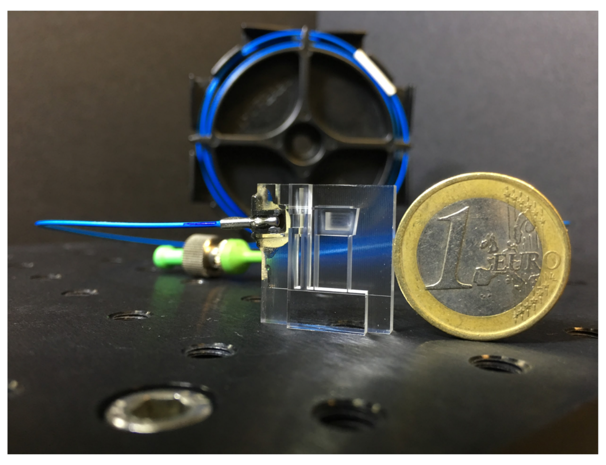
THE UNIVERSITY OF ARIZONA
College of Optical Sciences

Optomechanical Resonators and Finite Element Analysis

PIs: F. Guzmán (UA), D. Wilson (UA)
Team: E. Clark, J. Gillis, A. Hines, A. Laurain, C.M. Pluchar, L. Richardson, H. Wisniewski

Motivation

Developments in optomechanical devices have yielded compact high-Q optomechanical resonators capable of sensitive displacement measurements, and by extension accelerations [1,2]. At a macroscopic scale these resonators utilize an integrated a Fabry-Perot cavity which can be optically interrogate test-mass displacement, yielding applications to gravitational wave detection, gravimetry and hybrid sensing with atom interferometers. At a mesoscopic scale, extremely high-Q resonators fabricated from high-stress silicon nitride films can be integrated with optical cavities [3] used to observe quantum effects such as radiation pressure shot noise or cooling a mechanical resonator near its motional ground state [4]. In this work we focus on development, improvement and application of compact optomechanical systems. We model the performance of these devices using finite element analysis, and subsequently experimentally verify the results. Small displacement signal is enhanced through the use of an optical Michaelson interferometer.



The monolithic fused silica resonator shown above with a Euro coin for scale.

Optomechanics

High precision experiments require, at their core, sensors capable of measuring vibrations, acoustics, seismic or spurious forces acting on the test platform. While improvements in size and cost have been introduced by semiconductor based MEMS devices, breakthroughs in sensitivity have not transferred to commercial devices. Low loss, highly stable micro-mechanics combined with micro-optical sensors of unprecedented performance are being developed and merged with atom interferometers in order to enhance their performance and capabilities of deployment in environment exhibiting large seismic perturbations.

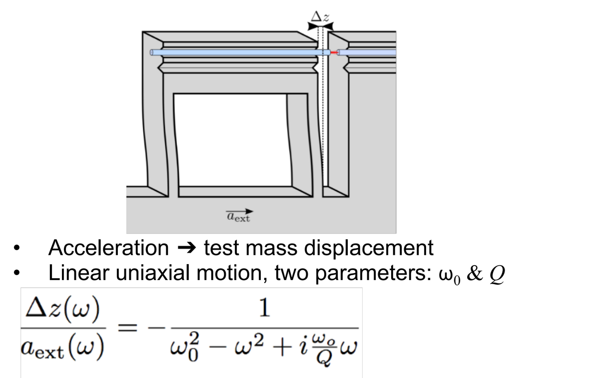


Fig. 1: Mechanical oscillator. We have demonstrated *mQ* up to 50 kg.

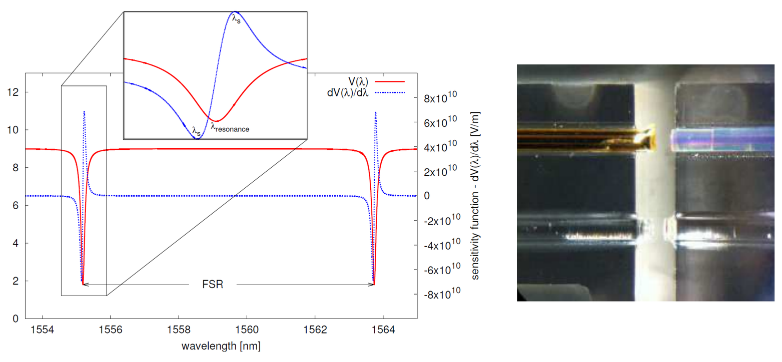


Fig. 2: Fabry-Pérot micro-cavities.

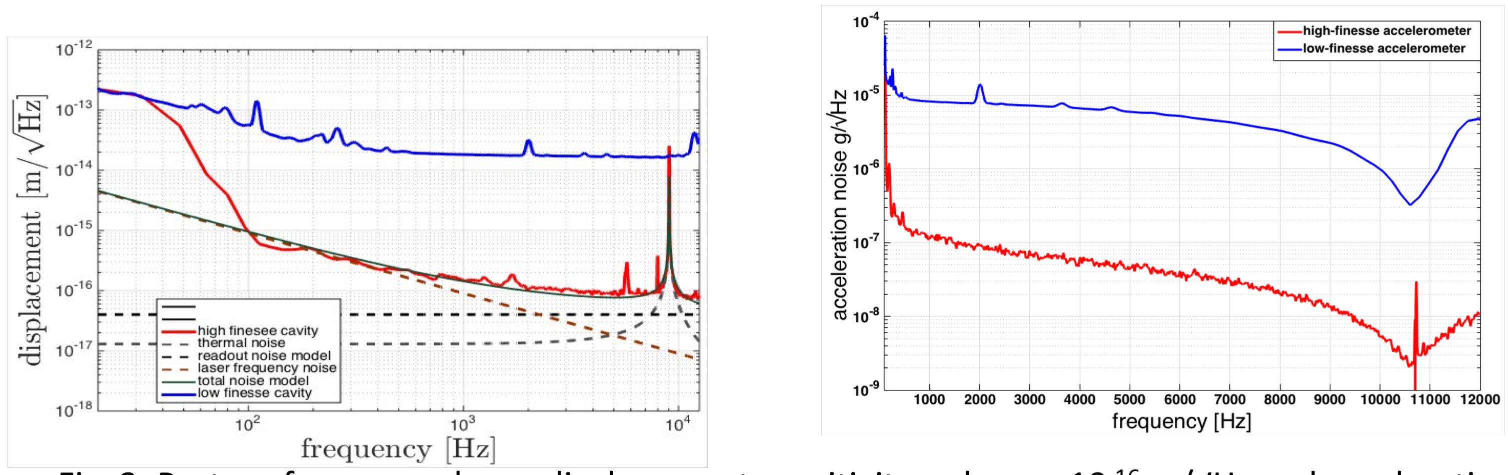
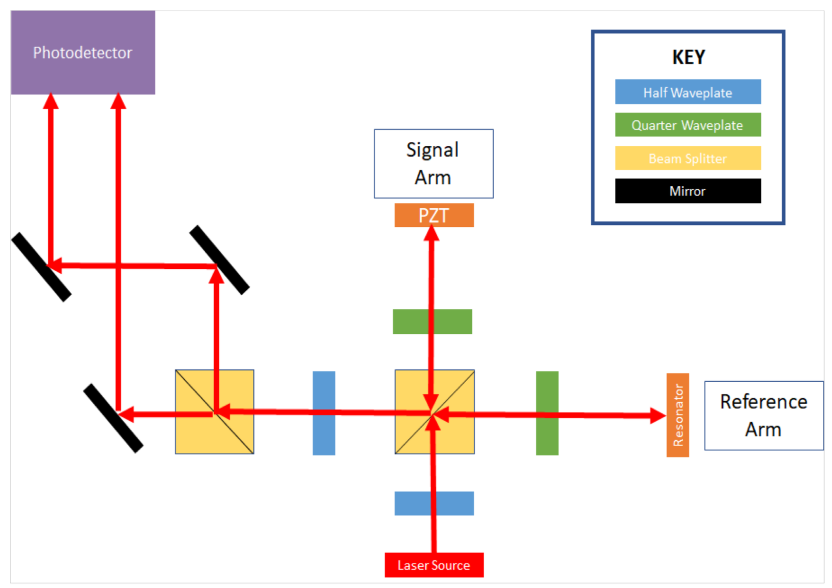


Fig. 3: Past performance shows displacement sensitivity as low as 10^{-16} m/√Hz and acceleration noise floor of 10^{-8} ms^{-2}/√Hz.

Enhancement of Mechanical Motion

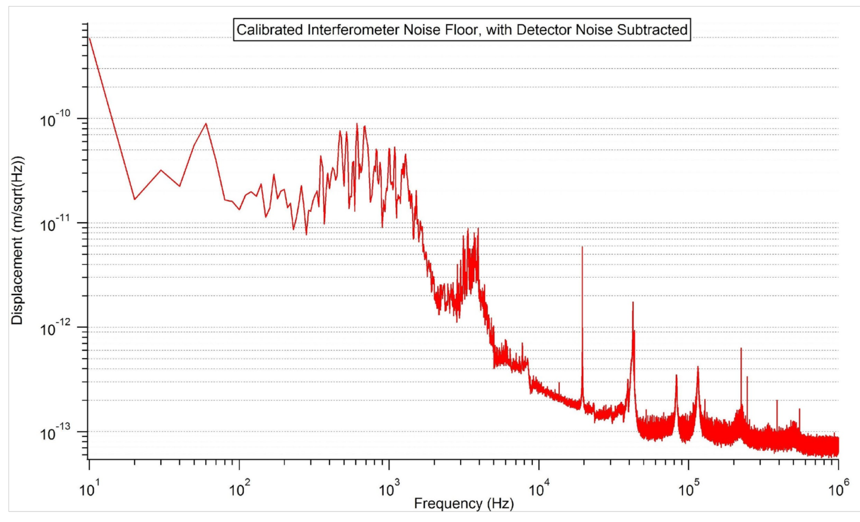
To increase signal to noise for small displacements of the test mass, signal from the optomechanical resonator is enhanced through use of a Michelson interferometer. To combat the effects of intensity noise, balanced detection is performed.



Interferometer Performance

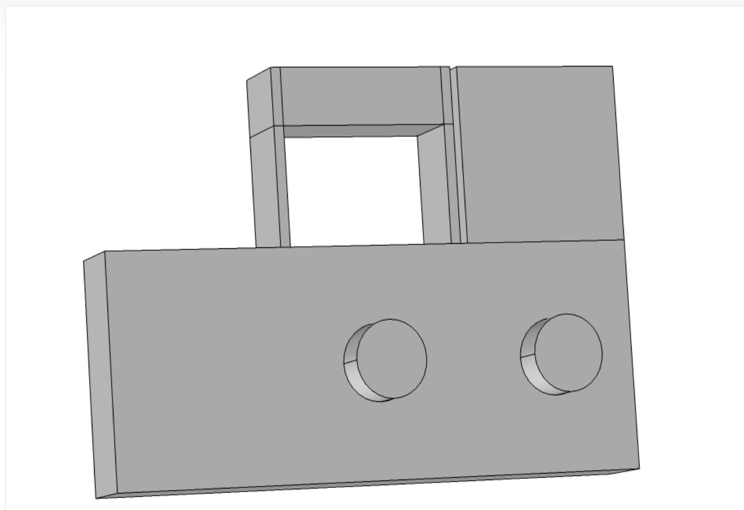
Calibrated interferometer noise floor for use with mechanical resonators with resonant frequency of $\omega_0 \cong 100$ kHz. It is able to resolve the thermal motion of the resonators. A version optimized for characterizing resonators with resonance of ~1 kHz is currently being built.

$$a_{th} = \sqrt{\frac{4k_B T\omega_0}{mQ}}$$

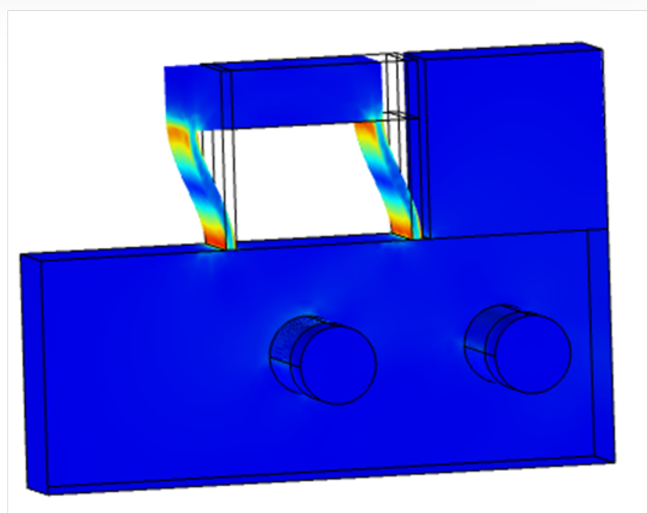


COMSOL Simulations and Finite Element Analysis

- Several factors affect the resonance frequency and quality factor of optomechanical resonators, such internal damping and phonon tunneling to support structures.
- Sensitivities of devices containing these resonators is heavily dependent on how the resonators are implemented.
- Resonators are being modeled in COMSOL, a finite element analysis software.
- Using COMSOL, we can predict eigenfrequencies and quality factors of resonators for different geometries, materials, and mounting methods.
- These models used to optimize optomechanical resonator implementation to achieve higher sensitivity in sensing devices.

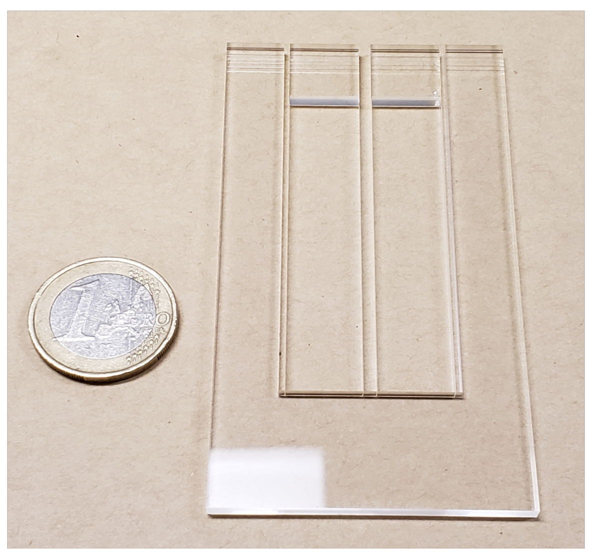


Model of a mechanical resonator created in COMSOL.



Analysis of the *von mises* stress in the model on the left.

Optomechanical Devices in Development



A 10 Hz optomechanical oscillator. A Euro is shown for scale.

•Inertial sensors
- Compact multi-DOF highly sensitive sensors.
- Optomechanical inertial navigation systems.

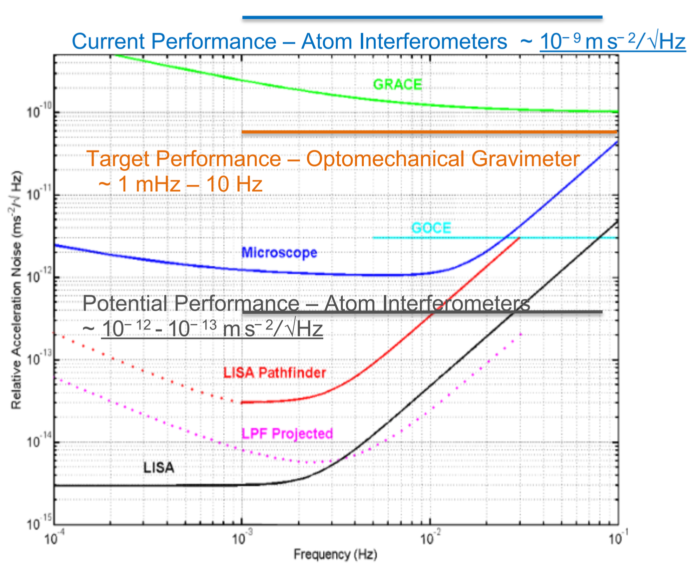
•Gravimeters and gradiometers
- Cost-effective, small and lightweight.
- Simple robust geometry.
- Ideal for space applications.

•Gravimetric Optomechanical Laser (GOL)
- Construction of VECSEL on fused-silica optomechanical resonator.
- Measurement dynamics of test mass through VECSEL frequency changes.

•Hybrid atom-interferometer optomechanical systems
- Combine zero drift of atom interferometers with high sensitivity and broad bandwidth of opto-mechanics.

Outlook

- **LIGO – Laser Interferometer Gravitational-Wave Observatory**
  - Group is a full member of the LIGO Scientific Collaboration (LSC)
  - Planned research:
    - Development of optomechanical inertial sensors
    - Seismic sensors for LIGO platforms and suspensions
    - Development of optomechanical inertial sensors for cryogenic environments: LIGO Voyager, Einstein Telescope
- **LISA – Laser Interferometer Space Antenna**
  - Group is a full member of the LISA consortium
  - Expertise in many aspects of the optical metrology for LISA and LISA Pathfinder.
  - Expertise in developing ground support equipment (GSE) for mHz laser interferometry
  - Ground testing of LPF optical metrology system: EM and FM
  - Thermal-vacuum tests of LISA Pathfinder



References

[1] Guzmán F., Kumanchik L., Pratt J., and Taylor J. M. (2014). "High sensitivity optomechanical reference accelerometer over 10 kHz". In: Applied Physics Letters Vol. 104, No. 22, p. 221111. doi: 10.1063/1.4881936.
[2] Gerberding O., Guzmán F., Melcher J., Pratt J. R., and Taylor J. M. (2015). "Optomechanical reference accelerometer". In: Metrologia Vol. 52, No. 5, p. 654. doi: 10.1088/0026-1394/52/5/654.
[3] D. Wilson *et al.* Phys. Rev. Let.. 103 (2009), 207204. https://doi.org/10.1103/PhysRevLett.103.207204
[4] D. Wilson *et al.* Nature 524 (2015) 325-329. https://doi.org/10.1038/nature14672