Cryogenic optomechanics with microtoroids

Olivier Arcizet
Rémi Rivière - Albert Schliesser
Georg Anetsberger - Tobias Kippenberg

Max Planck Institut for Quantum Optics - Garching
Microtoroids for Optomechanics

- Optical finesse: $10^6$
- Optical Q: $10^8$
- FSR: 1 THz
- Linewidth: 1 MHz

Radial breathing mode
- Frequency: 60 MHz
- Effective mass: 10 ng
- Mechanical Q: $>50,000$

Efficient optical coupling with tappered fibers
Broadband displacement sensing

Phase noise analysis of the transmitted optical field
Reduction of the clamping losses

Non trivial dependence of the mechanical damping on the silicon pillar size. Observation of mechanical modes avoided crossings
New generation of optomechanical toroids

Efficient reduction of the clamping losses by structure engineering

Qm of 80 000 at 400 K for the radial breathing mode
(mainly limited by intrinsic dissipation of glass)

Nature photonics, 2008
Optical cooling /heating the mechanical oscillator with a red/blue detuned laser.

Analog to laser cooling of ions

Resolved sideband regime

\[ \kappa \ll \Omega_m \]

-> optical back action does not prevent from reaching the ground state

(Doppler temperature: \( \hbar \kappa \leq \hbar \Omega_m \))

-> reducing the heating induced by light absorption

-> addressing individual modes
Resolved sideband cooling

- Intense cooling laser (red detuned)
  780 nm, very high optical Q

- Weak probe laser (resonant)
  1064 nm (lower optical Q)
Cryogenic apparatus

Chamber filled with an exchange gas for thermalizing microstructures

.01 to 100 mbar of Helium down to 1.6 K
Displacement sensing at low light intensity

- Low perturbation below 1 µW
- Dynamical back action significant above 10 µW
- Damages: 10 mW burns the fiber at 1.6 K and 100 mbar

Pound Drever Hall for locking and measuring (phase sensitive detection)

Using an EDFA allows to work with 50 nW (1550 nm, 3 dB above ideality)

Combined with low noise fiber laser (Koheras) 15 dB of signal to noise at 1.6 K with 100 nW
Thermalisation of the toroids

Mechanical noise thermometry

Equipartition:

$$\frac{1}{2} M \Omega_m^2 \Delta x^2 = \frac{1}{2} k_B T$$

(10 mbar, 1 µW)

F= 1e5 (30 MHz linewidth)

Resonantly probing the cavity

Less than .2 K of heating

For approximately 100 mW intracavity

540 initial thermal phonons at 65 MHz

Good thermalisation of the microstructures thanks to the buffer gas
Optical frequency shift

No degradation of the optical Q observed

+100 MHz/K @ 2K
(nb: - 2 GHz/ K @ 300 K)

\[ \frac{1}{\nu} \frac{d\nu}{dT} = -\frac{1}{R} \frac{dR}{dT} - \frac{1}{n} \frac{dn}{dT} \]
Thermal expansion  
Thermorefractive effect

Reversed dn/dT
- Significant contribution from Helium gaz
  (under varying pressure conditions)

- Silica’s contribution (?)  
  Possible effect of TLS in glass  
  (no measurement available)

-> Reversed thermal bistability  
  with “stable red side”
Optical Multistability

For higher input optical powers, observation of a tristability when $T_{\text{eff}} > 11\, \text{K}$

Good agreement with simulations

It provides an estimation of the light induced static heating.

$4\, \text{K}/\text{W}$

(or $\text{Pin} = 1\, \text{mW}$ for $F=1\times10^6$)

Limitation on the final phonon number.

Field:

$$\frac{1}{\Omega_c} \frac{d}{dt} \tilde{\alpha}(t) = (-1 + i\varphi(t))\tilde{\alpha}(t) + 1,$$

$$\varphi(t) = \varphi_0(t) + \varphi_{\text{nl}}(T_0 + \delta T(t))$$

Effective temperature:

$$\frac{\partial}{\partial t} \delta T(t) + \Omega_{\text{th}} \delta T(t) = \beta \alpha_{\text{max}}^2 |\tilde{\alpha}(t)|^2$$
Resolved sideband optical and cryogenic cooling

Combinaison of both cryogenic and optical cooling

Low noise Ti Sapphire laser
Displacement sensitivity:
$10^{-19}$ m/Hz$^{.5}$
Limited by quantum phase noise

88 000 phonons at 296 K
600 phonons at 1.6 K
62 phonons with 500 µW

(1.4 % of chance to be in the ground state)

Upper value for the sensor ideality:

$$S_x \cdot S_F \leq \frac{\hbar^2}{4}$$

Optical systems now operates on par with electro-mechanical devices (SSET, SQUIDS)
Superfluid Helium layer

Apparition of a superfluid layer (ca. 30 nm)

70 mbar, 2 K

Better heat extraction in presence of the superfluid layer
(faster : 100 kHz bandwidth observed)

But degradation of the mechanical properties
Phonon coupling to silica structural defect states

Non trivial temperature dependence of the mechanical damping.

Relaxation mechanisms consecutive to phonon coupling to structural defect states of glass.
Modelized by an assembly of 2 level systems
Thermally activated (>10 K) and tunneling assisted (<10 K) relaxation regimes

Further improve at lower temperatures (Q > 50 000 possible at .5 K)
Resonant interaction between phonon and TLS

In addition to the relaxation mechanisms, there also exists a resonant interaction.

Now: around 5% of the total damping

But same order of magnitude for higher frequencies (500 MHz) or lower temperatures (.5 K)

Saturation of the TLS

Possibility to control the TLS state with a radio-frequency (50 MHz homogenous linewidth)

Mechanical echoes for probing the mechanical state
Optomechanically induced transparency

In the optical domain, “dressing of the cavity resonance”

Optomechanically induced transparency.

\[ H_{\text{int}} = 2\hbar k \sqrt{\frac{\hbar}{2M\Omega_m}} a^\dagger a (a_m^\dagger + a_m) \]

\[ \kappa = 2\pi \, 3.5 \text{ MHz}, \quad \Omega_m = 2\pi \, 50 \text{ MHz}, \quad \Gamma_m = 2\pi \, 15 \text{ kHz}, \quad m = 10 \text{ ng} \]
A near field optomechanical sensor

Nano-resonator

Toroid microcavity

Laser → Tapered fiber → Detection

SiN membrane

mirror image

50µm

toroid

taper
A near field optomechanical sensor

A tunable optomechanical coupling.

A highly sensitive optical sensor for nano-objects
(10^-16 m/sqrt(Hz) for 10 pg objects)

Observation of back action effects with evanescent fields

Attractive force for thin membranes

Total decoupling from mechanics and optics
- interest in nano-mechanics.
  (graphene, nanotubes,...)
Optomechanical devices now perform as well as electromechanical devices (SSET, squids,..) (easier quantum limited operation)

Optical multistability observed and characterized
-> estimation of light absorption

Sources of mechanical dissipation well understood in microcavities
Phonon –glass TLS coupling
Further improvements expected at higher frequencies and lower temperatures (He3 cryostat soon)

Investigation of resonant coupling of phonons with TLS
(saturation effects / echoes experiments / ...)

Other materials (crystaline resonators)