Optical Micro-cavities

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Toroidal micro-cavities

Developed in Caltech, 2003

- Whispering gallery mode
- Ultra high optical Q > $10^8$, Finesse > $10^6$
- Coupled with tappered fibers (evanescent field)
  Efficiency > 99%
Applications

- Frequency comb generation
- Biological sensor
- Optomechanics

3 projects:
Optical frequency comb generation

Generation of a broadband output spectrum, with a high efficiency.

Four waves mixing, cascaded mechanism, assisted by the cavity:

Reduced dispersion (material and wave guide)

Bright (1 mW per line)

High repetition rate (> 1 THz)

Nature 2007
Equidistance of the lines

Comparison line to line with a Fiber based reference comb (Menlo-Systems)

Accuracy relative to the optical carrier:
5.5 mHz / 200 THz = 3 \cdot 10^{-17}
Frequency comb stabilization

Regulation of the pump intensity -> control of the optical pathlength via the thermorefractive effect

Fast: 10 kHz bandwidth (for a thermal effect)

\[ \nu_n = \nu_{\text{pump}} + n \Delta \nu(P), \quad n \in \mathbb{Z} \]

\[ P = P(P^{\text{in}}, \nu_{\text{pump}}) \]

PRL, 2008
Développement de ``millitoroides“, taux de répétition telecom (88 GHz), mesurables sur une photodiode ultra-rapide (u2t).

Asservissement du peigne et comparaison à un peigne de référence.

Essai de callibration d’un spectromètre infrarouge du VLT à Garching (ESO à 500 m)
Analysis of the comb stability

Similar stability obtained with 2 fiber based reference combs
Microcavity dispersion analysis

The microcavity dispersion limits the spectral extension of the comb.

Development of a new technique to measure the dispersion, with a scanned diode laser and a reference comb.
Future directions

Third harmonic generation of a visible comb

Use for comb stabilisation

Same modespacing as the IR comb

Sensitive to the pump frequency detuning

Possible use for locking the offset frequency of the comb

What is the comb induced stability?
Biological sensor

Optical resonances highly sensitive to the toroid environment.

Deposition of a bilipid membrane on the toroid surface.

Observation of the first biological signals: Insertion of GM1 molecules in the membrane.

*Increased sensitivity* in order to study the single molecule adhesion dynamics. (1 kHz optical frequency shift).
Microtoroids for Optomechanics

Radial breathing mode

Frequency 60 MHz
Effective mass: 10 ng
Mechanical Q >100,000 @ 400 K
Monitoring very small displacements

Measurement of the phase of the reflected beam

Sensitivity enhanced by the use of a Fabry Perot cavity

Best sensitivities achieved (LKB): $\delta x \simeq 10^{-20} \text{ m/}\sqrt{\text{Hz}}$ @ 1 MHz
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 100 000 at 400 K
(mainly limited by intrinsic dissipation of amorphous silica)

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 quantum 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

Nature Physics, 2008
Optomécanique quantique

Atteindre le régime où les fluctuations de position du résonateur mécanique sont gouvernées par les propriétés quantiques de la lumière.

Effets quantiques de la pression de radiation
Optique quantique (QND)

Limites de sensibilité (application aux OG)

$\hbar \Omega_m \geq \frac{k_B T}{2}$

20 MHz $\leftrightarrow$ 1 mK
Resolved sideband cooling

- Intense cooling laser (red detuned) 780 nm, very high optical Q
- Weak probe laser (resonant) 1064 nm (lower optical Q)

Nature Physics, 2008
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:
\[ \frac{1}{2} M \Omega_m^2 \Delta x^2 = \frac{1}{2} k_B T \]

Efficient thermalisation of the microstructures thanks to the buffer gaz

(10 mbar, 1 µW)
F= 10^5 (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
Optical Multistability

Reversed optical frequency shift

$$\frac{1}{\nu} \frac{d\nu}{dT} = - \frac{1}{R} \frac{dR}{dT} - \frac{1}{n} \frac{dn}{dT}$$

Thermal expansion Thermorefractive effect

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

Estimation of the light induced static heating.

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

Limitation on the final phonon Number. But resolved sideband regimes helps
Resolved sideband optical and cryogenic cooling

Combinaison of both cryogenic and optical cooling

- 88000 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:

\[ S_x \cdot S_F \leq 230 \frac{\hbar^2}{4} \]

Optical systems now operates as well as electro-nanomechanical devices (SSET, SQUIDS)
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)
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
Superfluid Helium layer

Apparition of a superfluid layer (ca. 30 nm)

20 mbar, 2 K

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

But degradation of the mechanical properties
Superfluid Helium layer: oscillatory thermal response

Strongly modified thermal response of the cavity.
Signature of a thermal Fabry-Perot cavity.
Investigations still under progress.
A near field optomechanical sensor

A way to combine nanomechanics and optical quantum limited read out.

Optomechanics with evanescent fields

Observing the quantum radiation pressure effects at room temperature?

Force sensitivity of 10 aN/Hz^{1/2}
A near field optomechanical sensor

A purely dispersive coupling

Ultrahigh sensitivity with nanomechanical objects (fm/Hz $^{1/2}$)

Optical back action possible via optical dipolar forces.

Parametric instability observed.
Optomechanically induced transparency

In the optical domain, "dressing of the cavity resonance"

Optomechanically induced transparency.

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

\( \kappa = 2\pi 3.5 \text{ MHz}, \Omega_m = 2\pi 50 \text{ MHz}, \Gamma_m = 2\pi 15 \text{ kHz}, m = 10 \text{ ng} \)
The group

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Capacitive cooling
Frequency comb
Biosensor

Optomechanics
Conclusions

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 (crystalline resonators)
Cryogenic optomechanics with microtoroids

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SiO\textsubscript{2} film (2\textmu m) on a Si wafer

CO\textsubscript{2} reflow

Silica pads

Silica disk

Developed in Caltech, 2003

• Whispering gallery mode

• Ultra high optical Q > 10\textsuperscript{8}, Finesse > 10\textsuperscript{6}

• Coupled with tapered fibers (evanescent field) Efficiency > 99%
Optical frequency shift

No degradation of the optical Q observed

$+100 \text{ MHz/K } @ \text{ 2K}$
(nb: $-2 \text{ GHz/ K } @ \text{ 300 K}$)

$$\frac{1}{\nu} \frac{d\nu}{dT} = - \frac{1}{R} \frac{dR}{dT} - \frac{1}{n} \frac{dn}{dT}$$
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”
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-mecanics.
(graphene, nanotubes,...)