C. R. Physique 12 (2011) 797–799

Contents lists available at SciVerse ScienceDirect

Comptes Rendus Physique

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Nano- and micro-optomechanical systems / Nano- et micro-résonateurs optomécaniques

Foreword

Optomechanical systems have received much attention for the past last years. These systems are usually made of mechanical resonators interacting with light beams through the mechanical action of radiation pressure, and novel effects are expected when working in the quantum regime. This field of *quantum optomechanics* has emerged as a rapidly developing research field since the first demonstration of laser cooling of a mechanical resonator in 2006, as it addresses many fundamental concepts of quantum mechanics. Applications of this field now range from novel force sensors with unprecedented sensitivity to fundamental tests of quantum theory itself, including the principles of quantum measurement and the observation of quantum fluctuations, entanglement and decoherence of macroscopic objects.

Effects of radiation pressure on mechanical objects have been known from the theoretical point of view for many years: Kepler, for example, already realized that part of the tail of a comet was deflected by the radiation pressure exerted by the sun's light. Modern concepts on radiation pressure however date from the foundation of Quantum Mechanics. Energy quantization and the existence of photons as proposed by Planck and Einstein have indeed renewed the vision on radiation pressure, which in this context appears as a momentum exchange between the photon and the mechanical object. It then has a quantum nature since the photon flux is random and responsible for radiation pressure fluctuations proportional to the intensity shot-noise of light.

These fluctuations were first theoretically studied in the 1970s in order to understand the fundamental limits in very sensitive optical measurements, motivating a large number of works in close connection with gravitational-wave detection. Radiation pressure indeed builds up correlations between intensity fluctuations and mirror displacements inside the optical interferometer and enforces quantum limits to its sensitivity. Overcoming such limits was a major motivation for the quantum optic experiments on squeezed-light generation performed since then.

From the experimental point of view, one had to wait until the early 20th century for the first demonstrations of the mere existence of radiation pressure. The force is indeed tiny, at the scale of the nanonewton for a 1-W laser beam reflected on a mirror, and it appeared quite difficult to eliminate spurious effects such as the thermal heating of the surrounding gas which for example makes the Crookes radiometer rotate in the wrong direction! The advent of lasers in the 1960s has drastically renewed the interest for radiation pressure, which is at the heart of the spectacular development of cold atom physics: combined with the large atomic response obtained when a light beam is resonant with an internal atomic transition, radiative forces are able to produce atomic accelerations 10^5 times larger than gravity.

Similar effects are now expected in the domain of the mechanical action of light on macroscopic objects. Since the first experimental demonstration in the 1980s of the bistable behavior of a cavity in which a mirror moves in response to the intracavity radiation pressure, and the theoretical studies of ponderomotive forces and quantum limits in interferometric measurements, huge progress has been made very recently thanks to the development of high quality micro- and nanoresonators. Although such macroscopic resonators are much more massive than individual atoms or ions and thus harder to push around with a tiny radiative force, impressive successes have been obtained in the control and cooling of the mechanical motion, with resonators covering a huge range of scales from 30-kg mirrors in gravitational-wave interferometers to sub-picogram nanoresonators.

These systems are entering a regime where the mechanical motion of the resonator is strongly influenced by the light field. The basic mechanism at the heart of the optomechanical coupling can be understood from the two elementary processes that occur when a photon of angular frequency ω_0 is reflected on a moving mirror oscillating at a mechanical frequency Ω_{m} (see Fig. 1). The first one, the Stokes process, corresponds to a phonon creation and accordingly to a photon energy decrease from $\hbar\omega_0$ to $\hbar\omega_0 - \hbar\Omega_{\mathrm{m}}$. The reverse mechanism is the anti-Stokes process which leads to a phonon absorption and a photon energy increase by $+\hbar\Omega_{\mathrm{m}}$. These two processes change the properties of both the field and mechanical motion. First, two sidebands appear in the reflected field at frequencies $\pm\Omega_{\mathrm{m}}$ around the incident carrier frequency ω_0. This leads to a phase modulation of the field, proportional to the resonator displacements, that can be used to monitor its motion: this effect is at the basis of the development of high-sensitivity optomechanical sensors, nowadays able to detect displacements as small as $10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$. Second, both processes obviously may change the phonon statistics and hence the energy of the resonator, in particular if one process is promoted with respect to the other. This is the case for example

1631-0705/$ – see front matter
doi:10.1016/j.crhy.2011.10.017

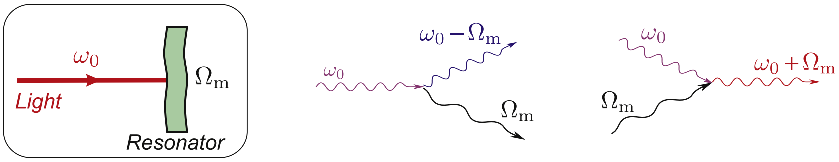

Fig. 1. Elementary processes responsible for the optomechanical coupling between an incident photon of energy $\hbar\omega_0$ and a mirror oscillating at an angular frequency Ω_m: the Stokes process (middle) corresponds to a phonon creation together with a decrease of the photon energy, whereas the reverse anti-Stokes process (right) corresponds to a phonon annihilation and a photon energy increase.

by detuning the cavity in such a way that the anti-Stokes process becomes resonant, thus leading to the cooling of the resonator.

Different objectives are pursued within the context of optomechanics, from the demonstration of quantum backaction and quantum limits in interferometric measurements, the generation of entanglement and squeezed states of both light and mechanical motion, and the ground state cooling of a mechanical resonator. The latter is certainly the hottest topic to date, with successful results obtained very recently: it consists in using light to cool a macroscopic mechanical oscillator down to its fundamental ground state, and then to monitor its residual quantum fluctuations or to couple this quantum system to a quantum bit. The observation of such a quantum phenomenon with a macroscopic object is of great interest from a conceptual point of view, as it corresponds to thought experiments developed by the founding fathers of Quantum Mechanics. Ground state cooling is also the key prerequisite for the preparation of non-classical states of motion, and, on a more technological level, for the development of micro- and nanomechanical sensors with an unprecedented sensitivity only limited by quantum noises. Applications are thus expected in the fields of metrology, sensing, actuation, or in the context of integrated devices in which mechanical quantum states may play a decisive role for the storage and transfer of quantum information.

This special issue of the *Comptes Rendus Physique* presents a survey of some recent advances in the field of optomechanics. Its purpose is also to give an overview of the domain and to provide an insight into topics at the frontier with other fields, such as gravitational-wave detection and Casimir force.

Three papers are devoted to main experimental aspects of the optomechanical coupling. They illustrate the diversity of optomechanical systems considered so far, both for their geometrical structure from nanoresonators to micromirrors and for the mechanisms used to detect their motion through evanescent optical fields, superconducting electrical circuits, or optical cavities. The paper by G. Anetsberger et al. gives an overview of cavity optomechanics using the coupling of nanomechanical resonators to the evanescent field of a toroid optical resonator. The paper of S. Etaki et al. presents the use of a dc squid (superconducting quantum interference device) to detect the mechanical motion of a micromechanical resonator embedded in the superconducting loop of the squid. The paper by P. Verlot et al. describes larger scale microresonators used as end mirror in a high-finesse Fabry–Perot cavity. These papers demonstrate experimental results on very sensitive measurements of the resonator displacements, on dynamical effects of backaction cooling and amplification, and on radiation-pressure-induced correlations between the light and the resonator motion.

Three papers present theoretical developments on optomechanics. The dynamics of multimode optomechanical systems are studied in the paper by G. Heinrich et al., with an emphasis on two important aspects: the photon dynamics in a system where a thin mechanical membrane is inserted in the middle of an optical cavity, and the cavity-induced coupling between two oscillators, either two membranes or one membrane and an atom. Using optomechanical systems to perform quantum optic experiments is a long-term goal addressed in the paper by D. Vitali et al.: radiation pressure induces mirror displacements which play in a cavity a role similar to optical index variations of nonlinear media; as a consequence, optomechanics can drastically change the quantum behavior of light and in particular generate squeezed states. Finally, radiation pressure is not the only force that can mechanically control the motion of macroscopic objects, and the first demonstration of optomechanical laser cooling was actually made using photothermal forces. The paper by J. Restrepo et al. studies this kind of optomechanical coupling and its ability to reach the mechanical ground state.

Many extensions or connections with other domains in physics may be found today while the field of optomechanics is rapidly expanding. The last three papers of this special issue present some important issues in this respect. The paper by D. Hunger et al. provides an overview on recent strategies proposed to couple atoms and mechanical oscillators, introducing various theoretical proposals and pioneering experiments. Such an interface between two very different quantum systems would be of great benefit in particular for the full quantum control of one system by the other one. As already stated in this foreword, radiation pressure induces quantum limits in very sensitive interferometric measurements. It also plays an important role at the classical level and the paper by W. Chaibi et al. describes the optomechanical issues expected from optical spring effects in advanced interferometers for gravitational-wave detection. Finally, the paper by J. Chevrier presents a review of the Casimir force and related problems in connection with nano- and micromechanics. In particular, this paper discusses the interplay between mesoscopic mechanical systems and quantum or thermal fluctuations.

We finally would like to warmly thank all the authors for their contribution and all the staff and Editorial Board at *Comptes Rendus Physique* and *Elsevier* who made this special issue possible.

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