Exploration of Metamaterial Designs for LIGO Mechanical Systems

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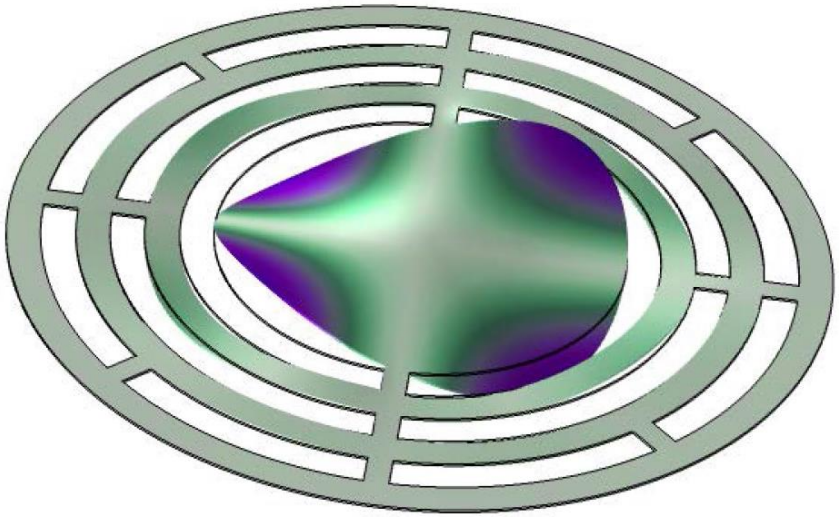
Outline

- Overview of metamaterials
- Metamaterial applications for LIGO
- Analytical models
- Finite element analysis
- Geometry optimization

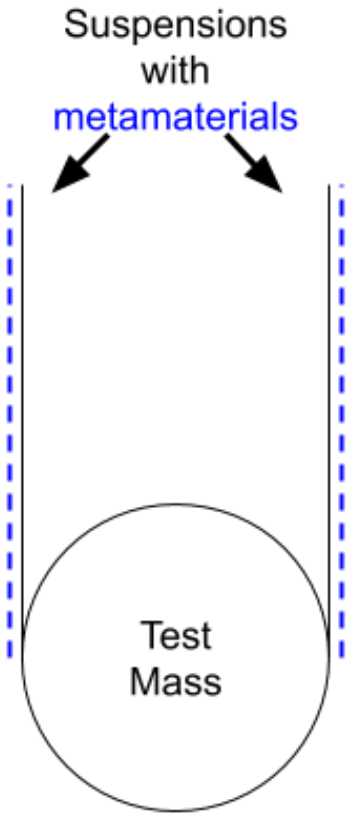
What are metamaterials?

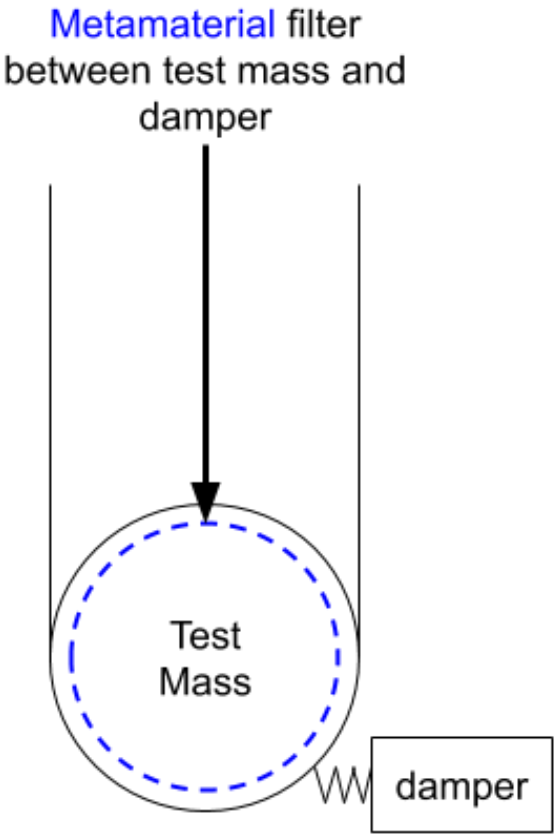
- Materials engineered to produce exotic behaviors based on their structure
- Can manipulate the propagation of waves through an object

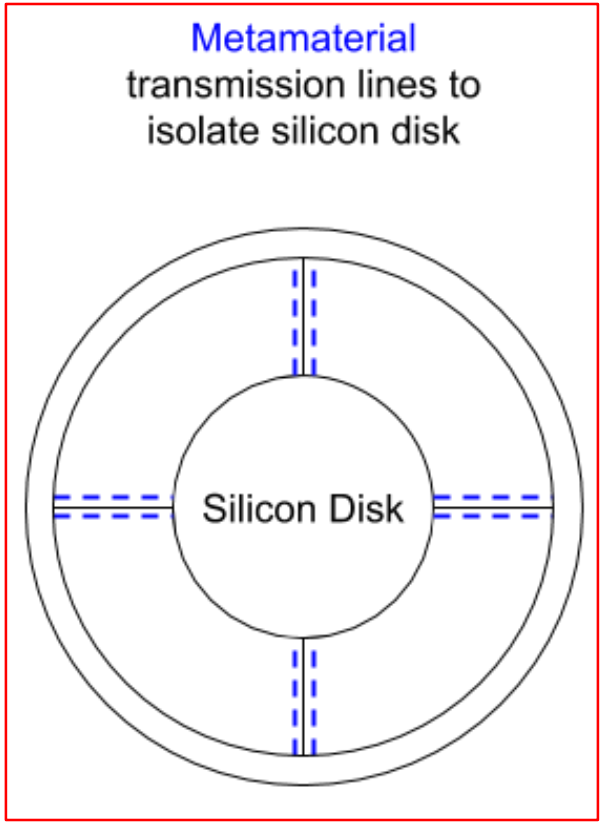


Metamaterials for LIGO

- Three possible metamaterial applications for LIGO

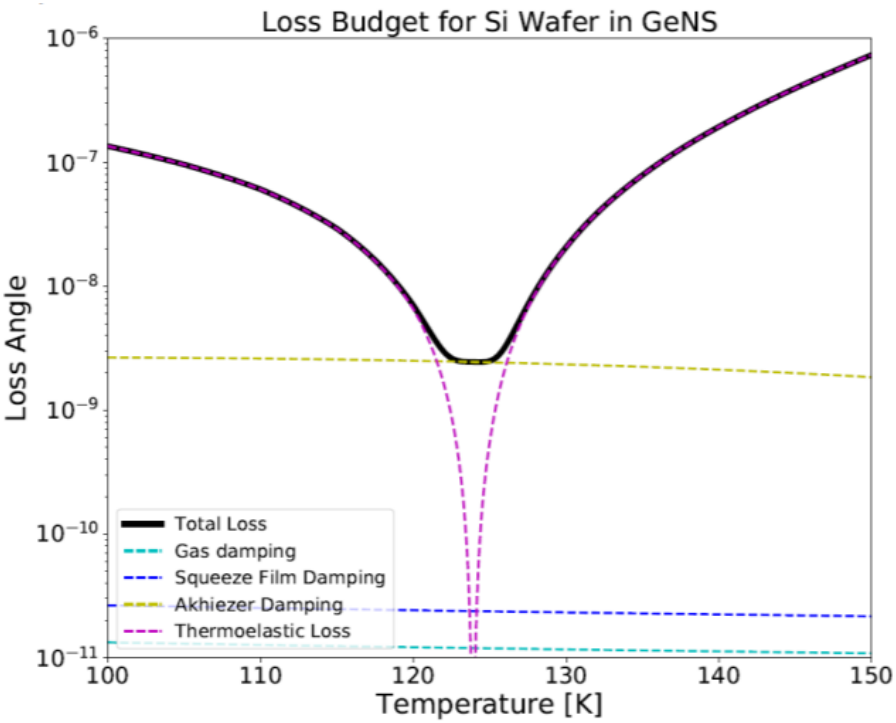


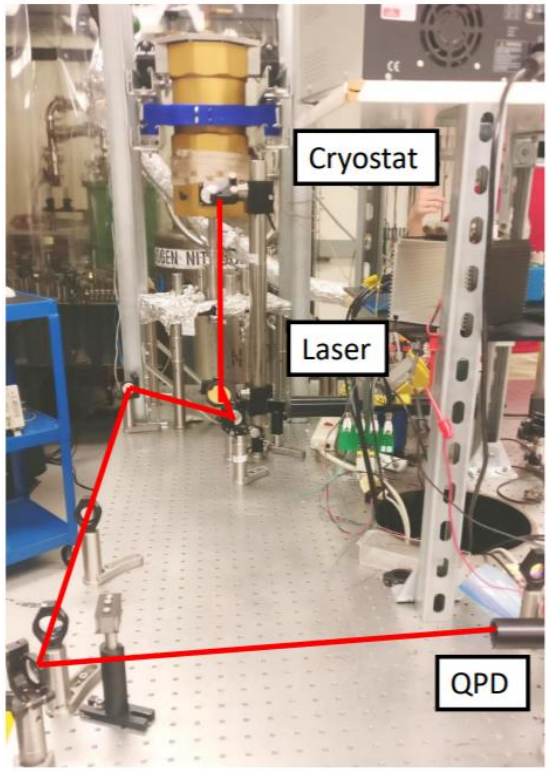




Cryo Lab

- Cryogenic silicon measurements for LIGO Voyager noise budget

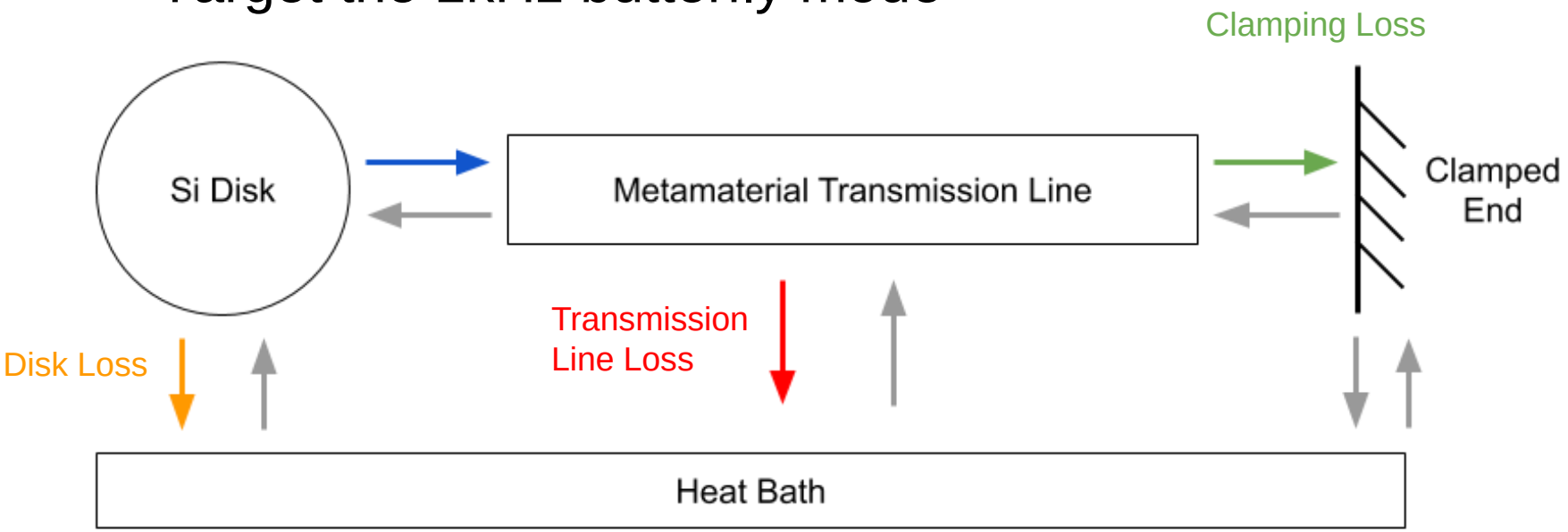




SURF 2019 presentation by Shubhabroto Mukherjee (DCC T1900384-v1)

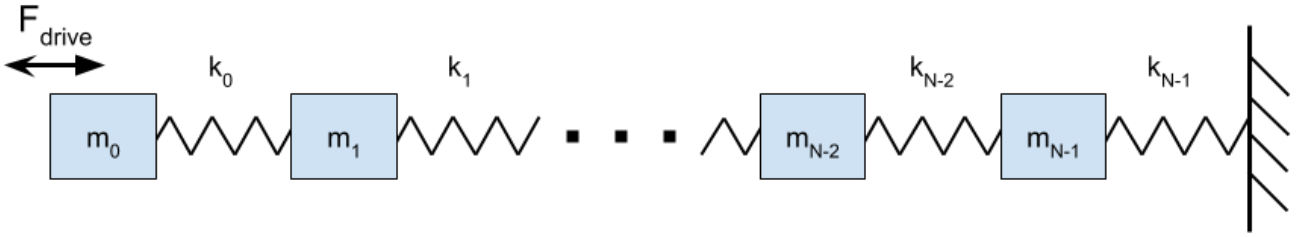
Disk Isolation System

- Control system temperature via conduction cooling
- Mimic mechanical isolation with a metamaterial layer between a clamped frame and the disk
- Target the 1kHz butterfly mode

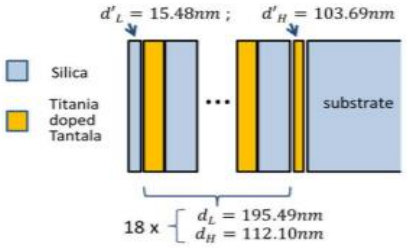


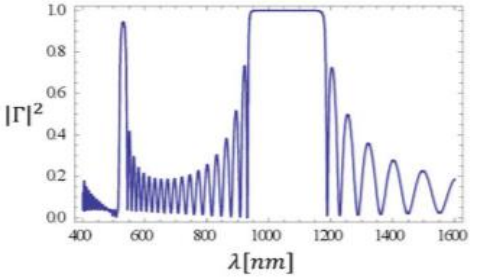
Spring-Mass Models

- Used spring-mass system to study the transfer function for a series of resonators



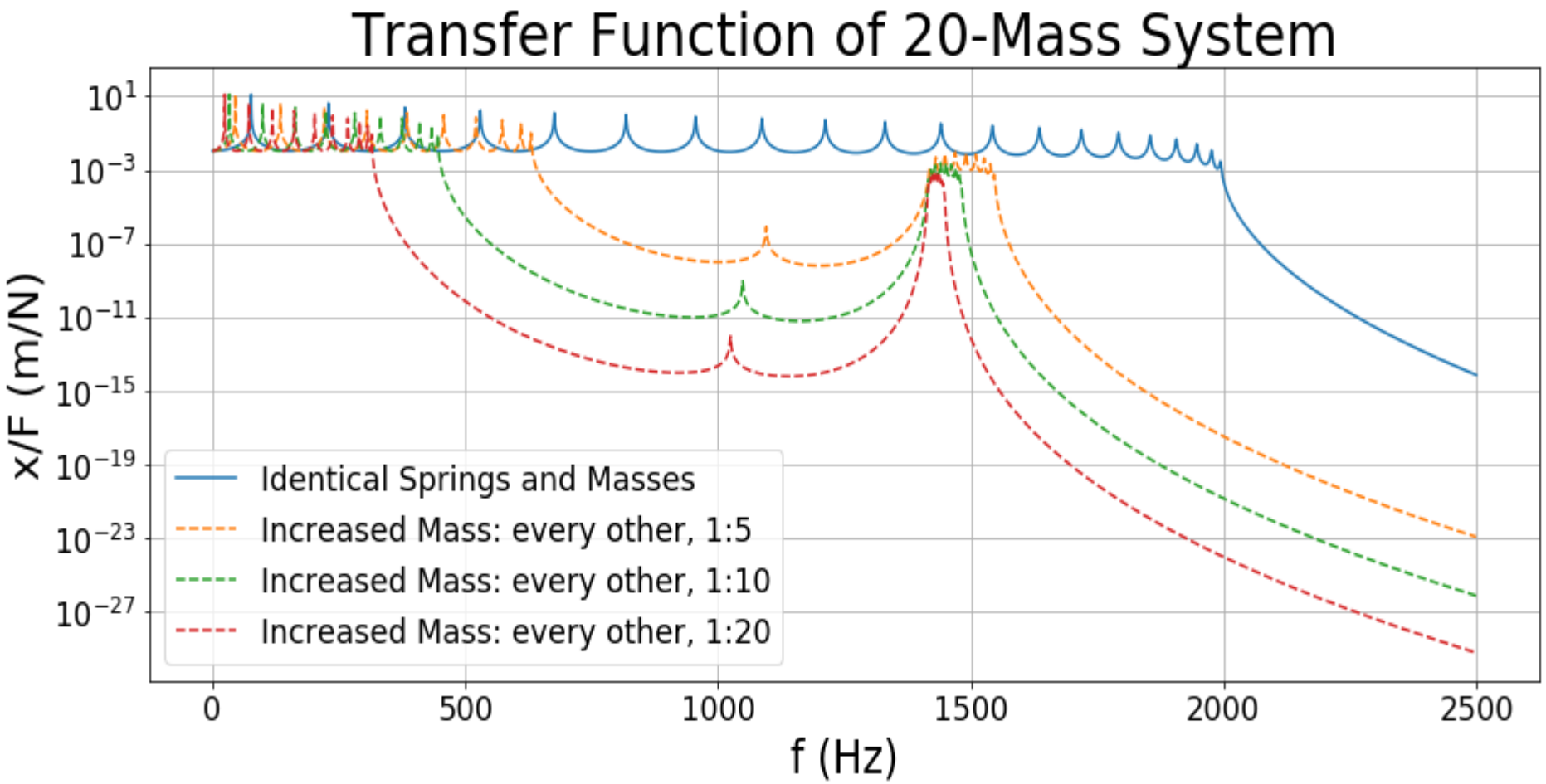
- Bandgap produced by alternating spring constant/mass values [1], more effective with more resonators
- Analogous to Bragg reflection analysis for LIGO mirror coatings [2]





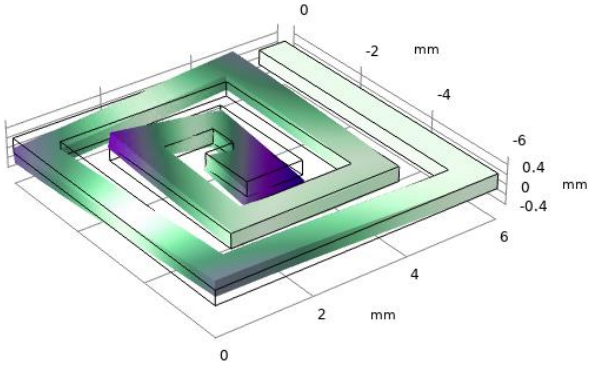
[1] Jensen, J.S.. (2003). Phononic band gaps and vibrations in one- and two-dimensional mass–spring structures. Journal of Sound and Vibration. 266. 1053-1078. 10.1016/S0022-460X(02)01629-2.
[2] Maria Principe, " Opt. Express 23, 10938-10956 (2015)

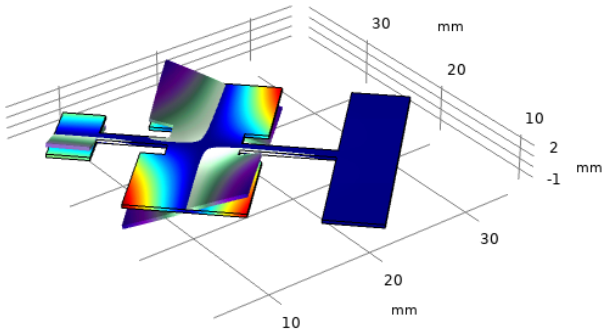
Spring-Mass Model Results

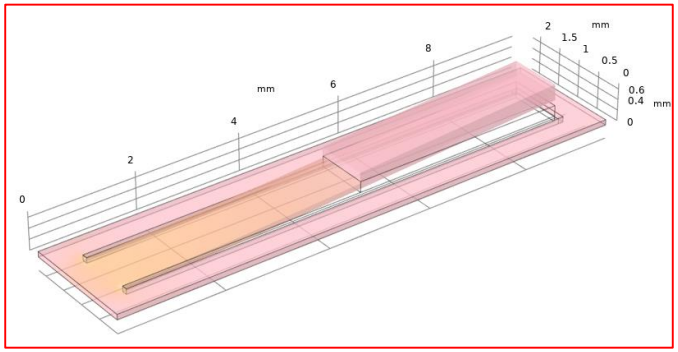


Finite Element Analysis

- Build resonator systems and study their reactions to external loads using COMSOL
- Resonator requirements
  - Sub-cm scale
  - ~1kHz eigenfrequency
  - Coupling to transverse modes
  - Structural stability/simplicity

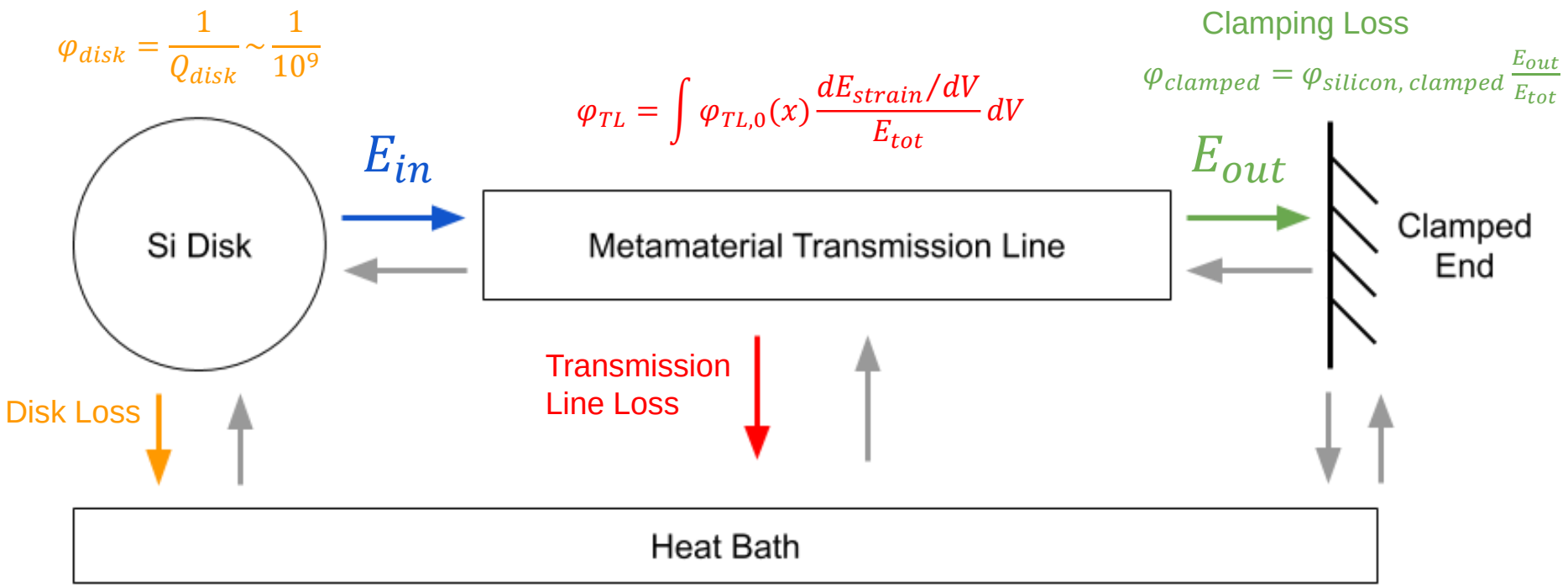






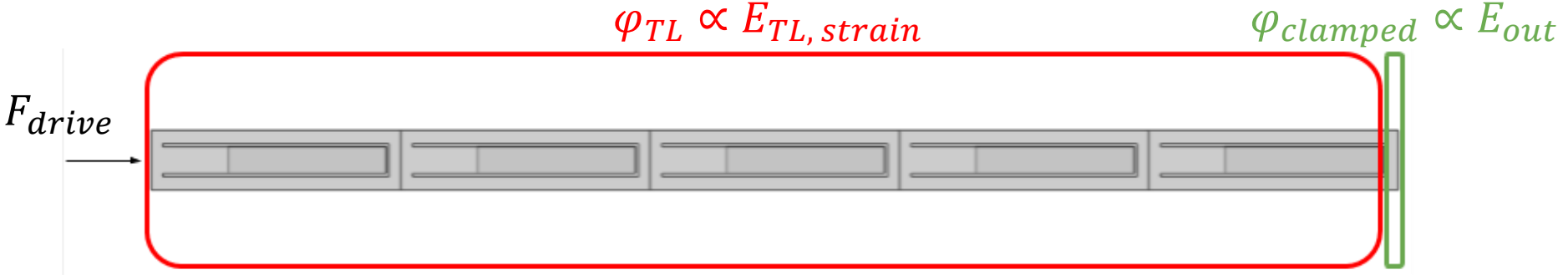
Loss Characterization

$$\varphi_{total} = \varphi_{disk} + \varphi_{TL} + \varphi_{clamped\ end}$$

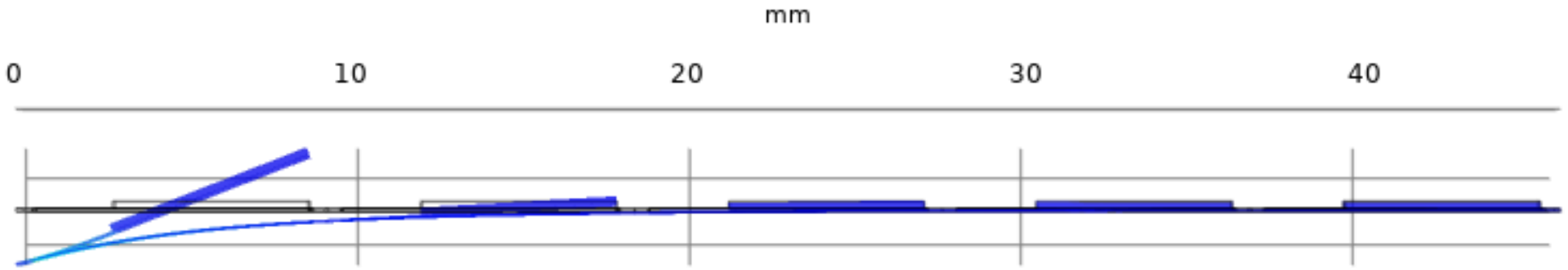


Cantilever Transmission Line

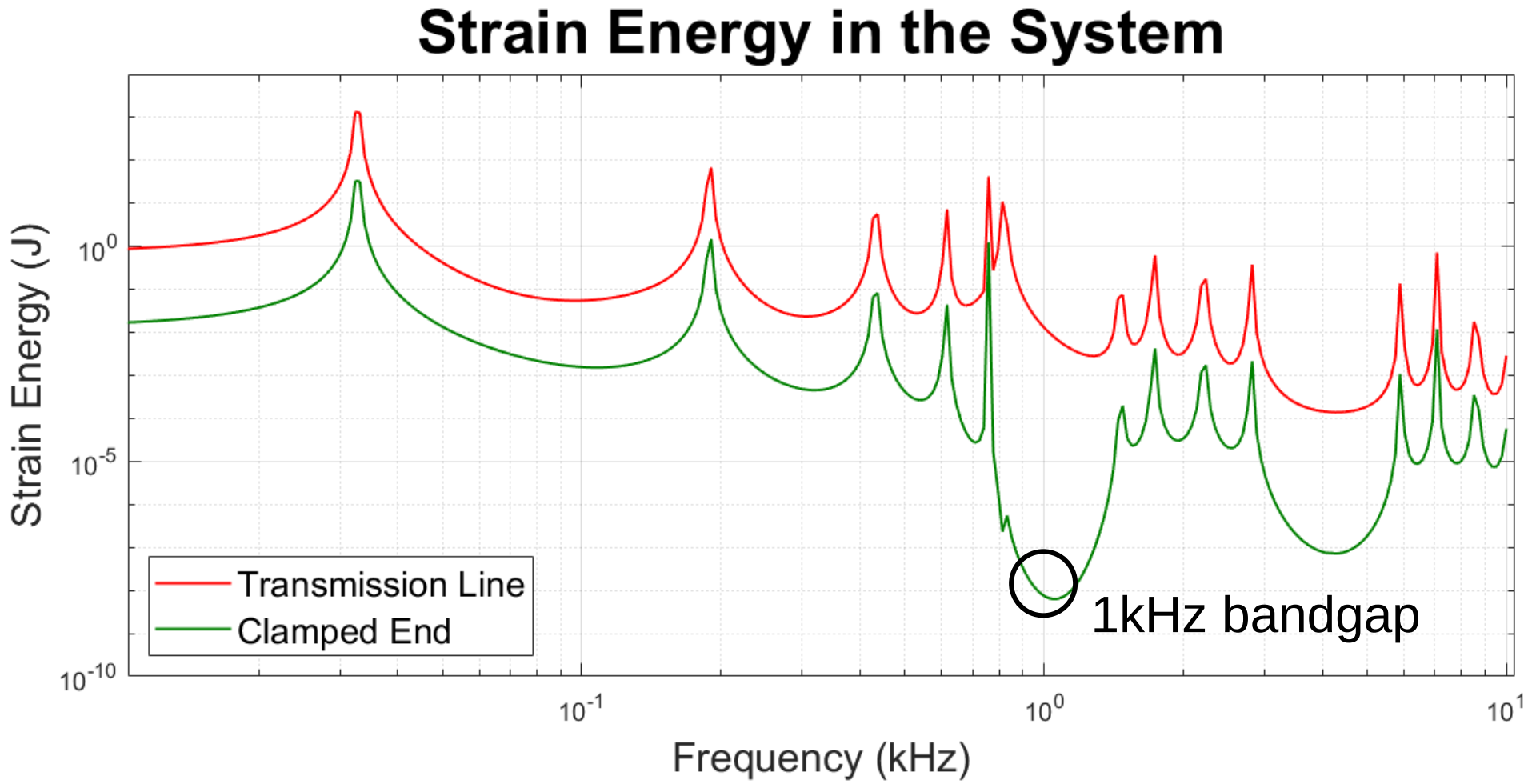
- Can probe strain energy in different domains in COMSOL



- Isolation mechanism at 1kHz



Simulation Results



Geometry Optimization

- Minimize the losses φ_{TL}, $\varphi_{clamped}$ introduced by the metamaterial
- Constrained nonlinear optimization algorithm ‘fmincon’ in MATLAB

Cantilever Length = 9.268 mm
Cantilever Thin End = 2.984 mm
Frame Length = 0.366 mm

Conclusions

- Resonator-based metamaterials can be used for mechanical isolation
- Cantilever resonators at sub-cm scale can be used to target the 1kHz butterfly mode of a silicon disk

Next Steps

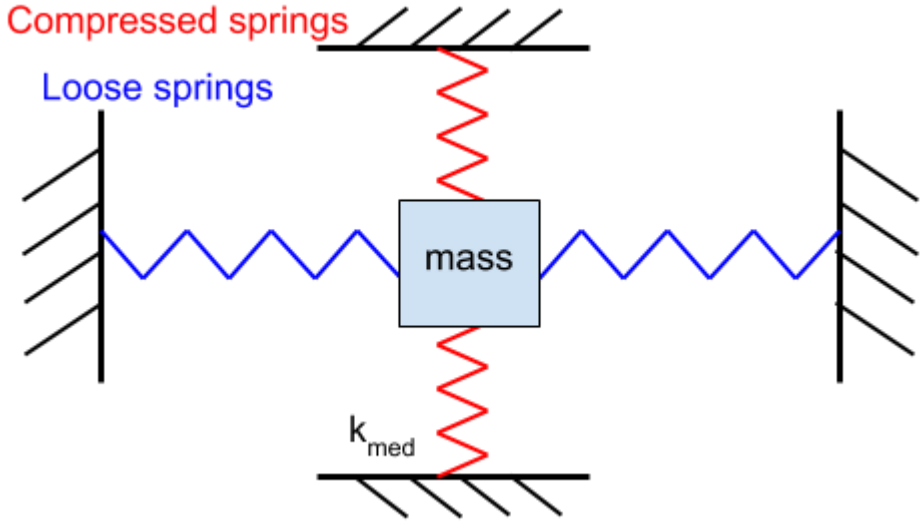
- Simulate full system including the disk in COMSOL
- Fabricate system in a nanofabrication cleanroom
- Test!

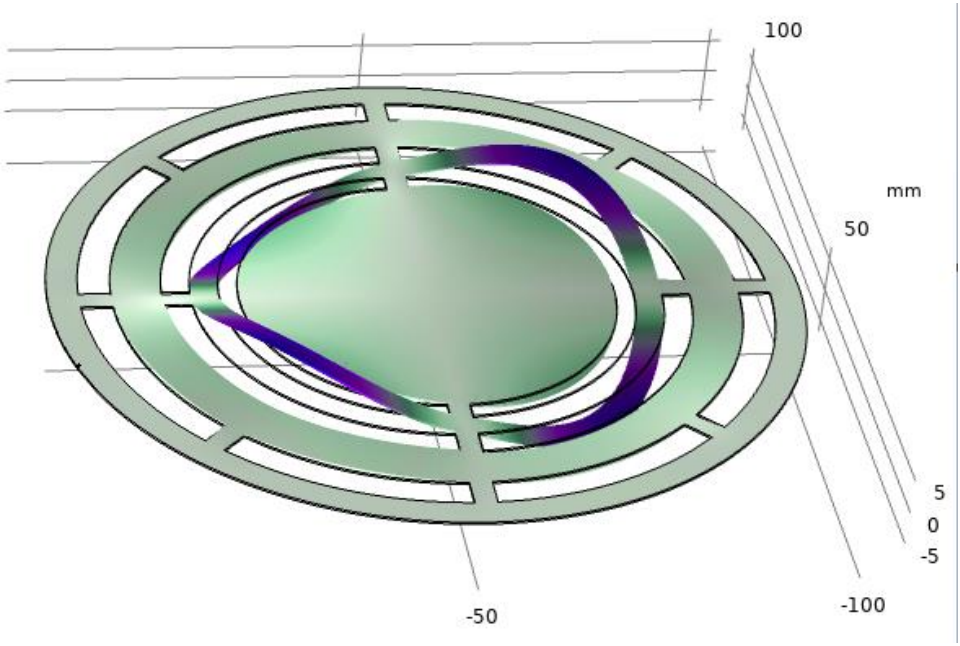
Acknowledgements

- Aaron Markowitz, Christopher Wipf, Rana Adhikari
- LIGO SURF Program
- NSF
- Caltech

Other Ideas

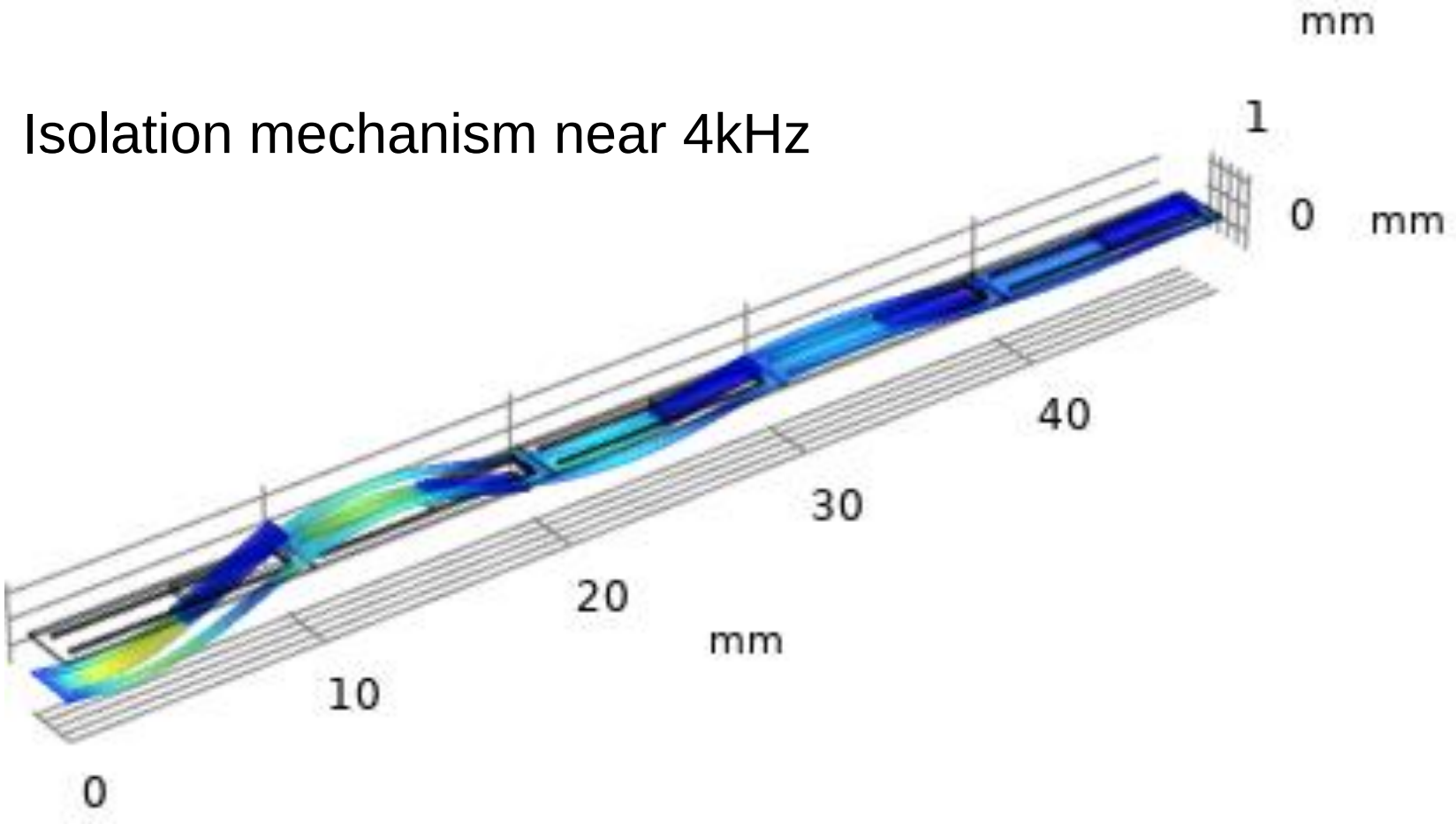
- Buckling geometry to achieve same frequency resonances at smaller scale
- Spiderweb structure utilizing larger-scale structures as resonators



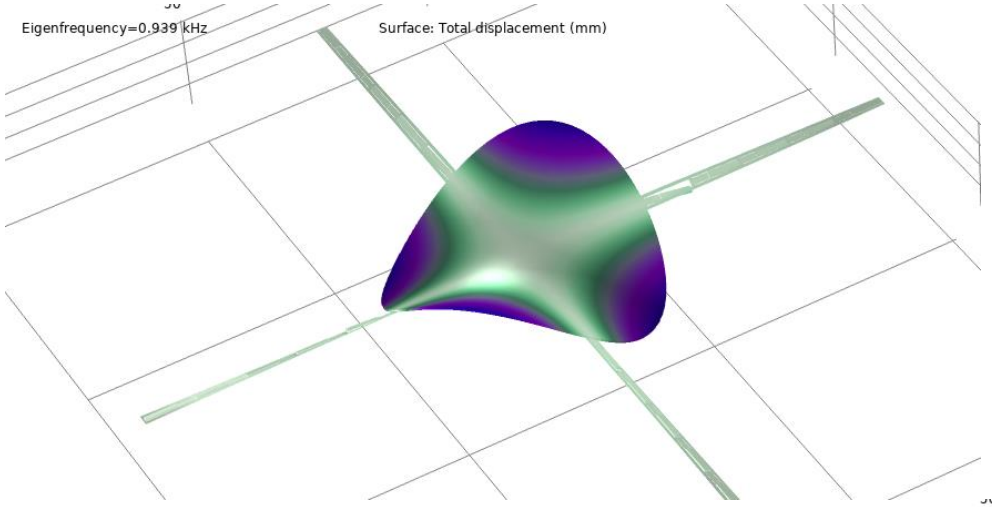


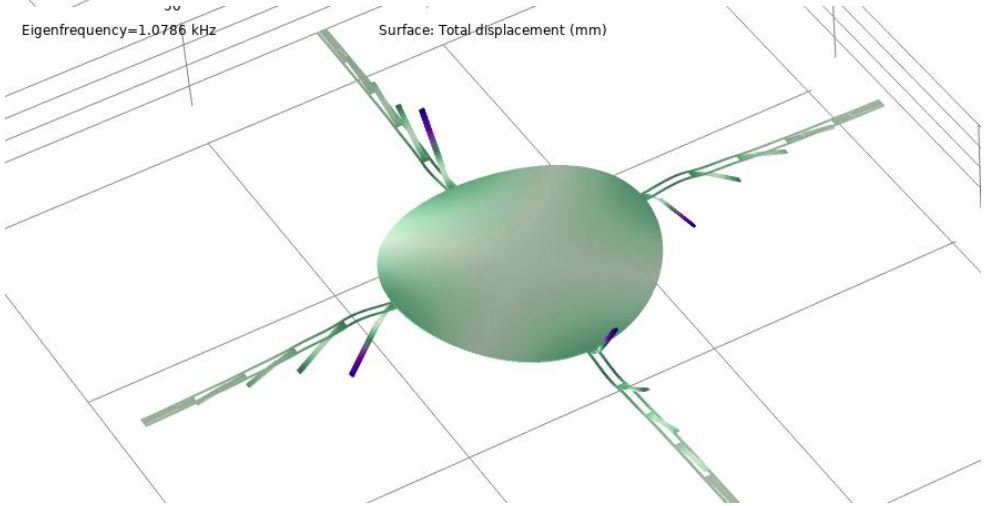
Cantilever Resonator

Isolation mechanism near 4kHz



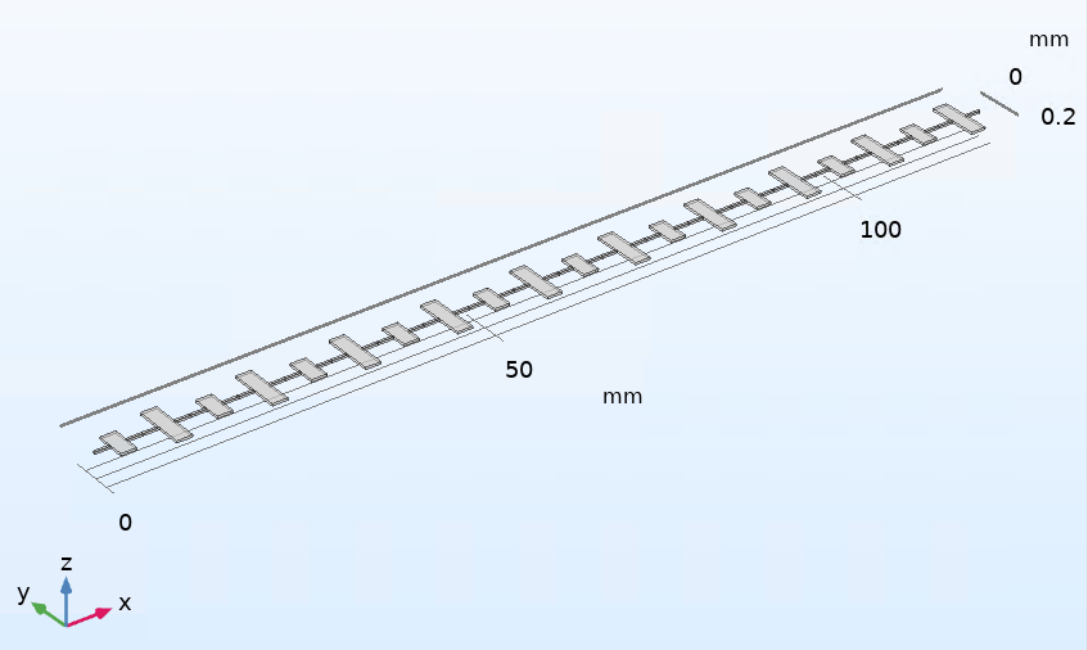
Full System Concept





Torsional Resonator

- Fails to account for coupling of modes
- Butterfly modes of the disk are transverse, will not couple well to torsional oscillators



Torsional Resonator Results