Mobius Microsystems

Newton: A Library-Based Analytical Synthesis Tool for RF-MEMS Resonators

Authors: Michael S. McCorquodale, James L. McCann, and Richard B. Brown

Lecturer: Michael S. McCorquodale, Ph.D.
Mobius Microsystems, Inc.

ASP-DAC 2006, Yokohama

Mobius
Microsystems

Outline

Introduction to MEMS simulation and synthesis approaches

- Finite element analysis
- Nodal analysis
- Automated design synthesis
- Library-based analytical synthesis (*Newton*)

Example analytical expression and computational algorithm

- CCB resonator design overview
- Euler-Bernoulli method

Tool framework

- Graphical user interface
- Synthesis engine

A synthesis example and experimental results

Conclusion

Introduction to MEMS simulation and synthesis approaches

Mobius
Microsystems

Introduction

Challenges with MEMS design automation

- Devices are similar to analog circuits
- Myriad of devices
- Fabrication processes not standardized and vary

Current MEMS DA approaches

- Simulation
- Synthesis

MEMS simulation approaches

Finite element analysis

- Application: arbitrary device-level design
- Approach: develop solid model for device, decompose into finite elements (mesh), set mechanical boundary conditions, perform simulation or analysis
- Pros/cons: accurate and versatile, but requires substantial design effort

Nodal analysis

- Application: arbitrary device-level design
- Approach: construct devices from parameterized geometric building blocks (e.g. beams, gaps, anchors) and simulate using nodal approach
- Pros/cons: faster than FEA, though design iteration required

MEMS synthesis approaches

Automated design synthesis

- Application: arbitrary device-level design
- Approach: evolutionary using multi-objective genetic algorithms
- Pros/cons: enables rapid design space exploration though requires design iteration

Library-based analytical synthesis

- Application: direct synthesis of specific devices from performance objective
- Approach: use parameterized analytical formulations to directly synthesize physical design and equivalent electrical model
- Pros/cons: very fast though accuracy limited to model quality and synthesis limited to specifically supported devices

Newton: A library-based analytical synthesis tool

Mobius
Microsystems

Motivation for and overview of *Newton*

- Only a finite number of MEMS devices have utility
- MEMS process technologies slowly consolidating
- Library-based approach is fastest and draws closest analogy to circuit design automation and synthesis
- Need to develop highly accurate analytical models
- Need to develop extensible software framework to support multiple devices

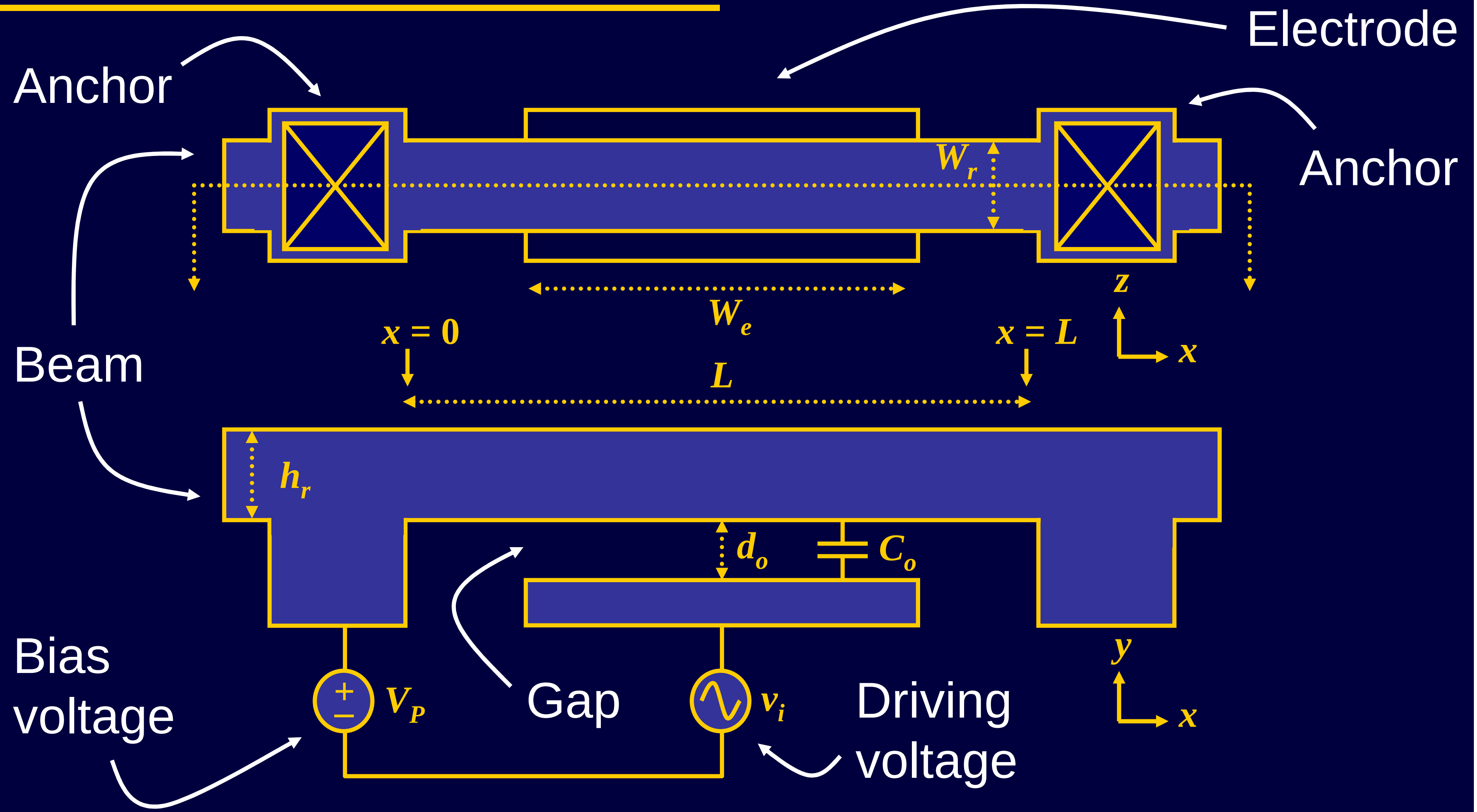
Example analytical expression and computational algorithm

CCB resonator design overview

Clamped-clamped beam RF-MEMS resonator

- Mechanical beam clamped at each end and suspended over an electrode
- Beam designed to resonate at a distinct frequency
- Applications in frequency/clock synthesis and RF filtering
- Device fabricated with a surface micromachining process
- Process technology defines subset of variables
- Primary design objective is accurate prediction of resonant frequency

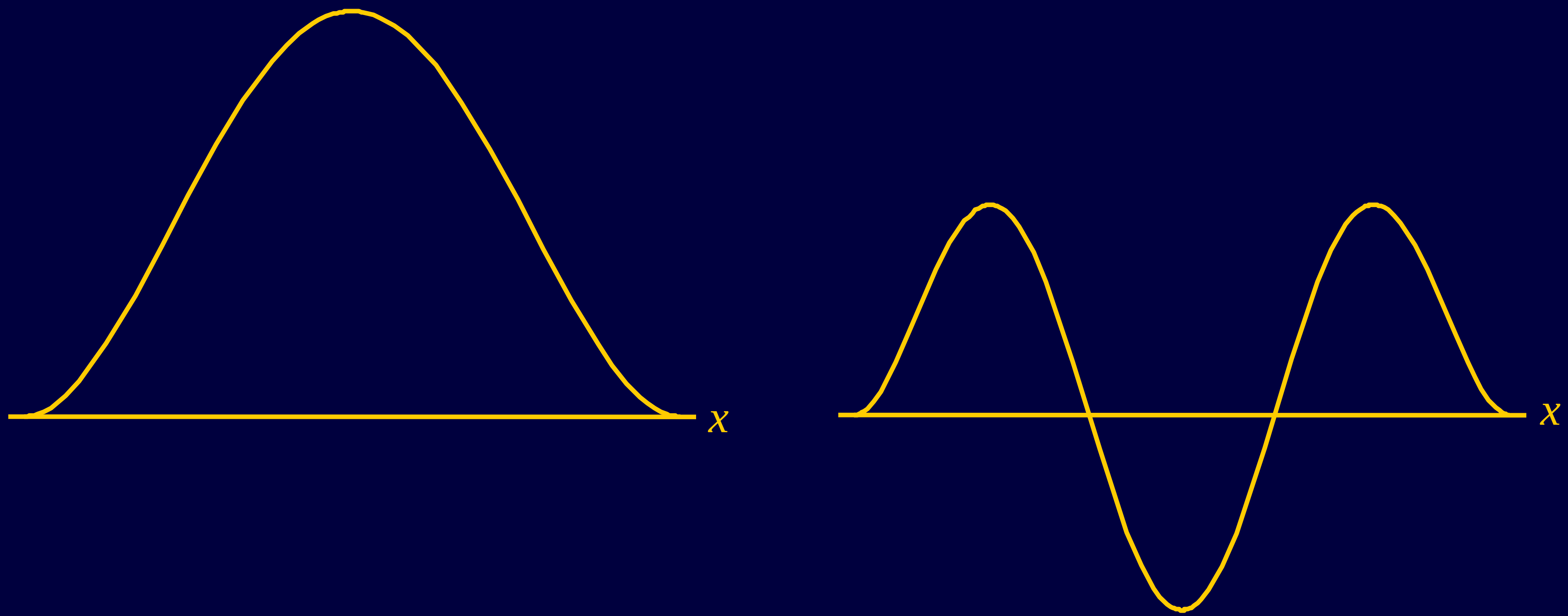
CCB resonator design overview



CCB resonator design overview

Resonant modes

- Device can resonant in one of many modes (first and third shown)
- Resonant mode will be parameterized in analytical model

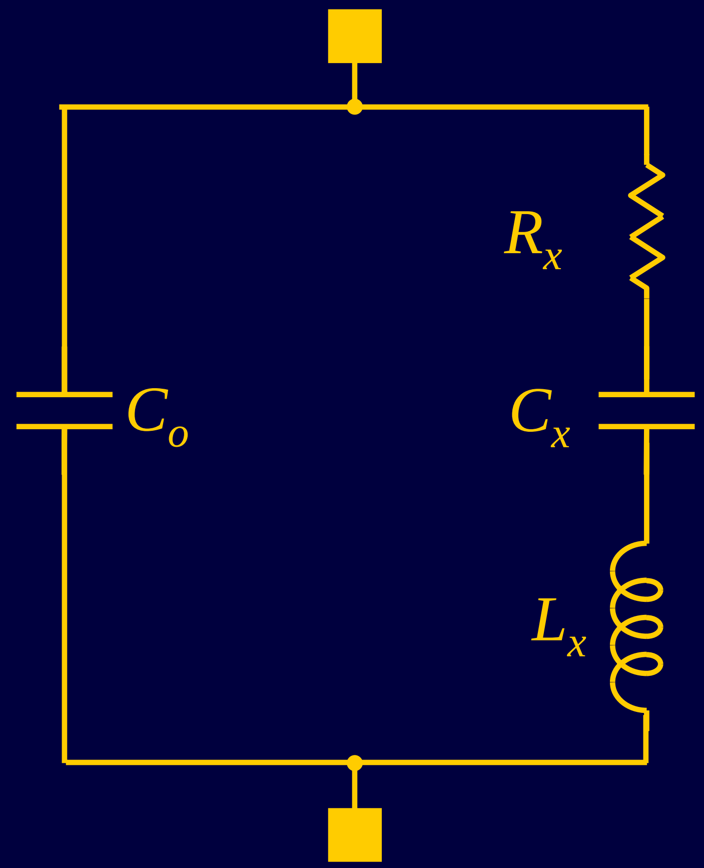


CCB resonator design overview

At resonance, CCB resonator can be modeled by a series RLC circuit

Use electromechanical analogy to determine device model parameters

Synthesize netlist for SPICE co-simulation with transistor devices



Euler-Bernoulli method

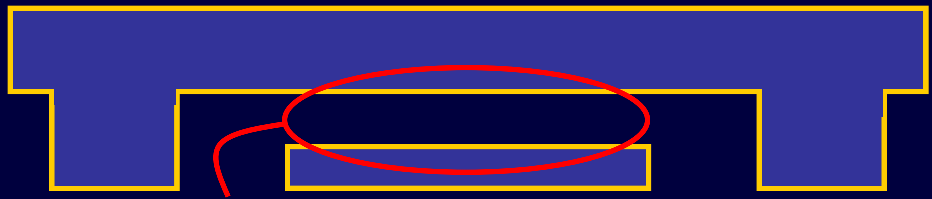
Begin with simple physics-based analytical formulation

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_m}{m}}$$

Account for "spring softening" due to subtractive electrical spring constant

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_m - k_e}{m}}$$

Spring softening is nonuniform across beam



Softening limited to electrode-beam overlap region

Use equivalent mass technique to derive accurate analytical expressions

Synthesis engine variables

Mobius Microsystems

CCB resonator process and performance variables

Design variable	Type	Description
ρ	Process	Density
E	Process	Young's Modulus
h_r	Process	Beam height
d_o	Process	Beam-electrode gap
k_n	Performance	Determine by mode
V_P	Performance	Bias voltage
W_r	Performance	Beam width
W_e	Performance	Electrode width
f_o	Performance	Resonant frequency

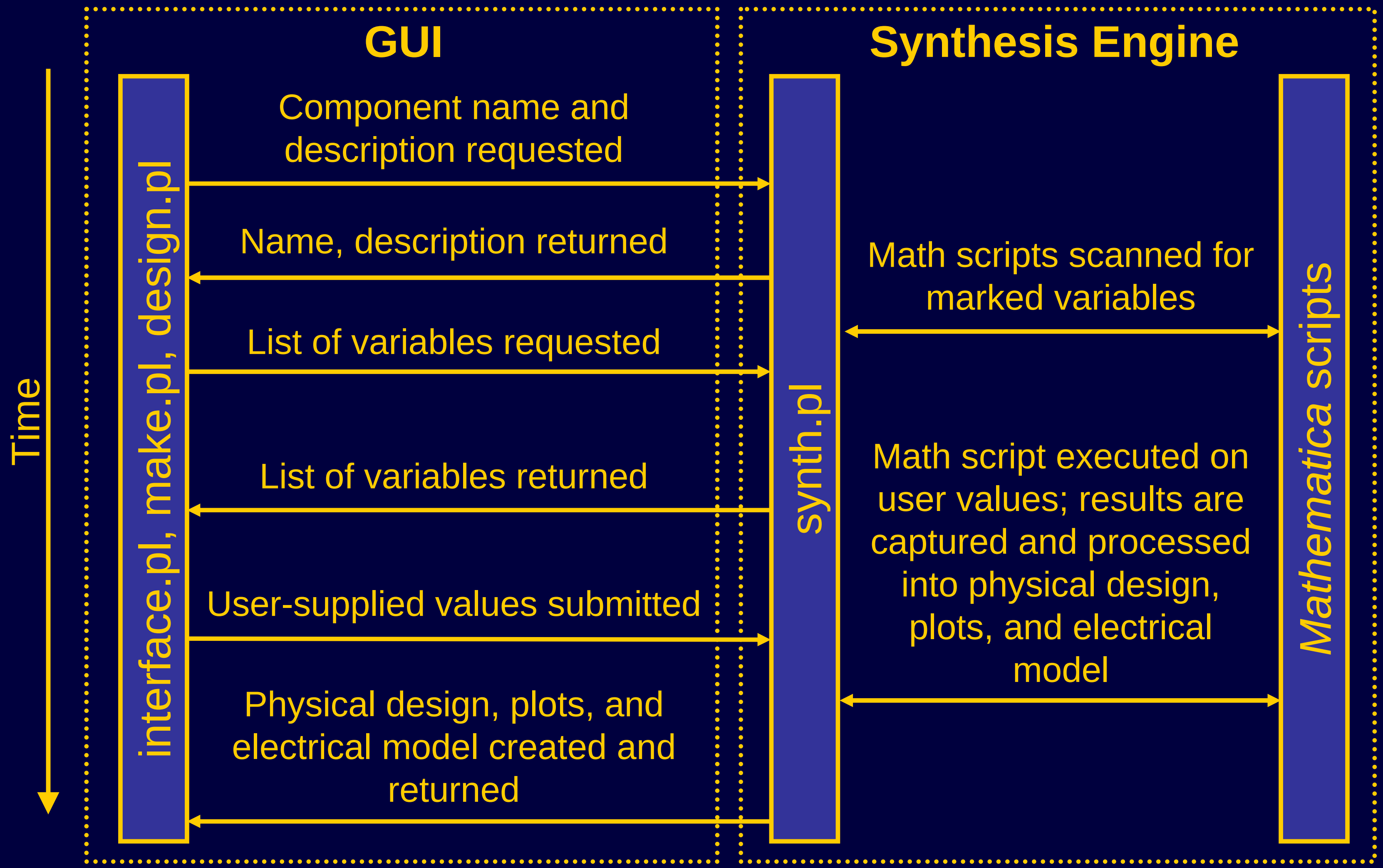
Synthesis engine variables

CCB resonator constant and derived variables

Design variable	Value/Expression	Description
ε	8.85x10^{-12}	Permittivity of free space
A	$A = W_r h_r$	Beam cross-sectional area
I	$I = (1/12) W_r h_r^3$	Moment of inertia
$u(x)$	Determined by mode	Mode shape function
L	Synthesized	Beam length

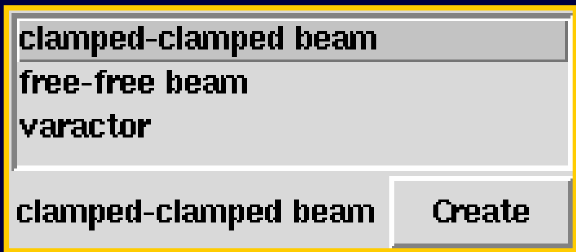
Tool framework

Framework overview



Graphical user interface

Library component browser

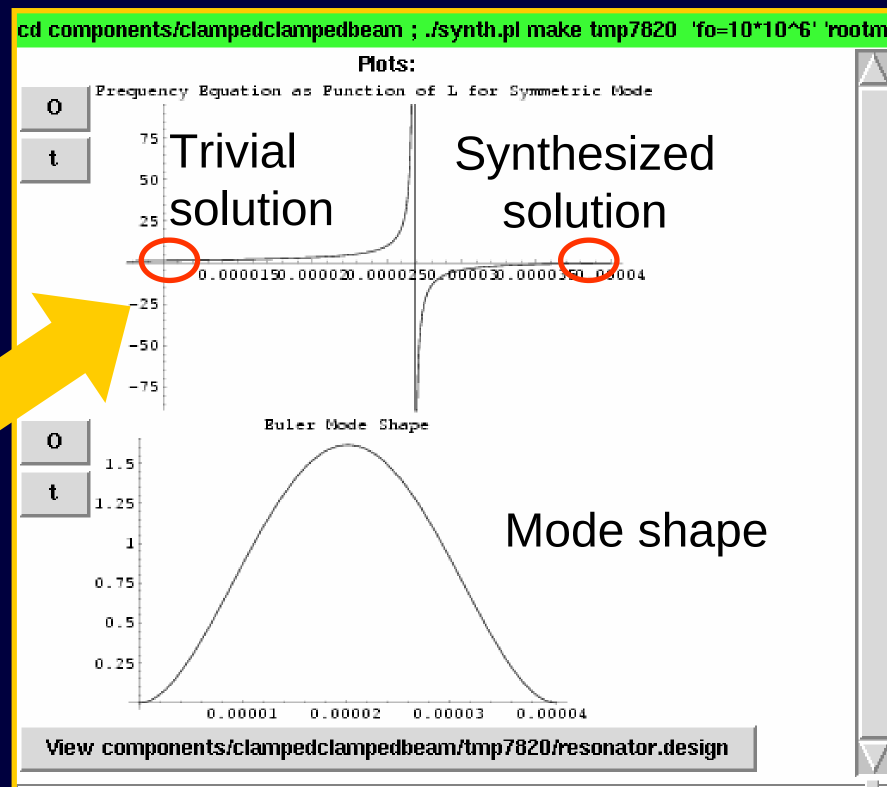


Component parameter interface

Variable	Value	Description
fo	10*10^6	resonant frequency (Hz)
rootmode	1	harmonic number of mode shape
Vp	10	bias voltage (V)
Q	10000	quality factor
do	500/10^10	electrode-to-beam spacing (m)
We	L/2	width of the electrode (m)
Wr	6/10^6	width of the beam (m)
hr	2/10^6	height of the beam (m)
Ws	1/10^6	width of the supporting beam (m)
hs	2/10^6	height of the supporting beam (m)
Ey	150*10^9	Young's Modulus for poly (Pa)

Make

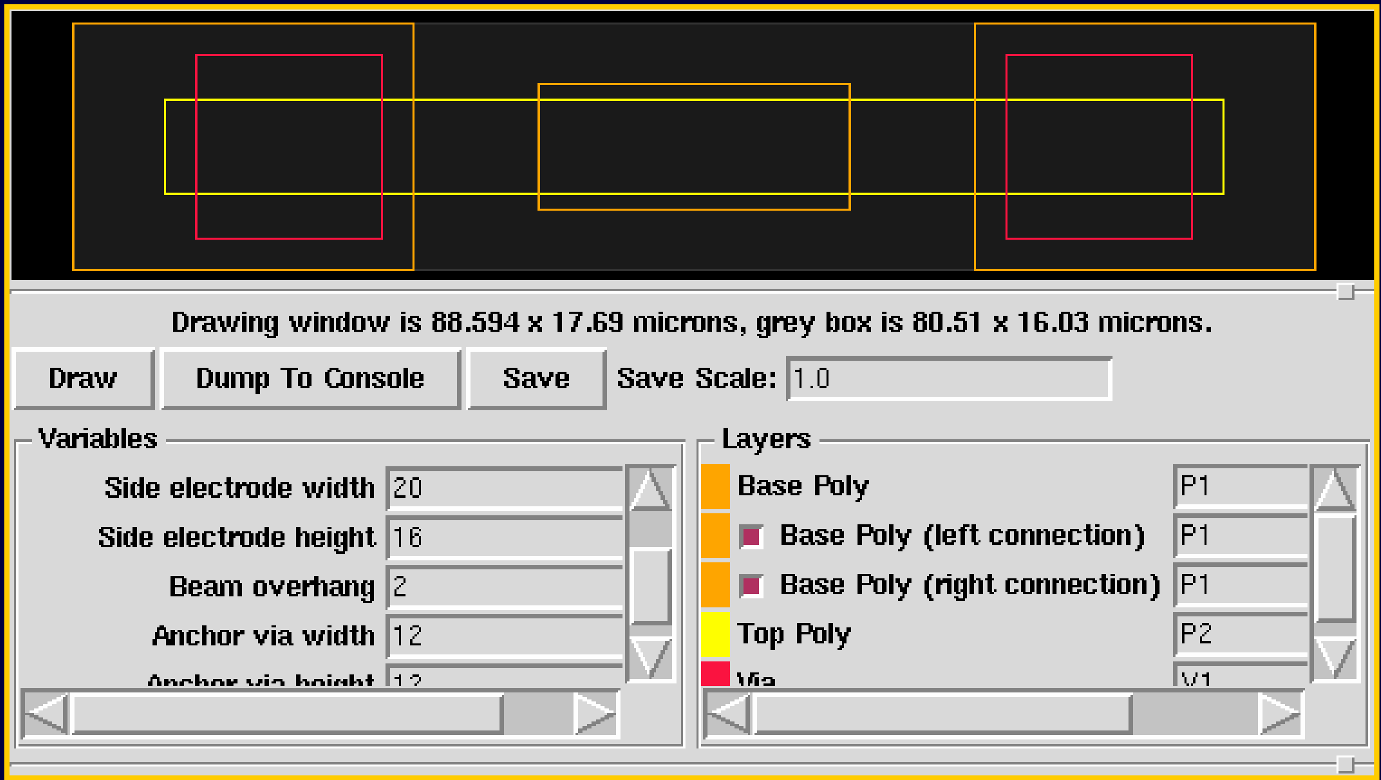
Synthesis results



Graphical user interface

Physical design viewpoint

- Modify performance-independent parameters
- Export to CIF and generate netlist



Mobius Microsystems

Synthesis engine

Implemented in *Mathematica*

- Pros: useful for symbolic integrals in derived analytical expressions, fast, extensible, supports plotting
- Cons: requires license

Future work: integrate analytical expressions using a math and plotting package

- Pros: self-contained
- Cons: substantial effort

A synthesis example and experimental results

Mobius
Microsystems

Synthesis example

Performance-Driven	Value
Resonant frequency, f_o	10MHz
Resonant mode number, n	1
Resonator width, W_r	6μm
Bias voltage, V_P	10V
Electrode width, W_e	L/2

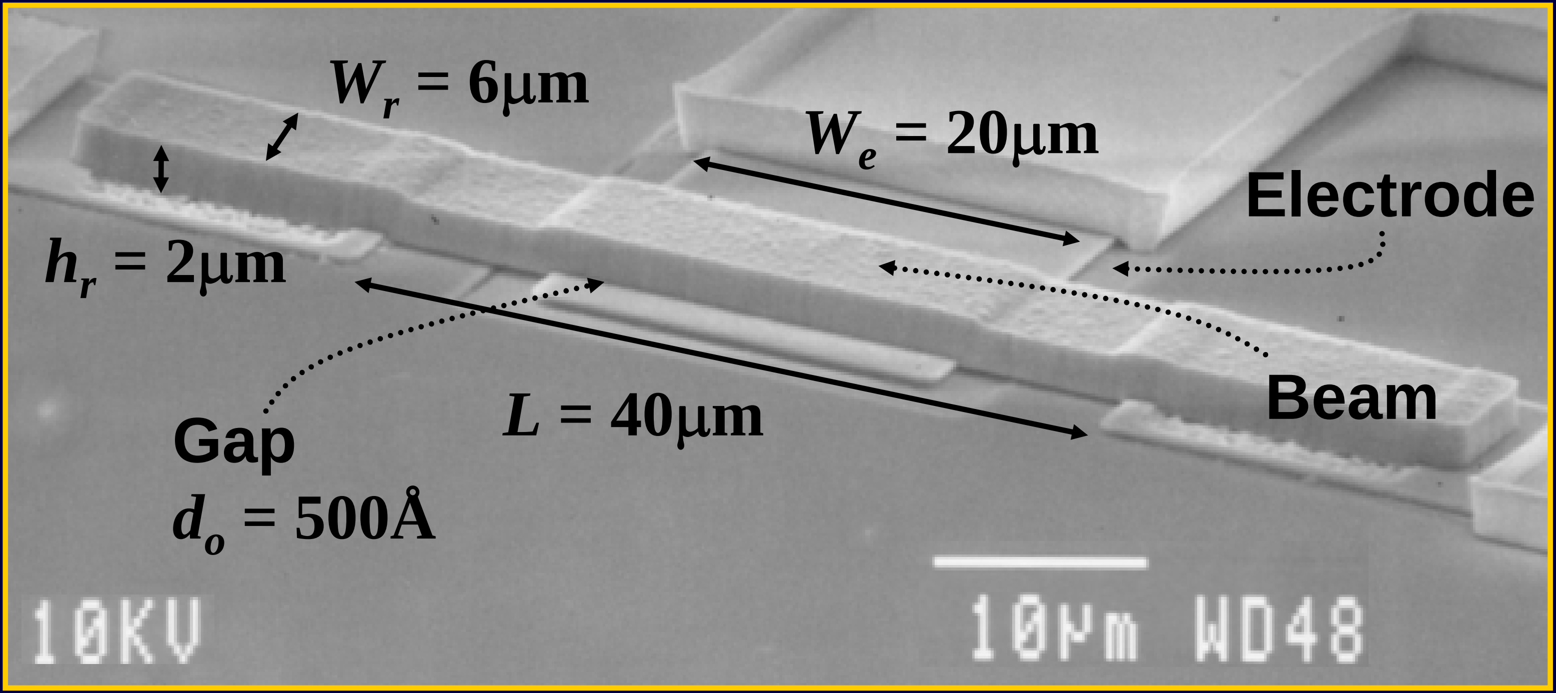
Process-Dependent	Value
Density, ρ	2330kg/m^3
Young's Modulus, E	150GPa
Resonator height, h_r	2μm
Resonator-electrode gap, d_o	500Å

Mobius Microsystems

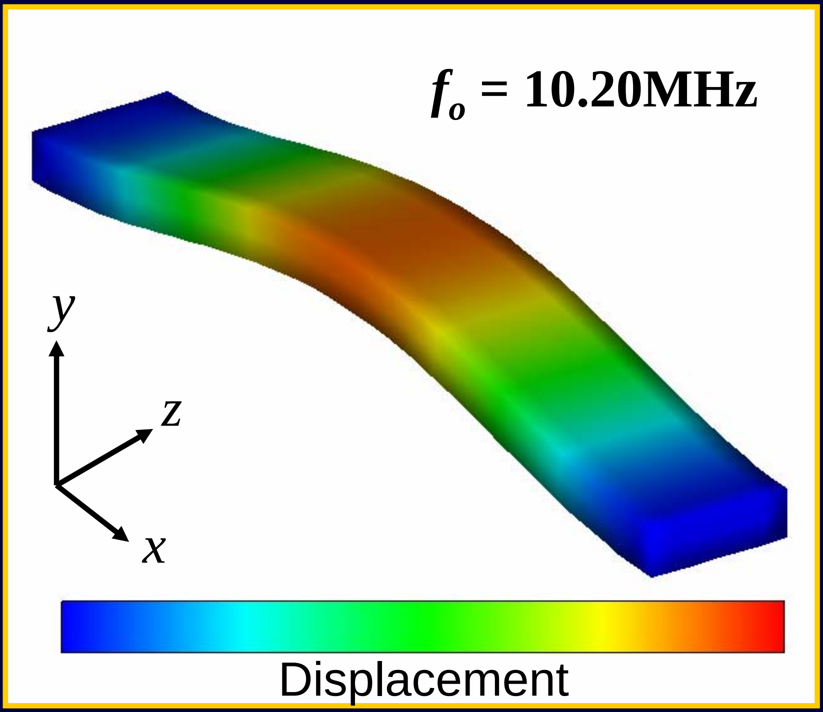
Experimental results

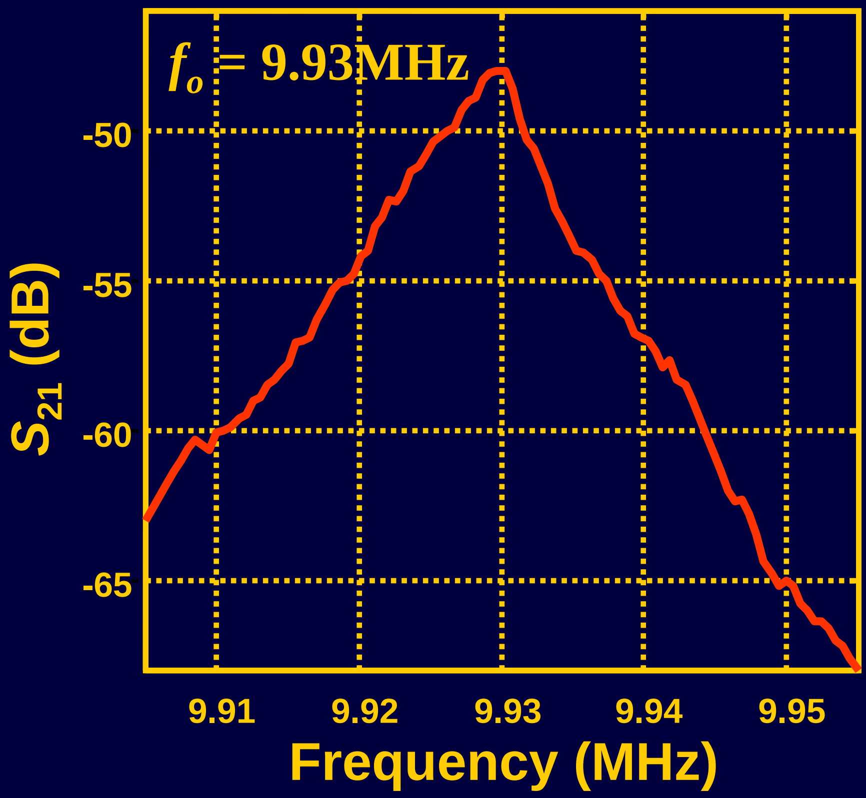
Electron micrograph of fabricated CCB resonator

- Surface micromachined poly-Si process at U. of Michigan
- Resonant frequency tested under vacuum with spectrum analyzer



Experimental results





FEA with *Coventorware*

- >10hrs. design/mesh + 15min. sim.
- 2.70% error in f_o comp. to meas.

Meas. results from *Newton* design

- <1min. design and synthesis
- 0.70% error in f_o comp. to target

Conclusion

Conclusion and future work

Mobius Microsystems

Achievements

- Demonstrated the first complete and extensible analytical CAD tool for the direct synthesis of MEMS devices
- Demonstrated rapid synthesis with high performance accuracy verified through measurement of fabricated devices (0.70% error)

Future work

- Verify accuracy of analytical formulations for larger sample sets
- Develop analytical formulations for new devices and verify through fabrication and test
- Automate process-dependent parameter selection based on standard foundries
- Integrate *Mathematica* notebooks into math package

Questions welcome