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Optomechanics of deformable optical cavities

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Resonant optical cavities such as Fabry–Perot resonators or whispering-gallery structures are subject to radiation pressure pushing their reflecting 'walls' apart. Deformable optical cavities yield to this pressure, but in doing so they in turn affect the stored optical energy, resulting in an optical back-action. For such cavities the optics and the mechanics become strongly coupled, making them fascinating systems in which to explore theories of measurements at the quantum limit. Here we provide a summary of the current state of optomechanics of deformable optical cavities, identifying some of the most important recent developments in the field.

The optomechanics of deformable optical cavities has seen a recent surge of interest. Research in this field, which started about 40 years ago, was and still largely remains driven by questions relating to the physics of measurements at the quantum fundamental limit. Good examples of this are the theoretical proposals formulated in the 1990s to perform quantum non-demolition measurements of the electromagnetic energy contained in a Fabry–Perot resonator by measuring the cavity elastic deformation under the effect of photon pressure. At that time, Braginsky, who pioneered the field, wrote that such a photon pressure probe, owing to "severe technical problems in its realization, is more a thought experiment than a foundation for a real measuring device"[1]. But now, technological advances in making deformable cavities, including nanofabrication techniques and high-quality optical coatings, are on the verge of allowing such a gedanken experiment to be practically explored in the laboratory. Here we present a brief overview of this rapidly evolving field of research.

Optical interferometers are ubiquitously used in length measurements requiring very high precision. When an interferometer is designed in such a way as to deform under the external action of an applied stress, the system is a precision force detector. Such force sensors are used in atomic force microscopy in the form of a deformable miniature Fabry–Perot interferometer[2], and are also at the heart of gravity-wave detectors[3] in the form of a deformable Michelson interferometer for detecting remote cosmic cataclysmic events. A schematic view of a deformable Fabry–Perot force sensor is shown in Fig. 1a: the two mirrors are attached to each other by a spring and the cavity is probed by a laser. In the simplest point of view, a force applied to one of the mirrors modifies the cavity length, which in turn modifies the cavity's optical transmission and reflectivity. A change of optical intensity at the detector, measuring for instance the transmission, is converted into force information. In the lowest level of approximation, light is just used to probe the cavity length changes and acts as a passive spectator. But to appreciate fully the fundamental detection limit of such an idealized force sensor, one needs to include the force added by the photons introduced into the cavity to perform the measurement in the first place. In the next level of approximation, the photons filling the cavity exert a pressure on the mirrors, causing them to displace and in turn detune the cavity with the result of modifying the very density of photons that were pressing against the mirrors to begin with. The mechanics and optics of the cavity are in fact coupled through the back-action of the photons on the mirror position. The

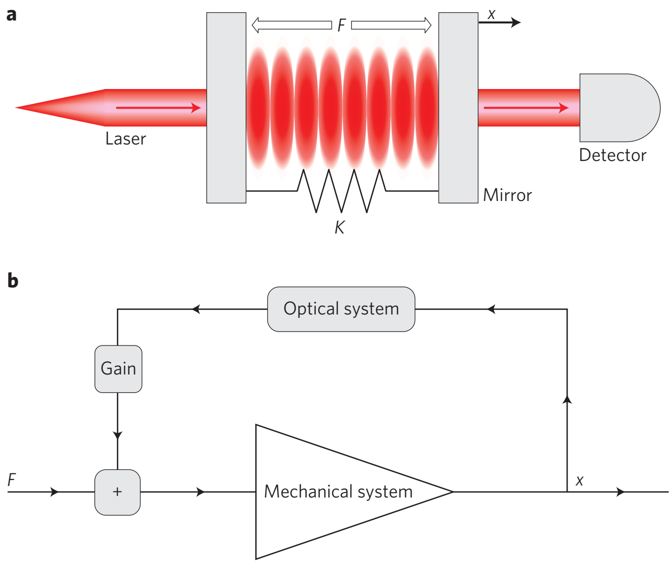

Figure 1 | Generic schematics of optomechanical sensors. a, Fabry–Perot interferometer force sensor. A force F acts on the right mirror (the mechanical system) of mass m, which is mounted on a mechanical spring K, while the laser probes the changes in cavity transmission. **b**, Feedback mechanism in an optomechanical sensor. The mechanical system moves under radiation pressure and fundamental fluctuations, and this displacement x modifies the density of light stored in the optical measuring device (the interferometer), leading to a change in the photo-induced force acting back on the mechanical system. This back-action is intrinsic to the deformable interferometer dynamics ('natural' self-cooling), but can also be externally implemented and amplified ('artificial' cold damping).

theoretical and experimental investigation of this apparently simple problem has recently flared into a number of rich and sometimes unsuspected new results.

The 'photon-spring'

Braginsky and co-workers published in 1970 a paper in which they investigated the effect of microwave power on a cavity with a deformable wall[4]. They provided a pioneering model in which a simple harmonic oscillator describes the mechanics of the deformable wall, laying the foundations of the optomechanics of

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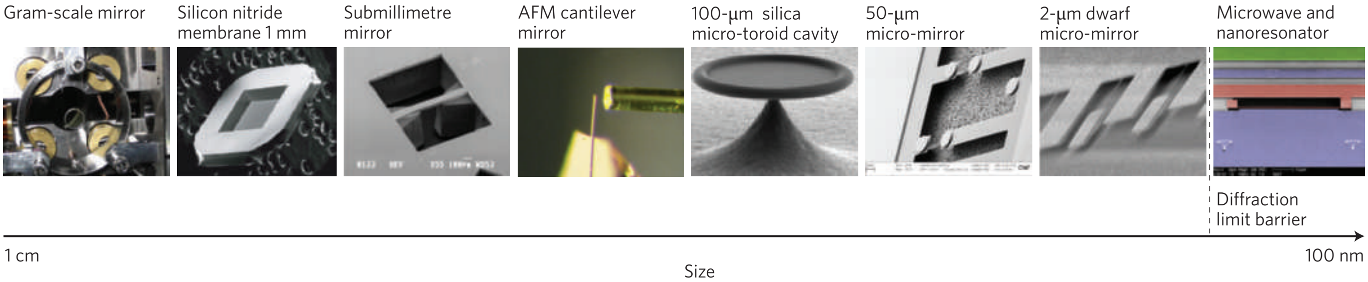

Figure 2 | Wide range of sizes of optomechanical deformable cavity systems showing self-cooling effects. Images show integrated mechanical systems ranging from centimetre size down to 100 nm. From left to right: a wire-suspended gram-scale mirror about 1 cm in size (image courtesy of MIT); a silicon nitride membrane[30] with ultra-high mechanical-*Q* (© 2008 NPG); a submillimetre ultra-high-reflectivity mirror (image courtesy of Laboratoire Kastler Brossel); a gold-coated AFM cantilever mirror forming a cavity with a coated optical fibre facet[29]; a high-optical-*Q* silica micro-toroid cavity[50]; a highly reflective Bragg micro-mirror deposited on a cantilever (image courtesy of Caltech); a metal-coated dwarf mirror at the diffraction limit[42] (© 2007 AIP); and a mechanical nanoresonator integrated in a strip-line microwave resonator[43] (© 2008 NPG).

deformable cavities[5]. Their analysis using Newtonian dynamics predicts that under the back-action of radiation pressure the mechanical oscillator displays an electromagnetically modified elastic spring constant K and a modified damping rate Γ. In short, the presence of radiation in a slightly detuned cavity introduces an added rigidity ∇F (that is, 'photon-spring') because the radiation density in the cavity, and consequently the radiation force F, depends on the oscillator's position. There is one subtlety, however: the photon back-action force acting on the cavity walls is not instantaneous, but is delayed with respect to sudden changes in the cavity size, and this is because the building of a new steady-state radiation density in the cavity requires a finite time-constant τ which is typically the electromagnetic energy storage time for the cavity. Like all retarded effects in dynamics, its contribution is to modify the amount of irreversible energy losses, namely the damping in the mechanics of the system. The net effect of introducing photon back-action is that the mechanical oscillator seems to be described by a shifted resonance frequency with a modified damping rate. In analogy, and in the spirit of modern quantum-optical language, one might say that the mechanical oscillator is 'photon-dressed'. In the limit of a rigid mechanical harmonic oscillator, for which the spring constant K dominates over the photon back-action spring (that is, $\nabla F << K$), the 'dressed' resonance ω and the damping Γ both have approximate analytical expressions in relation to their 'bare' counterparts ω_0 and Γ_0 (ref. 6):

$$\omega \approx \omega_0 \sqrt{1 - \frac{1}{1+\omega_0^2\tau^2}\frac{\nabla F}{K}} \quad (1)$$

$$\Gamma \approx \Gamma_0 \left(1 + Q\,\frac{\omega_0\tau}{1+\omega_0^2\tau^2}\frac{\nabla F}{K}\right) \quad (2)$$

where $Q = \omega_0/\Gamma$ is the bare mechanical quality factor, which is usually large (that is, $Q >> 1$). The peculiarity of such an optomechanical system is that these contributions to the mechanical resonance and the damping can be tuned to be positive or negative, by choosing the sign of the cavity detuning (that is, the photon-spring constant ∇F can be adjusted to be positive or negative).

The 1970 experimental results of Braginsky and co-workers showed, in the microwave domain, a hint of radiation-induced changes of the mechanical damping[4]. Shortly afterwards, they demonstrated in a beautiful experiment[5,7] that, still in agreement with their prediction[5,8], the resonance frequency of a torsion mechanical oscillator could also be shifted under the effect of radiation pressure in the visible domain. They dubbed their effect "light-rigidity"[5], but it is now better known as the optical spring effect. In 1983, Dorsel and co-workers investigated the strict analogue of Braginsky's microwave deformable cavity; they conducted an experiment using a deformable optical Fabry–Perot interferometer operating this time in the visible range[9]. Their measurements showed that under intense laser illumination the mechanical rigidity of the interferometer could be optically modified to the point of complete cancellation, leading to sudden mechanical instability in the mirror position. This seminal experiment was followed by a number of theoretical studies relating to gravity-wave antenna from which it emerged that the Braginsky effect was apparently detrimental to optimal gravity-wave sensing, so schemes were essentially proposed to counteract the effect.

The photon back-action in the deformable cavity can be described as a feedback element linking the output to the input of a mechanical system (Fig. 1b). Today, deformable optical cavities exist in various forms of devices, as shown in Fig. 2. In the world of engineering, systems with feedback are very well understood in electronics, as well as in mechanical and electromechanical circuits, and, as is the case for the optomechanical effects investigated by Braginsky[5], the response function of a closed-loop system is generally very different from its open-loop counterpart. Closed-loop circuits involving a mechanical resonator and an optical feedback are, however, less known in device engineering. A nice system of an optomechanical circuit with a light-induced force external feedback was first used in a force detection scheme in atomic force microscopes (AFM)[10] to increase the mechanical damping artificially by optical means.

Laser cooling towards the quantum regime

Not only rigidity and damping but also fluctuations such as Brownian fluctuations are modified by back-action in a closed-loop circuit. In other words, the circuit effective temperature characterizing the system fluctuations can be controlled through back-action.

As early as 1953, the Brownian noise of an electrometer based on a torsion mirror galvanometer was greatly reduced by using a time-delayed electrical feedback acting on the mechanical system[11] prompting the authors to conclude with the visionary words that they had achieved "artificial cold damping to cryogenic temperature level usually only realizable in cryogenic laboratories". The idea of cold damping of fluctuations in the mechanics of a deformable Fabry–Perot cavity using an artificial optical feedback through radiation pressure was proposed and investigated theoretically in 1998 by Mancini and co-workers[12], and soon after was demonstrated in a beautiful experiment by Cohadon and co-workers[13]. In 2002, Braginsky and Vyatchanin[14] proposed to use the photon back-action damping intrinsic to a deformable cavity as a natural feedback mechanism to suppress the Brownian fluctuations in the mirror dynamics. Such a

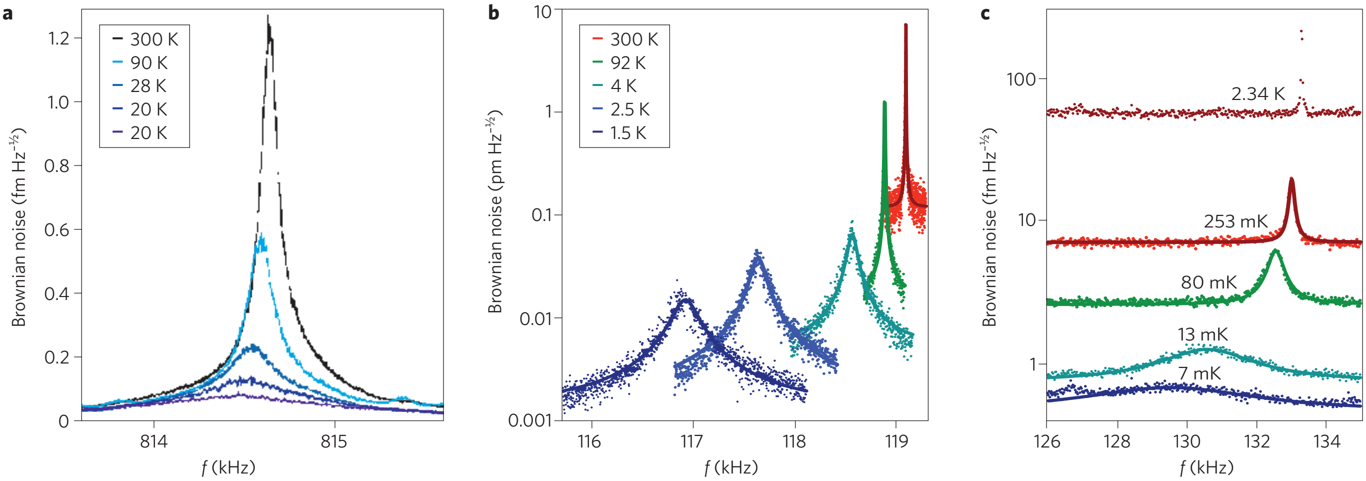

Figure 3 | Optomechanical radiation pressure self-cooling of deformable cavities. The spectra of Brownian fluctuations of various deformable Fabry–Perot cavities are shown for increasing strength of the 'photon-spring' contribution ∇F of radiation pressure (see text) at λ = 1,064 nm. The area under the curve is proportional to the mechanical oscillator fluctuation effective temperature. **a**, Data from ref. 21 and A. Heidmann *et al.* (personal communication), showing temperature reduction factor of 15 for Q = 10,000 and bath temperature of 300 K. The cavity finesse was ~30,000. **b**, **c**, Data from ref. 30 and J. G. E. Harris *et al.* (personal communication). The mechanical oscillator is a 1-mm^2 membrane of 50-nm thin silicon nitride placed at 300 K in 10^{-6} mbar vacuum within a high-finesse Fabry–Perot oscillator (finesse ~15,000). In **b**, $Q \approx 10^5$, and in **c**, $Q \approx 10^6$. Owing to lower mechanical dissipation of the oscillator, the cooling effect is increased and leads to a large temperature reduction factor of about 45,000.

'natural cold damping' (better known as self-cooling) turns out to be based on the same physical principles that lie behind laser cooling of ions[15] or vibration modes localized around impurities in semiconductors[16]. In 2004, optical self-cooling of a deformable Fabry–Perot cavity was demonstrated for the first time[6] under the effect of photothermal pressure. The effect showed that the Brownian fluctuations of a silicon microlever mirror could be cooled from 300 K down to 18 K. The prerequisite for self-cooling was first for the researchers to show that under the effect of optical back-action, deformable optical cavities displayed the expected optical control of rigidity and damping[17,18] as well as self-induced mechanical oscillation[19,20], which is the converse effect of self-cooling when the sign of the feedback is reversed. Soon after this, self-cooling of deformable cavities by radiation pressure was demonstrated almost simultaneously in various laboratories[21–24], triggering the race to extend self-cooling down to the quantum limit. An example of such cooling is shown in Fig. 3. Around the same time, there was a resurgence of interest in the method of artificial cold damping. Temperatures in the millikelvin range were achieved[25-27] by using externally amplified feedback, with record temperatures even down to the microkelvin range, in this case using electromechanical feedback[28].

Figure 3 shows the Brownian fluctuation noise spectrum for a few selected examples of cavity self-cooling. Clearly the effect of light back-action is to shift the resonance frequency, a very large modification of the linewidth (that is, damping rate) accompanied by a large change in the area covered under the Brownian resonance peak which provides a direct measurement of the vibrational temperature. For a rigid ($\nabla F << K$) mechanical harmonic oscillator the effective vibrational temperature reached with self-cooling is given[6,14,29] by $T_{eff} = T(\Gamma_0/\Gamma)$ which is minimized for a maximum increase of the 'dressed' damping Γ. What is the lowest temperature that a mechanical harmonic oscillator can reach by optical self-cooling? According to equation (2), the optical back-action on damping is optimized for $\omega_0\tau$ = 1, that is, when the delay time constant τ becomes of the order of the mechanical oscillation period at resonance. For such a rigid oscillator, the minimum effective temperature T_{min} reachable by self-cooling is directly related to the bath temperature T, the bare mechanical quality factor Q and the relative shift in resonance frequency $\Delta\omega/\omega_0$ induced by radiation pressure back-action directly measured in the Brownian noise spectrum:

$$T_{min} \approx \frac{T}{1 - 2Q\,(\Delta\omega\,/\,\omega_0)} \qquad (3)$$

This formula is valid in a classical approximation of self-cooling in that it neglects photons quantum fluctuations and is expressed in the rigid harmonic oscillator limit (that is, $\Delta\omega << \omega_0$), which is the usual limit in experiments. It allows a simple and convenient evaluation of the minimal expected reachable temperature by optical self-cooling given the bath temperature T, the mechanical oscillator's 'bare' resonance frequency and the quality factor Q, while the cavity parameters and light intensity are all included in the negative frequency shift $\Delta\omega$ induced by the optical back-action. The quantum limit for the mechanical fluctuation is reached when the average number of vibrational quanta $N = k_B T_{min}/\hbar\omega_0$ becomes close to or even less than unity. For such a rigid oscillator with $\omega_0\tau$ = 1 and in the limit of $Q >> 1$, the conditions to be fulfilled for the bath temperature and the related number of initial vibrational quanta N_T are, respectively, $k_B T < 2Q\hbar\Delta\omega$ and $N_T < 2Q\Delta\omega/\omega$.

In the rigid approximation $\Delta\omega << \omega_0$, we see that using a very large mechanical quality factor Q is central to self-cooling towards the quantum limit. Let us illustrate the point quantitatively. In Fig. 3b and c, a mechanical oscillator of high $Q \approx 10^6$ is placed in a high-finesse optical cavity[30]. The effect of photon back-action shifts the vibrational resonance up to $\Delta\omega/2\pi \approx$ 3 kHz for a bare resonance of $\omega/2\pi \approx$ 130 kHz while reducing the effective vibrational temperature down to ~7 mK from room temperature. Using the relations above, one would need to start ideally with a bath temperature of T = 50 mK in order to reach the quantum regime by self-cooling down to an effective temperature of $T_{min} \approx$ 22 μK. This assumes, of course, that the light is not turned into heat by absorption in the mechanical resonator and that the condition $\omega_0\tau$ = 1 is fulfilled.

Reaching the quantum limit for the vibrational mode of a harmonic mechanical oscillator means that it becomes decoupled from the incoherent thermal fluctuations present in its mass, and the result would be a purely coherent macroscopic state of the mechanical vibration. Its observation would be a good starting-point for studies

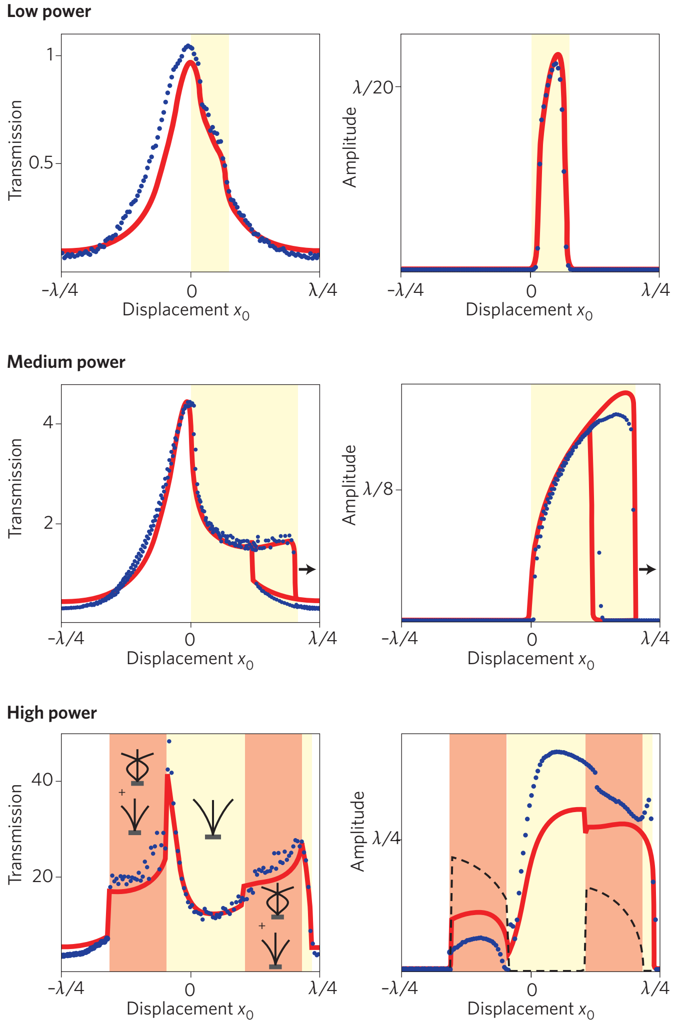

Figure 4 | Nonlinear dynamics of an optomechanical system. Left, optics: transmission of a deformable Fabry–Perot cavity as a function of cavity length variation *x*. At low optical power, the transmission is close to the transmission resonance of a conventional stiff Fabry–Perot cavity. Increasing the power leads to a complex behaviour, with the appearance of hysteresis and secondary transmission maxima. Right, mechanics: amplitude of the mechanical system self-oscillation driven by the photon back-action force. Reproduced with permission from ref. 46. © 2008 APS.

of quantum decoherence of massive mechanical systems[31–33], with expected new understanding of the boundary between quantum and classical physics[34]. At the time of writing and to the best of our knowledge, deformable optical cavities have not yet been cooled to their vibrational quantum ground state, but this goal seems in reach. Should they come closer to this limit, a full quantum theory of the optomechanical coupling governing their dynamics and their fluctuations is required, especially as the classical approach leading to equation (3) does not include quantum noise of the radiation, which can counteract self-cooling. In 1995, Law[35] provided a Hamiltonian description of radiation pressure on a moving mirror. This work was the basis for a quantum theory of optomechanical self-cooling in the case of radiation pressure coupling[36,37] as well as a description of optomechanical instability in the quantum regime[38]. The quantum theory of self-cooling by radiation pressure predicts[36,37] that the final vibrational occupation number will become lower than one only when $\omega_0\tau > 1$. The maximum cooling ratio is still obtained for $\omega_0\tau = 1$, but for this case it turns out that the photon fluctuation noise limits optical cooling to a vibrational occupation number of unity at best[36,37]. In the case of optomechanical systems coupled through other optical induced forces such as photothermal effects, the interaction involves a much larger number of degrees of freedom (phonons, electrons) and a Hamiltonian description is not yet available. This also applies to cooling through artificial cold damping, because the optomechanical interaction is mediated through a physical apparatus in the laboratory, which so far involves a quasi-infinite degree of freedom.

Trends

Efforts are currently being devoted to overcoming technical barriers to reaching the quantum regime. One of the challenges is still to design a system that minimizes both optical and mechanical losses. A possible strategy is to separate the functions of the mechanical oscillator from the optical one, allowing independent optimization of each. Thompson and co-workers[30], for instance, introduced a very high-*Q* thin flexible silicon nitride membrane into an otherwise stiff Fabry–Perot cavity of high finesse[39–40]. Figure 3b and c shows that this approach allows a reduction of the effective temperature down to 7 mK from room temperature. A related approach that has recently been proposed[41] would eventually allow researchers to venture below the diffraction barrier that usually limits optomechanical settings[42] and open the route to the use of nanomechanical objects for which the quantum limit could be reached close to the millikelvin range. In the visible and near-infrared range, subwavelength-sized nanostructures acting as the mechanical resonator introduced into a high-finesse optical cavity forming a coupled nano-optomechanical oscillator[41], are expected to show increased photon back-action. In the same spirit but in very different experiments, cooling of nanostructures by cavity perturbation was recently demonstrated in the microwave regime[43]. Another alternative approach proposed recently was to use the wavelength dependency of periodic structures near their band-stop to amplify laser Doppler cooling of a photonic crystal mounted on a flexible structure[44]. Such a nanophotonic device would also profit from photon back-action if its photonic band structure was tailored appropriately.

Finally, besides self-cooling and artificial cold damping, the strong coupling between optics and mechanics also leads to interesting nonlinear dynamics of the deformable cavity, still comparatively little investigated. Such a regime, first explored by Marquardt and co-workers[45] who predicted a rich phase diagram involving multistability parameter regions, has recently been observed[46], as seen in Fig. 4. Chaotic behaviour was also recently reported in high-finesse micro-toroid cavities[47]. Reducing the size, nano-optomechanical systems integrating extremely low-mass nanomechanical oscillators in a small optical volume should increase the coupling strength and allow exploration of these complex dynamical behaviours more deeply. Hybridized with high-*Q* optical micro or nanocavities, they could serve as a new platform in future optomechanics experiments.

In conclusion, the technology of optomechanical force sensors has evolved to the point where they are becoming a topic of research to explore their own fundamental quantum limit. They are, for example, viewed as ideal systems in which to verify theories in quantum measurement[1,48,49]. The quantum limit of an optomechanical system has not been reached yet, but the goal seems not too distant, thanks to recent advances in optical cooling methods. Such progress increases the prospect of applications in the field of quantum sensing devices. As yet, we barely know what to expect from such devices, and surprises are probably in store.

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