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Laser Cooling of a Micro-mechanical Oscillator

Scientists at Max Planck Institute of Quantum Optics achieve efficient cooling by the pressure of light

Quantum particles and macroscopic objects are often conceived as belonging to different worlds each ruled by its own laws of physics. It is however of utmost interest to explore the areas where these worlds meet, i.e. under which conditions quantum particles behave in a classical way and, on the other hand, macroscopic ("big") objects develop quantum properties.

A team of scientists around Dr. Tobias Kippenberg, leader of the Max Planck Junior Research Group "Laboratory of Photonics" at the Max Planck Institute of Quantum Optics (MPQ) has now succeeded in cooling a micro-mechanical oscillator consisting of more than 10^{14} molecules from room temperature (about 300 Kelvin) down to 11 Kelvin (- 260 degree Celsius) (Phys. Rev. Lett. 97, 243905). The novel method they applied is related to a laser cooling technique that is now widely used in atomic physics. The experiment showed unambiguously that the temperature reduction was purely caused by the radiation pressure of the photons. With this new method it could become possible to reach the quantum mechanical ground state of the system where its *eigen*-oscillations are reduced to the fundamental quantum mechanical limit. The method could also be used to enhance the performance of atomic force microscopes where thermally driven cantilever vibrations reduce sensitivity.

The conventional, atomic laser cooling technique mentioned above works as follows: atoms are irradiated with laser light of energy slightly below resonance. Hence the particles absorb the light whenever they travel towards the beam - only then they become resonant due to the Doppler effect - and are slowed down in this direction.

That radiation pressure can also cool a mechanical oscillator mode – by coupling the mechanical mode to a high finesse optical cavity – has been predicted theoretically first by the Russian Physicist Vladimir Braginsky. When light is confined in a cavity, and the average photon cavity dwell time is comparable to the mechanical oscillation period, significant retardation effects occur: which allow both amplifying and cooling the mechanical oscillator. These phenomena - both cooling and amplification of mechanical modes – are two sides of one coin: they are a manifestation of *dynamical back-action*. Dynamical back-action has in particular been under scrutiny in the Laser Interferometer Gravitational Wave Observatory (LIGO) as it disturbs the underlying principle: displacement measurements inside an optical resonator. However reaching the regime where *dynamical back-action* leads to efficient cooling of a mechanical resonator has been highly nontrivial as it requires oscillators with high mechanical frequency and high optical and mechanical Q-factor.

In the present experiment a lithographically fabricated, chip based toroidal microcavity with a diameter of 50 micrometer is used. It behaves like a microscale tuning fork with a mechanical resonance frequency of 60 MHz (cf. figure 1). A 600 nm thin glass fiber feeds laser light into the cavity. The light is "red-detuned", i.e. its frequency is adjusted to slightly below the resonance frequency. The photons are trapped in the cavity and undergo many reflections. Since they strive to be in resonance with the system, they absorb energy (most of the time) when they collide with the wall. Thus the resonator's energy – and its temperature – is reduced. From the experimental results and their comparison to analytical model predictions the scientists were able to conclude that the cooling is caused by radiation pressure alone, thermal effects contributing less than 1%.

While the resonator temperature of the resonator is still far above the temperature of its quantum mechanical ground state temperature, which corresponds to 3 milli Kelvin, the merit of the experiment lies in being able to quantitatively asses this new cooling mechanism and to compare it to the theoretical predictions. Equally important, the presented cooling technique could in tandem with existing cryogenic procedures allow to reach here-to unattainable temperatures regimes, and might allow to cool oscillators to their ground state, thus crossing the border to a regime where macroscopic object behave quantum mechanical.

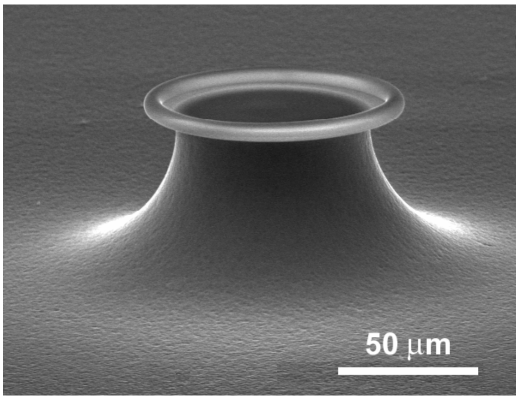

Figure 1: Scanning electron micrograph of a toroidal microcavity on a chip as used in the experiment

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