Quantum States of Light and Giants

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Ponderomotive predominance

- An experimental apparatus in which radiation pressure forces dominate over mechanical forces
- Ultimate goals
  - Generation of squeezed states of light
  - Quantum ground state of the gram-scale mirror
  - Mirror-light entanglement?
- En route
  - Optical cooling and trapping
  - Diamonds
  - Parametric instabilities
- Disclaimer
  - Any similarity to a gravitational wave interferometer is not merely coincidental. The name and appearance of lasers, mirrors, suspensions, sensors have been changed to protect the innocent.
Radiation pressure - mirror oscillator coupling
Radiation-oscillator coupling

→ Amplitude-phase correlations

1. Light with amplitude fluctuations \( \Delta A \) incident on mirror

\[
\hat{H} = \hbar \omega_0 \hat{b}^\dagger \hat{b} + \hbar \Omega_{osc} \left( \hat{Q}^2 + \hat{P}^2 \right) - 2 \hbar G \hat{b}^\dagger \hat{b} \hat{Q} + i \hbar E \left( \hat{b}^\dagger e^{-i \omega t} - \hat{b} e^{i \omega t} \right)
\]

2. Radiation pressure due to \( \Delta A \) causes mirror to move by \( \Delta x \)

3. Phase of reflected light \( \Delta \phi \) depends on mirror position and hence light amplitude, i.e. \( \Delta A \) and \( \Delta \phi \) fluctuations correlated
A “ponderomotive” squeezing source

Key ingredients

- Low mass, low noise mechanical oscillator mirror – 1 gm with 1 Hz resonant frequency
- High circulating power – 10 kW
- High finesse cavities 8000
- Differential measurement – common-mode rejection to cancel classical noise
- Optical spring – noise suppression and frequency independent squeezing
Optical springs

- Measuring radiation pressure induced squeezing requires high displacement sensitivity.
- The sensitivity requirement can be relaxed by using an oscillator (with some stiffness) instead of a free test mass.
- But stiff mechanical springs introduce large thermal noise → bad!
- Stiff optical springs do not change thermal force spectrum.

\[ S_F \propto 4k_B T \Gamma_m \]

Connect a high Q, low stiffness mechanical oscillator to a stiff optical spring.
- Detune a resonant cavity to higher frequency (blueshift)
- Opposite detuning than cold damping
- Real component of optical force → restoring
- But imaginary component (cavity time delay) → anti-damping
- Unstable
- Stabilize with feedback
### Assumed experimental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>Light wavelength</td>
<td>$\lambda_0$</td>
<td>1064</td>
<td>nm</td>
<td>Input mirror trans.</td>
<td>$T_{ITM}$</td>
<td>$4 \times 10^{-4}$</td>
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<td>Input mirror mass</td>
<td>$M_{ITM}$</td>
<td>0.25</td>
<td>kg</td>
<td>End mirror mass</td>
<td>$M_{ETM}$</td>
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<td>g</td>
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<tr>
<td>Arm cavity finesse</td>
<td>$\mathcal{F}$</td>
<td>$1.6 \times 10^4$</td>
<td>–</td>
<td>Loss per bounce</td>
<td>–</td>
<td>$5 \times 10^{-8}$</td>
<td>–</td>
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<tr>
<td>Input power</td>
<td>$I_0$</td>
<td>1</td>
<td>W</td>
<td>Arm cavity detuning</td>
<td>$\delta$</td>
<td>$10^{-5}$</td>
<td>$\lambda_0$</td>
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<tr>
<td>BS refl. imbalance</td>
<td>$\Delta_{ES}$</td>
<td>0.01</td>
<td>–</td>
<td>Mich. phase imbalance</td>
<td>$\Delta \alpha_M$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mich. loss imbalance</td>
<td>$\Delta \varepsilon_M$</td>
<td>–</td>
<td>–</td>
<td>Input mirror mismatch</td>
<td>$\Delta_T$</td>
<td>$5 \times 10^{-6}$</td>
<td>–</td>
</tr>
<tr>
<td>Detuning mismatch</td>
<td>$\Delta \delta$</td>
<td>$10^{-7}$</td>
<td>$\lambda_0$</td>
<td>Arm cavity loss mismatch</td>
<td>$\Delta \xi$</td>
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<td>Susp. resonant freq.</td>
<td>$\Omega_0$</td>
<td>1.5</td>
<td>Hz</td>
<td>Susp. mech. loss angle</td>
<td>$\phi$</td>
<td>$10^{-6}$</td>
<td>–</td>
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<tr>
<td>Laser intensity noise</td>
<td>–</td>
<td>$10^{-8}$</td>
<td>Hz$^{-1/2}$</td>
<td>Laser frequency noise</td>
<td>–</td>
<td>$10^{-4}$</td>
<td>Hz/$\sqrt{\text{Hz}}$</td>
</tr>
</tbody>
</table>

Noise budget

The experiment
Experimental progress

- Experiment carried out in three phases
  - Phase I → linear cavity with two 250 g suspended mirrors, finesse of 1000, ~4 W of input power
  - Phase II → cavity with one 250 g and one 1 g suspended mirror, finesse of 8000, ~5 W of input power
  - Phase III → two identical cavities phase II and Michelson interferometer
Phase II cavity
- Steel shell of same diameter as LIGO auxiliary optics
- Suspended with magnets (actuation), standoffs (thermal noise)
- Mini mirror attached by two 300 micron fused silica fibers
Double suspension for mini mirror
Locking scheme

- Lock cavity with a frequency shifted subcarrier on resonance
- Frequency shift between carrier and subcarrier determines detuning
- Allows for large carrier detuning and acquiring lock at high power
Experimental results

Extreme optical stiffness
Stable optical trap
Optically cooled mirror
Extreme optical stiffness...

- How stiff is it?
  - 100 kg person
    - $F_{\text{grav}} \sim 1,000 \, \text{N}$
    - $x = F / k = 0.5 \, \text{mm}$
- Very stiff, but also very easy to break
  - Maximum force it can withstand is only $\sim 100 \, \mu \text{N}$ or $\sim 1\%$ of the gravitational force on the 1 gm mirror
- Replace the optical mode with a cylindrical beam of same radius (0.7 mm) and length (0.92 m) → Young's modulus $E = KL/A$
  - Cavity mode 1.2 TPa
  - Compare to:
    - Steel $\sim 0.16 \, \text{TPa}$
    - Diamond $\sim 1 \, \text{TPa}$
    - Single walled carbon nanotube $\sim 1 \, \text{TPa}$ (fuzzy)

$5 \, \text{kHz} \Rightarrow K = 2 \times 10^6 \, \text{N/m}$

Cavity optical mode → diamond rod

![Graph showing displacement/force relationship with frequency](image)
Stable Optical Trap

- Two optical beams $\rightarrow$ double optical spring
  - Carrier detuned to give restoring force
  - Subcarrier detuned to other side of resonance to give damping force
  - Independently control spring constant and damping

T. Corbitt et al., submitted (Nov. 2006)
Optical cooling

\( \frac{1}{2} k_B T_{\text{eff}} = \frac{1}{2} K x_{\text{rms}}^2 \)

- Increasing subcarrier detuning

T. Corbitt et al., submitted (Nov. 2006)
Quantum states of a giant

1 gm mirror $\rightarrow 10^{22}$ atoms
Reaching quantum ground state

- Number of quanta in mode
  \[ N = \frac{k_B T_{\text{eff}}}{\hbar \Omega_{\text{eff}}} \]
  \[ N \rightarrow 1 \]

- Decoherence time
  \[ \tau = \frac{2\pi}{\Gamma_{\text{eff}}} \left( \frac{k_B T_{\text{eff}}}{\hbar \Omega_{\text{eff}}} \right)^{-1} \]

- Number of oscillations before mode decays
  \[ \bar{n} = \left( \frac{k_B T_{\text{eff}} \Gamma_{\text{eff}}}{\hbar \Omega_{\text{eff}} \Omega_{\text{eff}}} \right)^{-1} \]
  \[ \bar{n} > 1 \]

Optical spring \[ \rightarrow \bar{n} \text{ increases} \]

Cold damping \[ \rightarrow \bar{n} \text{ conserved} \]
Cool mirror

- **Without optical trap**
  \[ \Omega_{\text{eff}} = \Omega_m = 2\pi \times 172 \text{ Hz} \quad T = 295 \text{ K} \]
  \[ \Gamma_{\text{eff}} = \Gamma_m = \Omega_m / Q_m \sim 0.3 \quad \bar{n} = 10^{-7} \]

- **With optical trap**
  \[ \Omega_{\text{eff}} = 2\pi \times 1800 \text{ Hz} \quad T = 0.8 \text{ K} \]
  \[ \Gamma_{\text{eff}} = \Omega_{\text{eff}} / Q_{\text{eff}} \sim 1885 \quad \bar{n} = 7 \times 10^{-7} \]

\( \bar{n} \) increased by factor of 7
Cold damping cannot change \( \bar{n} \)
Breaking news
(Corbitt, Wipf and Bodiya, 12/11/2006)
Cooler mirror

- Lower frequency mechanical resonance \( \rightarrow 13 \text{ Hz} \)
- Shorter cavity (0.1 m) \( \rightarrow \) less frequency noise
- Some acoustic features (beam clipping?)
- Electronic damping
- "Heating" spectra \( \rightarrow \) suppression of injected motion

\[
\begin{align*}
\Omega_{\text{eff}} &= 2\pi \times 1000 \text{ Hz} \\
\Gamma_{\text{eff}} &= \Omega_{\text{eff}} / Q_{\text{eff}} \sim 6000 \\
T_{\text{eff}} &= 6 \text{ mK}
\end{align*}
\]

- \( Q = 5, \ T_0/T = 6.7 \)
- \( Q = 5, \ T_0/T = 670 \)
- \( Q = 12, \ T_0/T = 4000 \)
- \( Q = 5, \ T_0/T = 11000 \)
- \( Q = 1, \ T_0/T = 40000 \)

- \( \bar{n} = 1 \times 10^{-4} \)
- \( N = 1 \times 10^5 \)
- Cooling factor \( = 4 \times 10^4 \)
Cold mirror

- Back to ponderomotive experiment with two cavities
- Without optical trapping
  \[ \Omega_{\text{eff}} = \Omega_m = 2\pi \times 1 \text{ Hz} \quad T = 295 \text{ K} \]
  \[ \Gamma_{\text{eff}} = \Gamma_m = \frac{\Omega_m}{Q_m} \sim 10^{-6} \quad \bar{n} = 10^{-7} \]
- With optical trap at 1 kHz
  \[ \Omega_{\text{eff}} = 2\pi \times 1 \text{ kHz} \quad T = 3 \times 10^{-6} \text{ K} \]
  \[ \Gamma_{\text{eff}} = \frac{\Omega_{\text{eff}}}{Q_m} \sim 10^3 \quad \bar{n} = 0.1 \]

\[ T_{\text{eff}} = \frac{\hbar \Omega_{\text{eff}}}{k_B} \sim 5 \times 10^{-8} \text{ K} \]
Lessons learned so far...
Parametric instability

Acoustic drumhead modes (28 kHz, 45 kHz, 75 kHz, …) become unstable when detuned at high power

- Viscous radiation pressure drives mode \( \rightarrow \) parametric instability
- Detuning in opposite direction reduces \( Q \) of the mode \( \rightarrow \) cold damping
- Mode stabilized through feedback to laser frequency

\[
\tau_{\text{eff}} = \frac{\tau}{1-R}
\]

\( R \) now greater than 100

What's next...
Next steps

- Second cavity for noise cancellation
- Low noise oscillator
  - Suspended as 1 Hz pendulum with desired Q
    ~ $10^6$
  - 12.7 mm diameter, 3 mm thickness
  - Magnets for actuation
    - 3 mm displacement from dc radiation pressure
  - Ultrahigh vacuum compatible
  - Fabrication challenges
- Eddy current damping (undesirable)
OSEM assemblies

Hole for transmitted light

Optical Sensor EM actuator for 0.25 kg input mirror (roughly to scale)

OSEM assemblies

Safety “catcher”

5 OSEMs in less space than a single LIGO OSEM
25 micron music wire. Actual wire to be used is 5 micron tungsten.
In principle...

- Present limit from laser frequency and VCO noise
- Expect 1000x suppression of this with second cavity (to be installed in Jan. 2007)
- Output light squeezing
  - Suspension and coating thermal noise low enough?
  - Optical losses low enough?
- Cooling
  - Temperature drops as noise$^2$ $\rightarrow$ expect to get to $\mu$K
  - Within factor of 10 to 100 of occupation number = 1
  - Prospect of seeing quantum behavior of an object with $10^{22}$ atoms by coupling it to an optical field with $10^{15}$ photons
Ultimate limit

- Our present measurement is limited by frequency noise of the laser
- Ultimate limit comes from the quantum noise of the optical fields
- What else might we measure?
  - Discrete energy levels?
  - Entanglement?
    - Between carrier and mirror?
    - Between subcarrier and mirror?
    - Between carrier and subcarrier coupling through mirror?
    - Bipartite entanglement vs. tripartite entanglement?
In conclusion

- Radiation pressure effects observed and characterized in system with high optical power and 1 gram mirror
  - Extreme optical stiffness
  - Free and stable optical spring
  - Optical trapping technique that could lead to direct measurement of quantum behavior of a 1 gram object
  - Parametric instabilities (photon-phonon coupling)
  - Control system interaction
  - Testing extremely high power densities on small mirrors (20 kW in cavity $\rightarrow$ 1 MW/cm$^2$)
    - Nothing has blown up or melted (yet)
- Establish path to observing radiation pressure induced squeezed light and quantum states of truly macroscopic objects
The End

NSF
LIGO Lab
Thorne, Girvin, Harris