Cavity Optomechanics: Controlling Light and Motion at the Quantum Level

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Our sense of sight is central to our experience of the world in every-day life. But light has also been, for centuries, *the* primary tool for scientists looking "deeper", trying to understand the inner workings of the universe we live in. Ever more sophisticated measurements with light have enabled us to study the laws that govern the world all the way from atomic to galactic length scales. Today, our most trusted physical theories, quantum mechanics and relativity theory, are, to a large extent, abstractions of observations made with optical instruments. These observations rely on the fact that most objects—be it a bacterium or a cloud of interstellar dust—interact with light, and modify its properties.

It is less widely known that when light interacts with these objects, it also acts back on them. In particular, light exerts forces. Historically, the concept of optical forces has been known for long: Kepler already speculated about their nature in the 17th century, inspired by the observation that the tails of comets always point away from the sun. Maxwell put this concept on more solid theoretical grounds in the 1860ies. However, still in the beginning of the 20th century, Heisenberg and Bohr debated the role of optical forces when they strived to understand the process of an optical measurement of a particle's position in quantum mechanical terms.

In the 1970ies, theorists around the world started to revisit the role of optical forces in precision measurements. They came to realize that these forces could be considered a particular form of *backaction*—a mechanism inherent to any measurement process obeying the laws of quantum mechanics. And remarkably, while the latter continued to be confirmed by ever more sophisticated experiments with atoms and ions, controversies on their implications for measurements involving larger objects remained open during all of the 20th century. The Russian physicist Vladimir B. Braginsky and his coworkers, and the US-American Carlton M. Caves could settle many of those, by working out a theory of backaction forces in optical measurements, embedded in the framework of a comprehensive theory of *Quantum Measurements* using electromagnetic waves[1-3].

Figure 1 shows a rendering of a *Gedankenexperiment* illustrating some elementary features of backaction forces in optical measurements: an interferometer, consisting of two mirrors, between which a laser beam bounces back and forth. The interferometer couples and traps the laser light best if the distance between the mirrors is an integer multiple of the laser's wavelength. If the wavelength is known, the instrument can thus be used to precisely measure the distance between the mirrors. However, optical forces may change this distance—illustrated here by a mirror mounted on a spring, ready to move when a force is applied. Unavoidable quantum fluctuations of the light's intensity may set the mirror into random motion, rendering its position, and therefore the distance to be measured, ill- (or less sharply) defined.

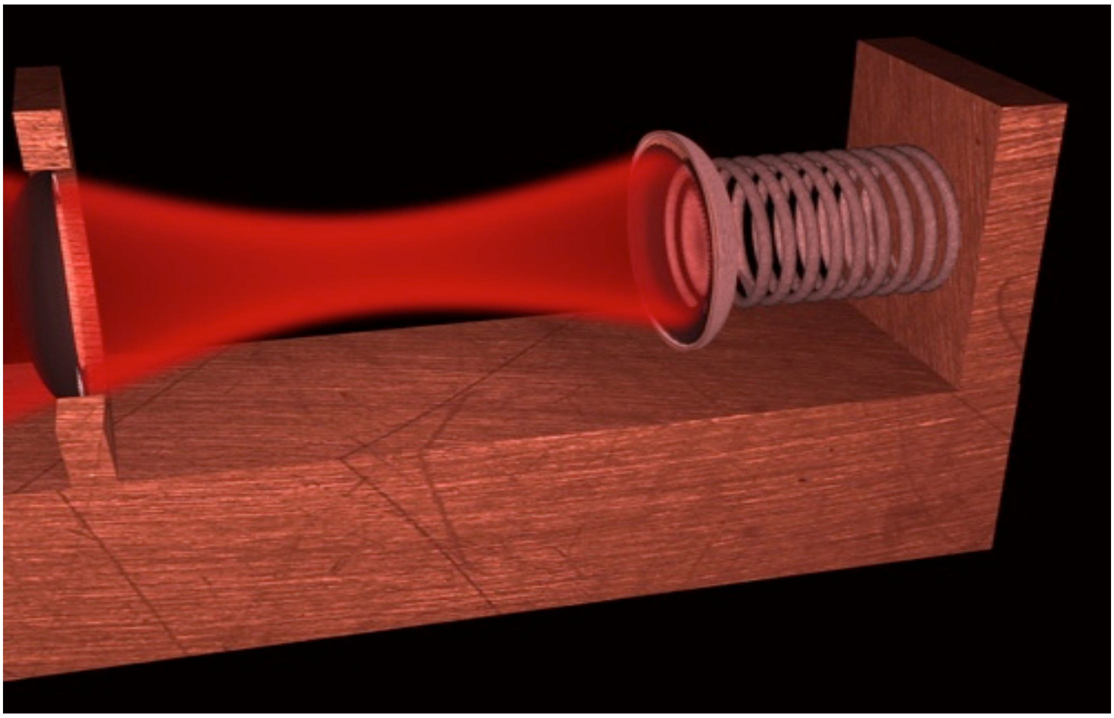

Figure 1. A generic optomechanical system: An optical interferometer consisting of two mirrors, one of which is moveable. Only if the distance between the mirrors equals an integer multiple of the laser's wavelength, laser light couples into the interferometer particularly well, and is trapped between the mirrors. Thus the distance between the mirrors can be measured. On the other hand, the presence of the laser light also exerts a force—which may deflect the spring holding one mirror, thus changing this distance.

It may seem that this effect, and the instrument shown in Figure 1, are a construct with little practical or scientific impact. The contrary is the case. In fact, such interferometers are at the heart of some of the most sensitive experiments that scientists have ever realized: Gravitational wave antennas (Figure 2 a) rely on a pair of such interferometers with suspended mirrors, each with kilometer-scale length for a new kind of observational astronomy[4]. A pair of black holes, for example, spiraling into each other, should induce measurable length changes due to the general-relativistic distortion of space-time that their motion induces. While astronomers hope to dramatically extend the observable space with this technique, they require sheer stunning sensitivity: At present, scientists can discern length differences of 10^{-18} meter if averaging their data for one second — that corresponds to 1/1000 of the diameter of a proton!—but higher sensitivity is still required in the hunt for the black hole's signatures.

In the Nanosciences, optical interferometers are routinely used to measure the motion of cantilevers known as prime force sensors. Indeed, the technique of magnetic resonance force microscopy (Figure 2 b) uses an interferometer in which one mirror is formed by such a flexible cantilever. The force exerted by a single electron spin on a tiny nano-magnet can be measured in this way, representing a many-orders of magnitude boost of sensitivity, for a potentially new approach to magnetic resonance imaging (MRI) of biomolecules[5]. Even higher sensitivity will be needed to measure nuclear spins, and again, optical forces could overwhelm the weak forces to be measured. The outlook of such ultra-precision experiments originally triggered Braginsky and his coworkers to re-think the physics of optical measurements, accounting for the fact that light has to be described in quantum mechanical terms, acting back on the object being measured via optical forces. These experiments are becoming a reality today.

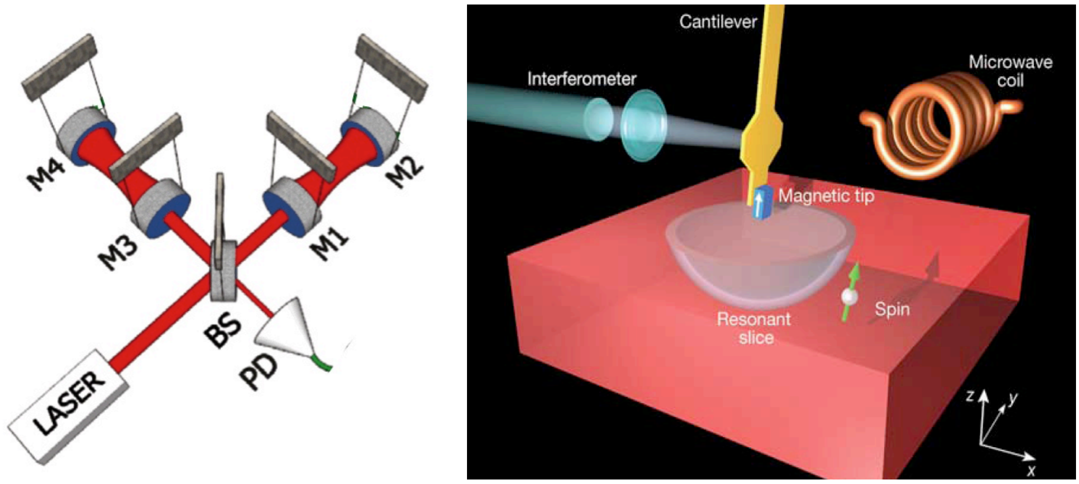

Figure 2 Ultraprecision scientific experiments based on optomechanical interferometers. (a) Laser interferometric gravitational wave antenna[6], and (b) single spin sensing experiment[5]. In both cases interferometers with movable elements—such as the one shown in Figure 1—are at the heart of the experiment. In (a), the mirrors are suspended like swings, and they are separated by kilometers. In (b), one interferometer mirror is formed by light reflection from a floppy cantilever.

The young research field of Cavity Optomechanics[7-11] has assembled researchers aiming to systematically explore this new realm of optical measurements. New micro- and nanofabrication technologies have brought forward a wide variety of platforms for these studies, revealing an array of new insights. Among them, maybe most remarkably, is the fact that backaction forces can not only be observed, but constitute a powerful tool to precisely manipulate the object being measured—in particular, the motion of the interferometer's boundaries (the movable mirror in Figure 1). They thus provide an unprecedentedly elaborate handle on another unexplored area of Quantum Physics: the quantum nature of the motion of mechanical objects of massively superatomic size. Indeed, Cavity Optomechanical systems have been scientists' prime tool to probe the quantum properties of nano- and micro-mechanical oscillators, an active research frontier for more than a decade[12]. Much of my own work has been done in this area, contributing to the development of the field of Cavity Optomechanics field from its beginnings. In the following, I will report on these contributions.

Ultrasensitive Interferometry with Glass Resonators

The workhorses of much of my research are "whispering-gallery-mode" resonators made of glass. In these devices (Figure 3), light runs in circular orbits along the rim of a thin glass ring, similar to words whispered in the gallery of London's St Paul cathedral—which gave this type of optical resonators their name. Our optical resonators are much smaller, though, with a diameter of the glass ring of some 100 µm or less; that is about the diameter of a human hair. Inspired by early research in Braginsky's lab[13], these resonators (or "cavities") were developed by Kerry Vahala and coworkers at Caltech, to study optical phenomena at the microscale[14]. At the Max-Planck-Institute of Quantum Optics, and—with a much wider palette of tools—at EPFL's Center of MicroNanoTechnology, we optimized the design and fabrication procedure, and could produce the samples for our research ourselves[15,16].

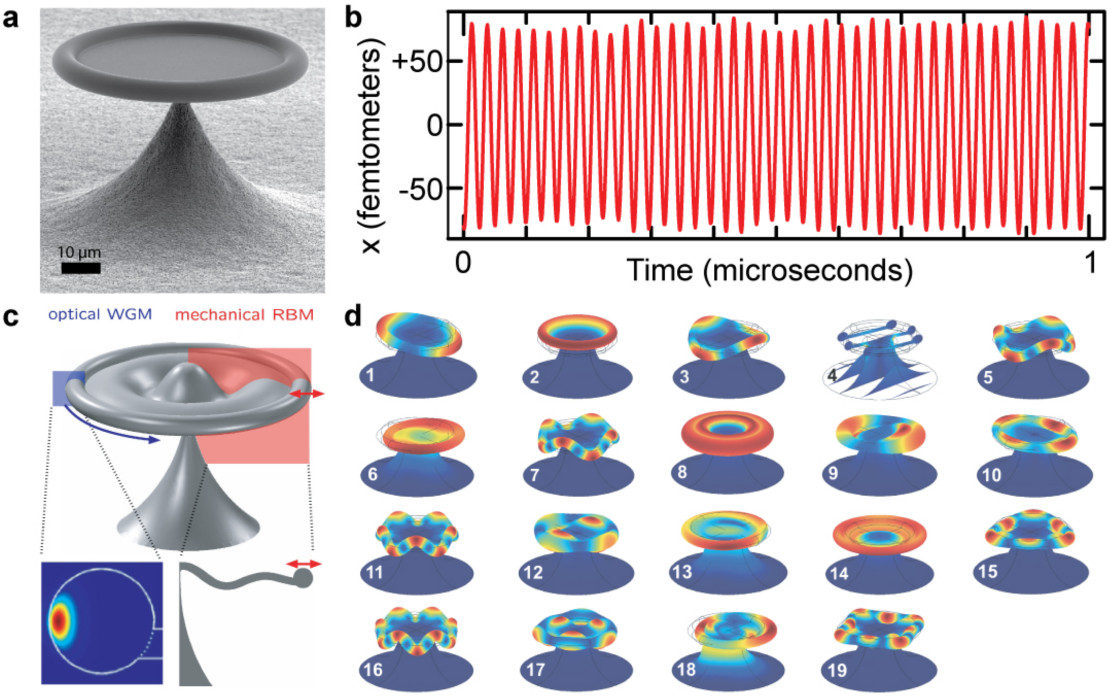

Figure 3 Glass microring (-or toroid) cavity used for our research in Cavity Optomechanics. (a) Scanning electron beam micrograph of the device. The glass ring (top) shows in grey as it is intransparent to electrons. The surface of the ring is atomically smooth and the material very clean. Thus light can be guided along the rim of the structure with very little losses, traveling hundreds of meters in the microstructure. (b) Oscillations of the radius of the structure measured optically. (c) Rendering showing both an optical "whispering gallery mode" (WGM)—essentially a circular light orbit along the ring's rim—as well as the a mechanical "radial breathing mode" (RBM), leading to a radial oscillation of the cavity boundary. (d) Illustrations of mechanical mode patterns, including the RBM (number 14), extracted from a computer simulation.

While their geometry is certainly different than the interferometer shown in Figure 1, these rings exhibit the same characteristic functionality: Light can complete a large number of round-trips (yet along a circular, instead of linear trajectory), and light from a laser is coupled in best at resonance, that is, if the path-length along the rim is an integer multiple of the laser wavelength. With that, the diameter of the ring can be accurately measured[17].

We found that the diameter of the ring is not stable in time, instead it fluctuates by many femtometers (1 fm=10^{-15} m), which our measurement can easily resolve (Figure 3b). These fluctuations can be attributed to the fact that the glass ring supports also acoustic modes, similar to a tuning fork, or a wineglass, which can "sing" a tone if struck mechanically. Figure 3d shows patterns of displacement that the ring undergoes when different *acoustic* modes—each corresponding to a different "tone", or oscillation frequency—are excited. Some look like the wound-up versions of a guitar string, but of greatest interest for our purposes is the "radial breathing mode" (no. 14): if this mode is excited, the radius of the ring periodically changes between 20 and 100 times per microsecond (20-100 MHz), leaving the clearly observable signature in the measurement of Figure 3b. The presence of such a mechanical mode completes the analogy to the system of Figure 1: Instead of a mirror mounted on a spring, the entire structure can be deformed when a force is applied. This naturally includes the optical forces arising from the fact that light trapped in the glass ring exerts radiation pressure pointing radially outwards.

Aiming to optically measure the radius of the glass ring with the highest possible sensitivity, we implemented state-of-the art quantum optical measurement techniques based on the cavities' principal suitability as an optical interferometer. Figure 4 shows the result of these efforts. When probing the radius of one particular device, fluctuations with a characteristic frequency of 40.6 MHz can be observed. This is evidenced by the sharp peak in the signal at this frequency, reflecting the oscillations of Figure 3b in a frequency-domain representation.

The background, or *imprecision* of this measurement, is given by the quantum noise of the light used in the measurement: the light arrives in energy packets, or photons, in the detector, where they are converted into electronic signals. A certain natural randomness of arrival times of the individual photons on the detector surface leads to a background noise—conceptually similar to the one heard when rain droplets impact on a metal roof, and commonly referred to as shot noise. If the radius fluctuations of the cavity were smaller than about 10^{-18} m, then the shot noise (blue points, measured independently) would obscure the weak optical signal to be measured within one second averaging time.

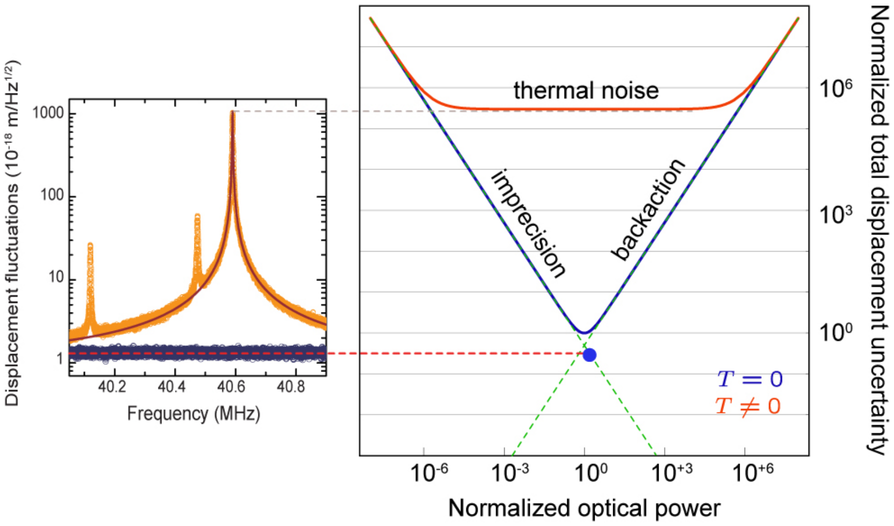

Figure 4. Measurement of radius fluctuations due to the radial breathing mode. (a) The fluctuations are very clearly discerned in the measurement, at a frequency around 40.6 MHz (yellow circles). The background of the measurement due to shot noise (blue circles) is much smaller, at about 10^{-18} meters in 1 second averaging time. (b) For the employed optical power, the imprecision of the measurement, due to shot noise, is already lower than the induced fluctuations due to optical backaction forces. However, as these measurements were taken at room temperature, the effects of backaction are masked by thermal noise.

By using more light, the imprecision could in principle be reduced further, as the signal strength increases more rapidly than the shot noise. However, according to the theory of Quantum Measurements, backaction fluctuations would at some point limit the sensitivity: shot noise is also present within the cavity, and the random bounces of photons against the cavity's wall would set it into random motion, obscuring the measurement of its radius. This backaction effect could not be discerned in our measurements, as the inherent fluctuations of the radius were larger (Figure 4). They are actually caused by the thermal motion of the molecules that constitute the resonator. Viewed from merely a different perspective, this corresponds to an excitation of the radial breathing mode (and all other mechanical modes) to a certain amplitude—the very amplitude observed in Figure 3a.

Nonetheless, backaction forces are present in this resonator. Indeed, the radial force exerted by the light is even enhanced by the number of round-trips that each photon completes (on average) in the glass ring—and this number can reach up to millions in this type of resonator. As a result, even when pumped with very modest light powers (much less than that of a laser pointer) the backaction forces can become significant enough to deform the resonator.

In this case, a particularly intricate effect can set in, referred to as *dynamical backaction*[18]: The force-induced deformation of the structure changes the optical path length. This may degrade (or improve) the matching of the laser's wavelength to the optical path-length along the rim, so that the resonator will in turn be able to accommodate less (or more) laser light—decreasing (or increasing) again the optical force. In the right circumstances, any naturally occurring radius fluctuation can thus stimulate a backaction force that exactly counteracts this radius change. This does also apply to the fluctuations associated with the thermal excitation of the radial breathing mode discussed above. That means that, even though the sample is at room temperature $T_s \sim 300$ K, the thermal fluctuations of this mode get reduced; it thus behaves as if the sample were held at a lower, effective temperature $T_{\mathrm{eff}} < T_s$.

Interestingly, this effect can also be understood as an analog to the techniques known for "laser cooling" the motion of atoms or ions, as suggested in the 1970ies by Hänsch and Schawlow[19], and Wineland and Dehmelt[20]: The laser beam sent towards the cavity is "red"-detuned, that is, the photons carry slightly less energy than necessary to excite the cavity's resonance (Figure 5). However, in a process called anti-Stokes scattering, the needed extra bit of energy can be taken from the motional degree of freedom—in our case, the vibration of the radial breathing mode. Thus, a photon with higher energy emerges from the cavity, leaving behind a slightly colder mechanical mode.

Figure 5 Cooling of the radial breathing mode based on dynamical backaction. (a) A laser beam whose frequency is lower by the mechanical frequency (Ω_m) than the cavity resonance frequency is sent towards the cavity. (b) Light from the cooling beam is upconverted to a higher frequency during a process called anti-Stokes scattering. The energy necessary for this upconversion is taken from the mechanical mode—which is thereby cooled.

In 2006, we were among the first three groups worldwide to demonstrate laser cooling of mechanical modes via dynamical backaction[21-23], achieving an effective temperature of 11 K. Since then, an avalanche of similar work all across the globe has been launched. With the aim of reducing the effective temperature T_{eff} closer to absolute zero, we have since continuously refined both the cooling techniques[24-26] as well as the employed experimental platforms[27,28].

Switching Light with Light

During these developments, we found that there exist more analogies between the concepts of atomic physics and optomechanical interactions than what was previously thought. In particular, optomechanical systems can exhibit a behavior now referred to as "Optomechanically Induced Transparency"[29,9], which is very closely related to electromagnetically induced transparency (EIT) known from atomic systems[30,31]. While the initial idea was already conceived during my doctoral thesis[29], it has been at EPFL where I have, together with my colleagues, fully developed this concept[32].

It is based on the observation that some atoms, which usually absorb light of a particular frequency, can be rendered transparent when illuminated by a second laser beam. The simultaneous presence of light of two frequencies prevents the atom from being excited—due to interference of excitation pathways. Figure 6 explains how this concept applies, completely analogously, also to an optomechanical system. A first, "probe" beam, that is usually coupled into the cavity, and absorbed there, can get transmitted through the system, if a second, “control” beam is activated. The combined backaction force of the two lasers then excites the mechanical mode, which in turn suppresses the coupling, and absorption of the probe beam via an interference effect. The probe laser thus simply gets transmitted.

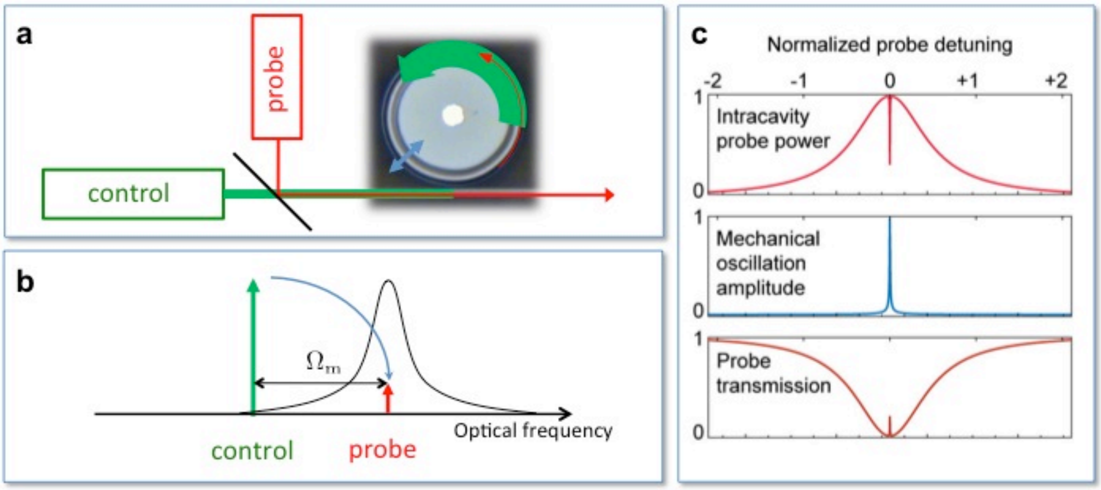

Figure 6 Optomechanically induced transparency. (a) Two lasers, a ‘probe’ and ‘control’ laser are sent towards the cavity, where they can both couple to the circular orbits (whispering gallery modes) of the glass resonators. If the frequency difference between the lasers is chosen to match the resonance frequency Ω_m of the vibration mode of the glass toroid, the combined backaction force of the two fields resonantly excites the mechanical mode, that is, the boundary of the structure is oscillating radially (blue arrow). (b) In a frequency picture, this leads, in turn, to scattering of light from the stronger control field, to the frequency of the probe laser. The scattered light interferes with the probe field—that is, its electric field exactly cancels the probe laser’s field in the cavity. The probe laser does therefore not enter into the cavity, but gets transmitted. (c) While the probe laser usually gets coupled into the cavity when tuned close to resonance, it is not coupled, and therefore transmitted, in a spectrally sharp region in the center—exactly when the combined backaction force of the lasers excites the mechanical mode.

With this technique it is therefore possible to tune on and off the transmission of the probe beam using the control beam. We have first demonstrated the phenomenon of Optomechanically Induced Transparency[32] at EPFL in 2010. More research has been carried out since[33], fueled not last by the prospect of applications as light switches and routers in integrated systems. Even more, EIT has been the physical phenomenon underlying the intriguing possibility to slow down and delay light, and eventually its storage in long-lived atomic states[34]. Optomechanical systems, whose key parameters can all be engineered within wide ranges (resonant wavelengths in particular), could provide an extension of these phenomena into the practical realm of telecommunications and optical signal processing.

Quantum Motion and Beyond

A strong focus of our research over the last years, however, has remained on the attempt to cool the mechanical degree of freedom to the lowest possible temperature T_{eff}. This endeavor has been motivated by the fascinating physics of trapped ions, which has also been highlighted by 2012's Physics Nobel Prize. In this field, researchers have accomplished full control over the motion of single ions held in vacuum using optical forces. Using laser cooling techniques, they can prepare such ions in the quantum ground state[35], that is, at an effective temperature so low that all but the most fundamental, quantum mechanical, position fluctuations are frozen out. An ion at such a low effective temperature can then be prepared in so-called Schrodinger cat states, in which it is located at two positions at the same time[36].

Such states have, to date, never been observed for a macroscopic object. Whether the reason is fundamental, or merely technical—preparation of quantum states requires suppression of all thermal fluctuations—is not known. However, with the new laser cooling techniques that can be applied to optomechanical systems, this could be probed for the first time. And indeed, we could show that we can prepare the radial breathing mode in the quantum ground state[16] with high probability. To date, this feat has only been achieved with a handful of optomechanical systems[37-39].

If the cooling laser is tuned to its highest powers (ca. 5 mW), the character of its effect changes qualitatively. In this regime the optical and mechanical modes couple so strongly via the light (Figure 7) that they loose their individual identity, and the new eigenmodes of the system are both mechanical and optical in character. Such hybrid excitations have been observed in the classical regime in early work at Vienna University[40]. At EPFL, we have pursued the long-standing goal of performing these experiments in the quantum regime.

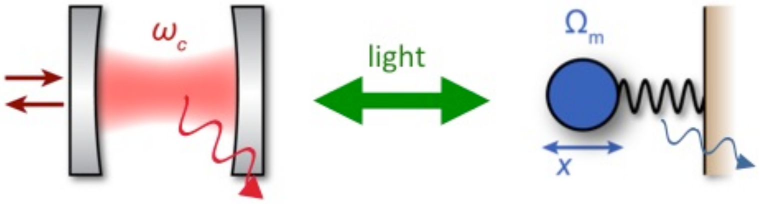

Figure 7 Coherent coupling in an optomechanical system. For very strong cooling laser fields, the light of the cooling laser couples the optical mode (left) and mechanical mode (right) so strongly, that they loos their individual identity, and rather have to be treated as a hybrid mode of both optical and mechanical nature.

We could eventually observe this photon-phonon hybridization in the quantum regime, both using spectroscopic, as well as time-domain techniques[16]. In the latter, we excited the cavity with very weak optical pulses, containing less than one photon on average. We could observe that this excitation cyclically transforms its character: into a mechanical excitation and back. The analysis of our experiments revealed that this cyclic transformation occurs on timescales that are faster than the ones of the known mechanisms of quantum decoherence—that is, the loss of quantum information from the system under experimental control to the uncontrolled "environment", consisting here of all mechanical degrees of freedom inaccessible to optical measurement.

We have therefore demonstrated an optomechanical interface across which quantum information can be coherently transferred. Such interfaces are of interest to quantum physicists[41] in particular for the versatility of mechanical devices: They can be coupled to other quantum systems such as atomic or solid-state qubits, or microwave photons, and massive efforts along these lines are now underway. Quantum-coherent links to an optical mode—via the mechanics—could help interconnect these systems via a simple piece single-mode optical fiber, thus providing a crucial building block for future heterogeneous quantum machines[42,43].

Acknowledgements

I am grateful to the *Fondation Latsis Internationale* and the Research Commission of the EPFL for their most generous encouragement of young researchers. I am indebted to Prof. T. W. Hänsch and Prof. T. J. Kippenberg for their long-term support and mentorship, and wish to acknowledge all of my co-workers who contributed to this research, in particular O. Arcizet, S. Deléglise, R. Riviere, E. Verhagen and S. Weis.

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