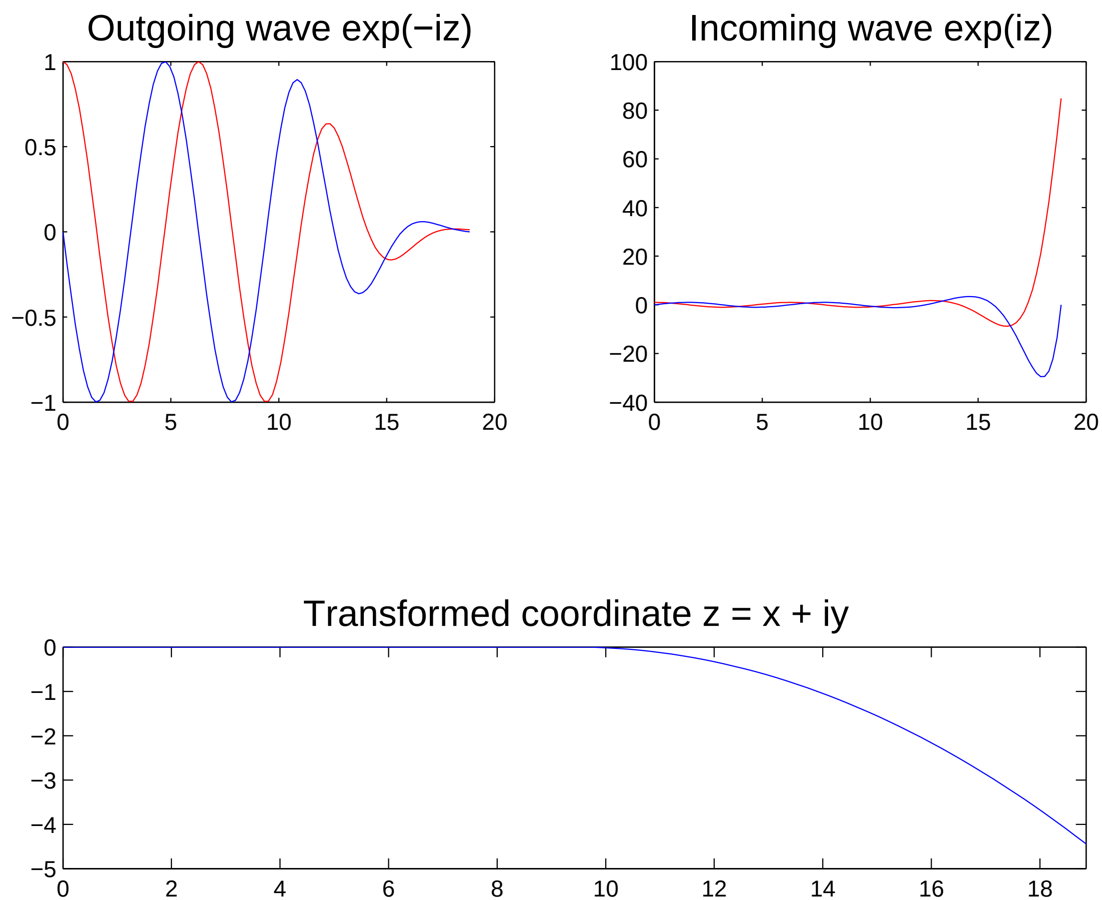
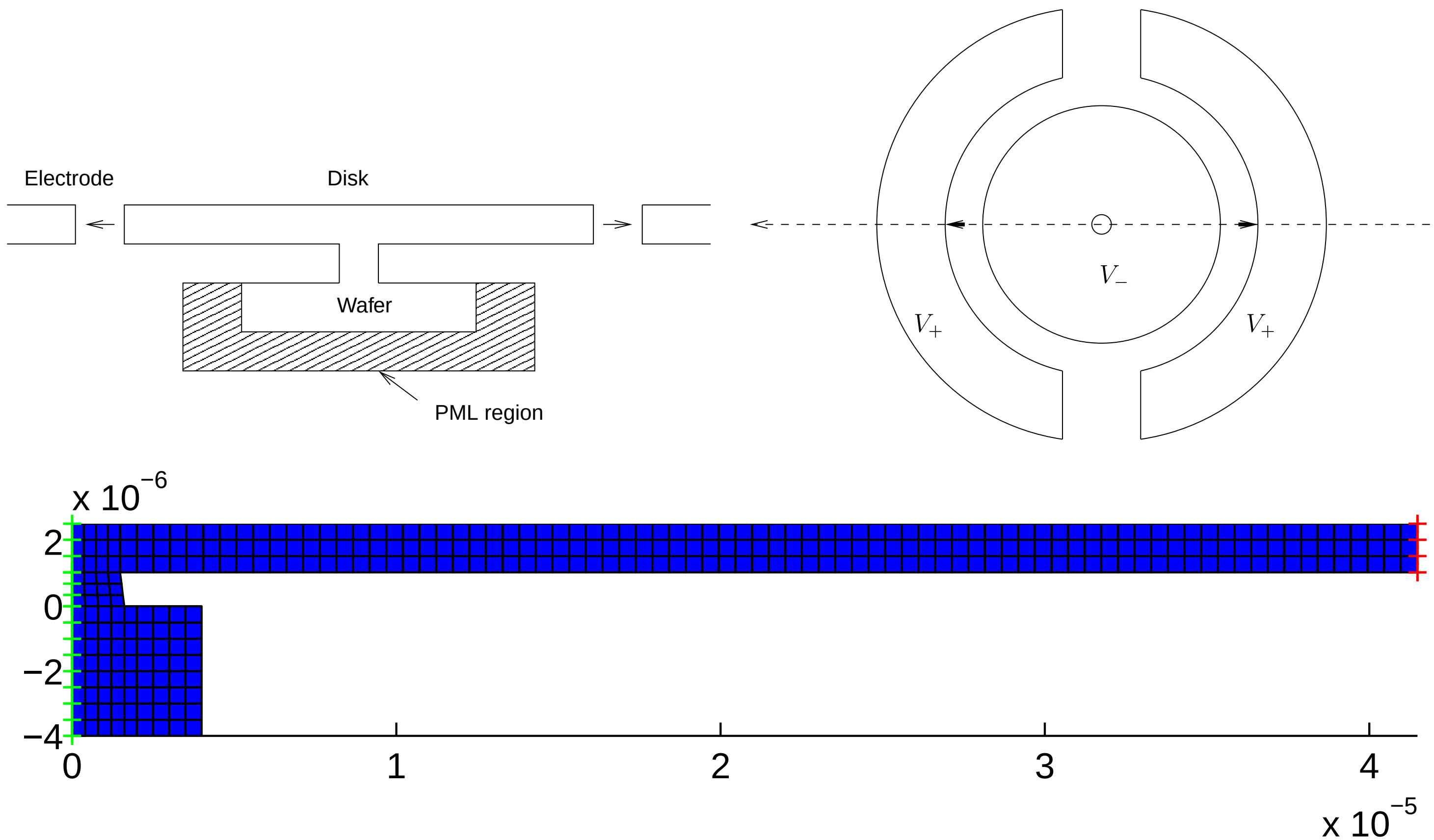


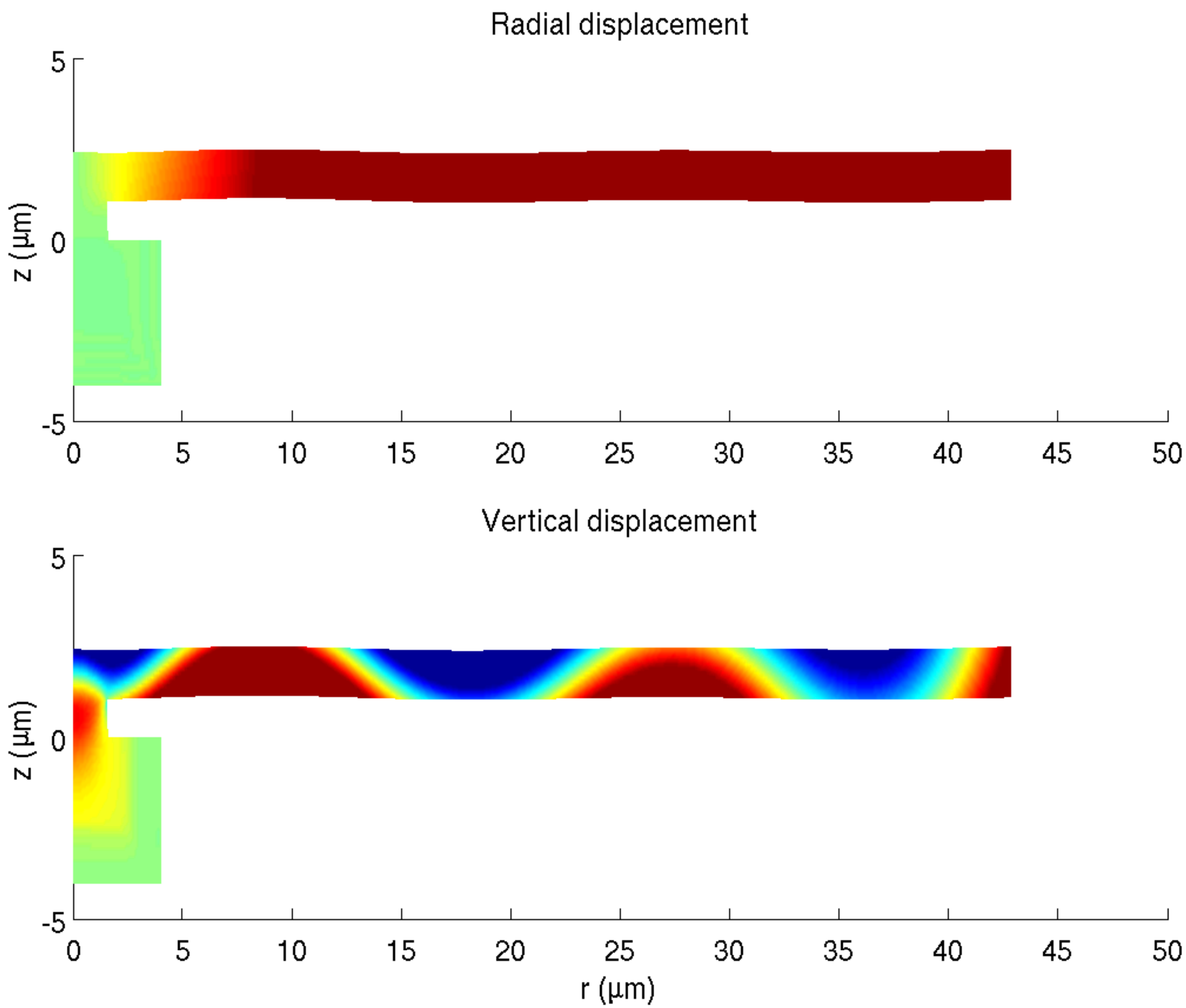
Clamp solution at transformed end to isolate outgoing wave.

Disk resonator mesh

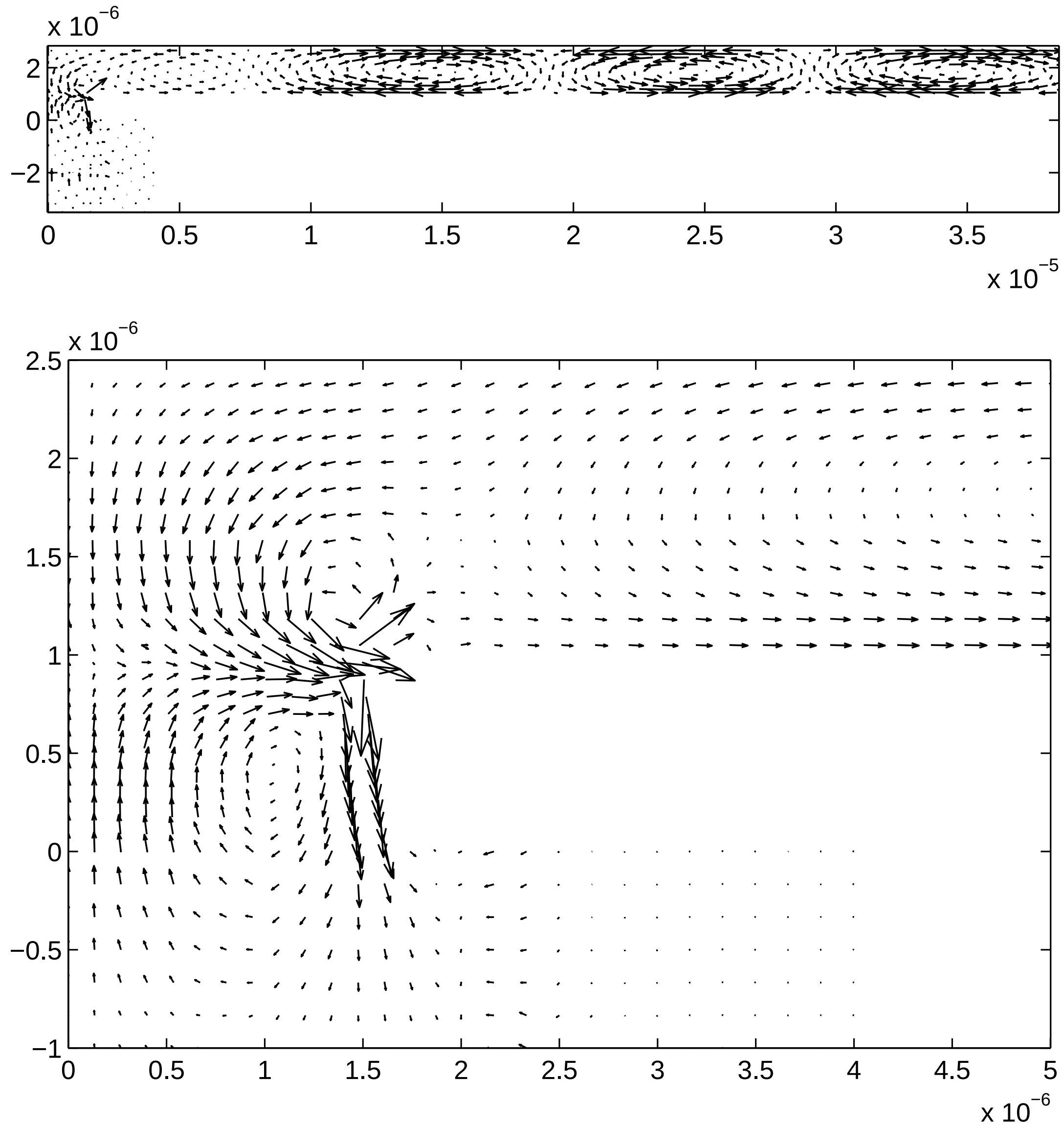


- Axisymmetric model with bicubic mesh
- About 10K nodal points in converged calculation

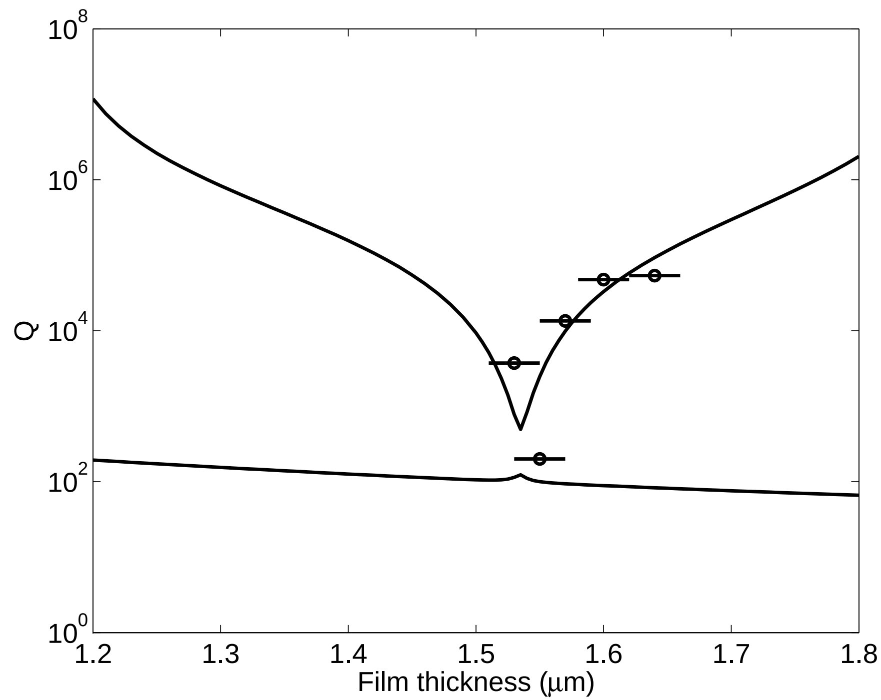
Response of the disk resonator



Time-averaged energy flux

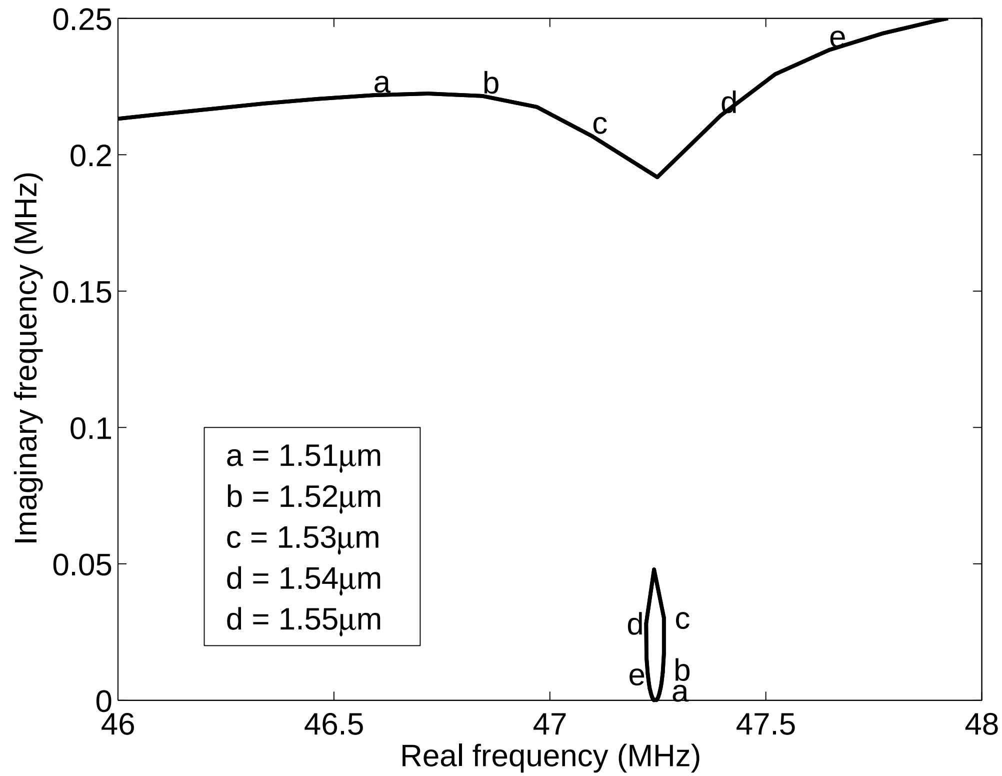


Q variation



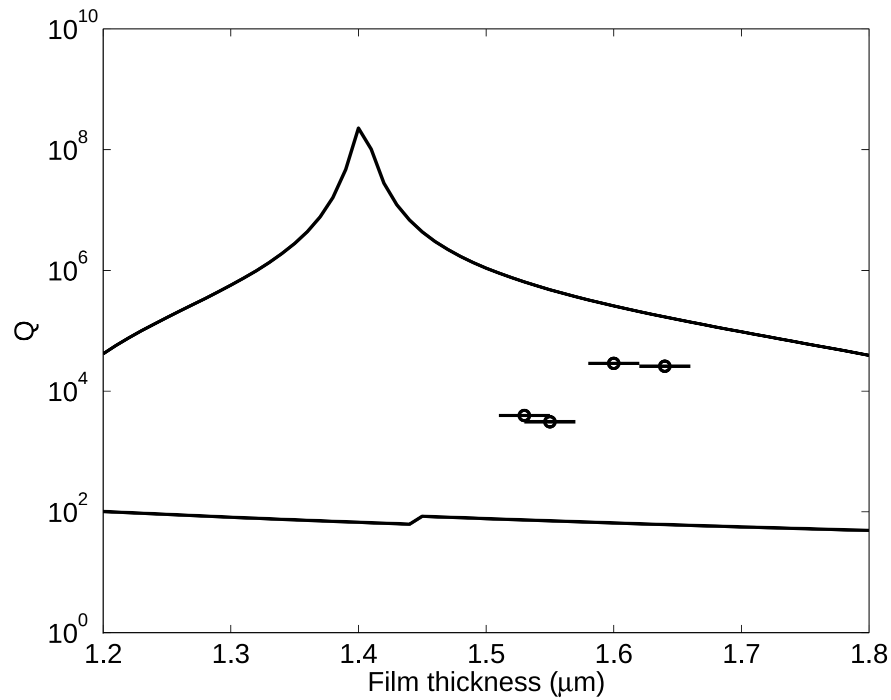
- Compute complex frequencies by shift-and-invert Arnoldi with an analytically determined shift
- Surprising variation – experimentally observed – in Q as film thickness changes!

Effect of varying film thickness



- Sudden dip in Q comes from an interaction between a (mostly) bending mode and a (mostly) radial mode
- Non-normal interaction between the modes

Truth in advertising



Data from a set of $30\mu m$ radius disks.

Conclusions

- Simulation tools are good for MEMS designers
  - Reduce expensive “build-and-break” design
  - Reveal behavior that is hard to measure directly
- MEMS problems are good for tool designers
  - Interesting physics (and not altogether understood)
  - Interesting numerical mathematics