Controlling Micro-Trampolines with Light

A Guitarist's Guide to Optomechanics

Introduction
• Membranes are tuning forks
• Optical cavities are guitar strings
• Mechanical damping is annoying

Optomechanics Experiments
• Laser cooling
• Current goal: optically-levitated membranes, sorta
Why am I Interested?

**Exquisite Force Detection (?)**: The best detectors see the best stuff.

**New Knob to Turn**: Optically tune a solid object's mechanical properties

**“Quantum” Stuff**: Lasers can make motion of solids “Quantum”

Grütter Lab measuring forces of individual atoms
Penrose: “Gravity might ruin quantum mechanics for heavy objects.”
Mechanical Resonator: 1,000,000 Hz
0.000000005 grams (50 nm thick)

Mechanical Resonator: 440 Hz
about 50 grams
Membrane Basics: Damping

Rings for a few seconds (about a million cycles)

= 

Rings for a few seconds (about a thousand cycles)

= 

energy
Membrane Basics: Damping

Rings for a few seconds (about a million cycles) = Rings for a few seconds (about a thousand cycles) = LIES and HALF-TRUTHS

energy
“Thermal Fluctuations”: Damping is a Two-Way Street

Rings for a few seconds (about a million cycles) =
Rings for a few seconds (about a thousand cycles)

= 

energy

=
“Thermal Fluctuations”: Damping is a Two-Way Street
“Thermal Fluctuations”: Damping is a Two-Way Highway

Simulation:
Implications for Technology

Mechanical Force Detectors: minimize noise from environment
Implications for Technology

Quantum Information Storage: Minimize randomization from thermal noise

Problem

“superposition”

information transfer

photon

Minimize me!
Why is There Damping?

Limits of Mechanical Devices
- Connection to frame (& earth)
- Pushing air molecules (sound)
- Flexing materials generates heat

Drumhead Vibrations
Solutions to Damping

Connection to frame (& earth)
- Traditional engineering / black magic

Pushing air molecules (sound)
- Remove air (vacuum)

Flexing materials generates heat
- Traditional engineering / black magic
- Replace materials with laser light
  predicted to ring for weeks!
Solid Objects Controlled by Photons

- kg
- g
- μg
- ng
- pg

- Nanotubes, BEC's, atoms...

- LIGO
- MIT
- ENS
- Vienna
- JILA, Caltech
- NIST-JILA
- UCSD, Leiden
- Lausanne
- Lausanne-LMU
- Oregon
- Yale
- UCSD
- LMU
- Yale (this talk)
- UMichigan
Solid Objects Controlled by Photons

Most Devices =

nanotubes, BEC's, atoms...

kg

NIST-JILA, Caltech

Laussane-LMU

Laussane

20 μm

UMichigan

UCSB, Leiden
Optomechanical Systems Are Guitars: Same Physics

Electric Field ~ Zero (i.e. "clamped")

Single Frequency:
200,000,000,000,000 Hz

Speed of Light:
300,000,000 m/s

String Motion ~ Zero (clamped)

Single Frequency:
440 Hz

Speed of Sound:
500 m/s

Embarrass self...
Optomechanical Systems Are Guitars: Same Physics

Both “Cavity” Systems:
- mostly-clamped ends, one clamp’s position can change
- resonant or “preferred” cavity frequency depends on length
- driven by single-frequency

Electric Field ~ Zero (i.e. “clamped”)

Single Frequency:
- 200,000,000,000,000 Hz

Speed of Light:
- 300,000,000 m/s

Speed of Sound:
- 500 m/s

Embarrass self...
(sorry)
When the Input Frequency Matches the Cavity Frequency

- 5 micronewtons
- weight of 100 grains of salt
- push a paper clip 1 cm in 2 seconds (in space)

~milliwatt input (weak laser pointer)

~ kilowatt circulating

more light = more force

less light = less force

a spring! (plus “wind”)
Surprisingly Stiff Photons

- Optical cavity
- One gram-scale mirror is free to swing (~170 Hz)
- “Optical spring” stiffens these vibrations to 5,000 Hz
- Column of light is stiffer than diamond (but brittle, “windy”)

T. Corbitt et. al., PRL (2007)
Laser Engines

Takes time for light to leak in and out

cavity light pumps mirror motion
“Damping” for this Optical Spring

Motion can be very close to **absolute zero**!

Power takes time to ramp up and down

Mirror motion pumps cavity light

“Laser Cooling”
“Damping” for this Optical Spring...

Power takes time to ramp up and down.

Mirror motion pumps cavity light, "Laser Cooling."

Motion can be very close to absolute zero!
At Yale: Laser Cooling in Cryogenic Environment

- 50 nanometer thick membrane, 1.5 x 1.5 mm², 261 kHz drumhead, $Q = 5$ Million
- System starts at 0.4 °C above absolute zero (i.e. 0.4 “Kelvin”)
- Shoot laser down a tube.
Test: Laser Cooling to Very Low Temperature

(Preliminary) Laser Cooling

Laser cooling to $0.0002$ K ($\approx$ factor of 40 above quantum minimum energy)

Next: vibration isolation, smaller membrane

- Should achieve $< 0.0000001$ K: motion limited by laws of quantum mechanics
- “fun”, also a milestone toward:
  - photon information transfer
  - “superposition”

Membrane Motion:
- $\approx 0.0000000000000002$ meters
- $\approx$ the width of a fat nucleus
Complete Analogy: “Tuning Fork Cooling” of Fingers

Motion could be cooled by a tuning fork.
This does not change the thermal noise!

Options:

• Continue Traditional Materials / Geometry Engineering

• **Replace material with photons (main goal in ERP B024)**
Direct Optical Levitation

Using light as a “material” support

- Circumvents traditional material limitations
- Predicted to rings for weeks when struck.

proof-of-principle experiment

D.E. Chang et. al. PNAS (2010)
O. Romero-Isaart et. al. NJP (2010)

T. Lee et. al. Science (2010)

...also A. Ashkin (1976)
Another Solution: Make Radiation the Dominant Force

- Create weakly-tethered, lightweight, floppy trampolines
- Add a very strong optical spring (with no "wind" or engine problem)
- Predicted to achieve similar performance (but no launching required)

Bouwmeester Group
UC Santa Barbara

balanced
Goals that Fit in a Storage Closet

Christoph
- Design and fabricate lightweight, floppy objects
- Assemble new UHV optical trapping system

Alexandre, Chris, Perry
- UHV rapid device characterization interferometer

Xinyuan, Julian
- Mechanical simulations
- Photonic crystal simulations
Additional Directions

Develop Practical Force Sensors
Cryogenic System to Reduce Thermal Noise
Compact Optical Fiber Packages
Diamond Mechanical Elements
Hybrid Quantum Systems

1. 100x smaller: lighter MEMS & higher per-photon impact, stronger coupling
2. Higher frequencies: less laser noise, fewer thermal phonons
3. No free-space optics (good for cryostat!)

Reichel-Style Cavity
- cleaved, coated optical fiber
- 250-micron membrane

Harris Lab
Summary

Basically I study slide guitars
- Laser springs
- Laser cooling

Research agenda
- Optically-supported objects with very low dissipation
- Sensing applications
- Hybrid quantum systems

McGill Optomechanics Lab
Christoph Reinhardt, Alexandre Bourassa
Xin Yuan Zhang, Julian Self, Chris McNally
Perry Phillipopoulos, Jack Sankey
Harris Lab Acknowledgments

**Experiment**
Jack Harris (P.I.)
Andrew Jayich
Benjamin Zwickl
Cheng Yang
Donghun Lee
Nathan Flowers-Jacobs
Scott Hoch
Woody Underwood
Lily Childress
Anna Kashkanova
Andrei Petrenko

**Theory**
Steve Girvin (P.I.)
Kjetil Børkje
Andreas Nunnenkamp