OPTOMECHANICS

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Abstract. We review recent progress in the field of optomechanics, where one studies the effects of radiation on mechanical motion. The paradigmatic example is an optical cavity with a movable mirror, where the radiation pressure can induce cooling, amplification and nonlinear dynamics of the mirror.

Key words: Optomechanics; Radiation pressure; Nonlinear dynamics

1. Introduction

Optomechanics is an emerging research topic that is concerned with mechanical effects caused by light, particularly in connection with micro- and nanomechanical structures that are deflected by radiation pressure. Thoughts about the mechanical effects of light can be traced back as far as Johannes Kepler. Observing the tails of comets always pointing away from the sun, he speculated that this might be due to the force exerted by the solar radiation. Ever since the first measurements of such radiation forces more than 100 years ago, optomechanical effects have been observed in various areas of physics and engineering: Spacecraft with solar sails are indeed being developed, radiation forces are setting fundamental limits for the precision of laser interferometers used in detecting gravitational waves, and these forces are also used to manipulate cold atoms. A recent addition is the use of optomechanical forces to drive, cool and read out micro- and nanomechanical devices (see a recent review in Kippenberg and Vahala 2008, and other recent developments in Marquardt 2008). To reach the ground state of a mechanical oscillator with a frequency of 100 MHz, it would have to be cooled down to about 1 mK. Achieving such ground state cooling would "put back mechanics into quantum mechanics" (Schwab and Roukes 2005), and quantum effects would become observable in a massive object consisting of roughly 10^{15} atoms.

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This brief review is organized as follows. In Sect. 2 we introduce the basic setup, an optical cavity, driven by a laser with one mirror placed on an oscillating cantilever. We explain the classical effects of retarded radiation forces. Similar physics was investigated in a variety of other system, like driven LC-circuits coupled to cantilevers (Brown et al. 2007) or single-electron transistors and microwave cavities coupled to nanobeams (Naik et al. 2006; Rodrigues and Armour 2007; Regal et al. 2008). Light-induced forces can not only cool the cantilever, but can also enhance the mechanical motion leading to an instability. In Sect. 3 we show how one can derive an intricate attractor diagram for the resulting self-induced oscillations (Marquardt et al. 2006), which have also been seen in experiment. Section 4 is devoted to a quantum description of the coupled cavity-cantilever system (Ludwig et al. 2008). A new optomechanical setup (Jayich et al. 2008; Thompson et al. 2008), which aims at Fock state detection, is discussed in Sect. 5.

2. The Basic Optomechanical Setup

The standard setup of optomechanics is shown in Fig. 1. It consists of an optical cavity driven by a laser impinging on the cavity through a fixed mirror. The other mirror of the cavity is movable. For example, it may be attached to a micro-cantilever as used in atomic force spectroscopy. In such a setup the mechanical effects of light are enhanced, as the light field is resonantly increased in the cavity and each photon will transfer momentum to the mirror in each of the numerous reflections it undergoes, until finally leaving the cavity.

The coupled cavity-cantilever system is described by a Hamiltonian of the form

$$\hat{H}_{\text{cav+cant}} = \hbar\left(\omega_{\text{cav}} - g\frac{\hat{x}_M}{x_{\text{ZPF}}}\right)\hat{a}^\dagger\hat{a} + \hbar\omega_M\hat{c}^\dagger\hat{c}\,. \tag{1}$$

Additional terms in the Hamiltonian describe the driving of the cavity by the laser beam, decay of photons out of the cavity and the mechanical damping of the cantilever. Here, ω_M denotes the oscillation frequency of a mechanical

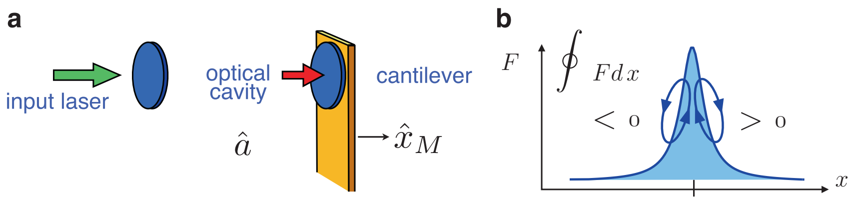

Figure 1. (**a**) The standard setup of optomechanics. (**b**) The dependence of the radiation pressure force (circulating intensity) on the cantilever position

oscillator, whose displacement can be expressed as $\hat{x}_M = (\hat{c}^\dagger + \hat{c})x_{\mathrm{ZPF}}$ in terms of ladder operators and the oscillator's zero point fluctuations $x_{\mathrm{ZPF}} = (\hbar/2m\omega_M)^{-1/2}$. The optical cavity, described by operators $\hat{a}^\dagger$ and $\hat{a}$, has a resonance frequency ω_{cav} if the cantilever is fixed at position $x_M = 0$.

The coupling term $\propto \hat{x}_M\hat{a}^\dagger\hat{a}$ with a strength depending on the coupling constant g can be understood by two equivalent ways of reasoning: The radiation pressure force should give rise to a term of the form $-\hat{F}_{\mathrm{rad}}\hat{x}_M = -\frac{c}{L}\hat{a}^\dagger\hat{a}\,\hbar k_{\mathrm{cav}}\,\hat{x}_M$, which leads to (1) with $g = \omega_{\mathrm{cav}}x_{\mathrm{ZPF}}/L$. Alternatively, we can understand the same term as stemming from the dependence of the cavity's resonance frequency on the cavity length, $L + x_M$, given by $d\omega_{\mathrm{res}}/dx_M = -\omega_{\mathrm{cav}}x_M/L$.

Two crucial new ingredients are added to the physics of radiation pressure by considering a cavity setup. First, the radiation pressure becomes strongly position dependent due to its proportionality to the total light intensity in the cavity $\propto \hat{a}^\dagger\hat{a}$. The light intensity shows resonances when the cavity length $L + x_M$ is varied. Their full width at half maximum (FWHM) depends on the decay time κ^{-1} of the cavity, $x_{\mathrm{FWHM}} = \kappa L/\omega_{\mathrm{cav}}$ .The resulting dependence of the radiation pressure force on the cantilever position in the stationary state is sketched in Fig. 1. Secondly, the decay time κ^{-1} introduces a delay between the mirror motion and the response of the light intensity.

To understand the effects of such a retarded response of the radiation pressure force, let us consider a cantilever at a position $x_M > 0$ to the right of the resonance (see Fig. 1) moving towards the resonance position, $\dot{x}_M < 0$. We consider small delay times and small excursions of the cantilever only. Moving leftwards the cantilever acts against the radiation pressure, which grows as the cantilever moves closer to resonance and the light intensity in the cavity increases. This increase, however, lags behind the movement of the cantilever, so that at any instance the force acting on the cantilever is smaller than its stationary value at the same position would be (see Fig. 1). Moving into the opposite, positive direction the delayed decrease of the intensity leads to an accelerating force on the cantilever, larger than the stationary one. Overall, there is a net input of work into the mechanical motion during one oscillation, given by the enclosed area in the force-position diagram in Fig. 1. Thus, for $x_M > 0$ (where the laser light is blue detuned with respect to the cavity resonance) the cantilever motion gets enhanced, while for $x_M < 0$ the same physics causes an additional damping. In the next section, we will extend these qualitative statements to a detailed description of the classical dynamics of the coupled cavity-cantilever system.

Retarded radiation forces were first investigated in pioneering studies by Braginsky, both experimentally and theoretically (Braginsky and Manukin 1967; Braginsky et al. 1970).

3. Nonlinear Classical Dynamics

Operating on the red detuned side of the resonance, any small thermal oscillation amplitude will be damped away more quickly than in the absence of radiation. On the opposite, blue detuned side, damping is effectively reduced. If this effect overcomes intrinsic friction, an arbitrary thermal fluctuation will be amplified into an oscillation with increasing amplitude, driving the coupled system into a nonlinear regime (Aguirregabiria and Bel 1987; Fabre et al. 1994; Braginsky et al. 2001; Marquardt et al. 2006). Finally, the system will settle into a stable, self-sustained oscillation, where radiation power input and dissipation are in balance. This will be the subject of the present section. These effects have already been observed in experiments (Höhberger and Karrai 2004; Carmon et al. 2005; Kippenberg et al. 2005; Metzger et al. 2008).

To derive classical equations of motion, we replace the operator $\hat{a}$ by the complex light amplitude α and the position operator $\hat{x}_M$ by the cantilever's classical displacement x_M. From the Hamiltonian equation (1) we then derive

$$\begin{aligned} \dot{\alpha} &= \left[i \left(\Delta + g \frac{x_M}{x_{\mathrm{ZPF}}} \right) - \frac{\kappa}{2} \right] \alpha - i \alpha_L \\ \ddot{x}_M &= -\omega_M^2 x_M + |\alpha|^2 \hbar g / (m x_{\mathrm{ZPF}}) - \Gamma_M \dot{x}_M \, , \end{aligned}$$

where α_L is the amplitude of the driving laser field, Γ_M describes the mechanical damping of the cantilever, and $\Delta = \omega_L - \omega_{\mathrm{cav}}$ is the detuning of the laser light with respect to the cavity resonance.

Beside a static solution $x_M(t) = \text{const.}$, the system can exhibit self-induced oscillations. The cantilever will then conduct approximately sinusoidal oscillations, $x_M(t) \approx \bar{x} + A \cos(\omega_M t)$, at its unperturbed frequency ω_M. Since radiation pressure effects are small, the amplitude A of the oscillations will change slowly over many oscillation periods only.

From this ansatz, an analytical solution for the coupled dynamics of $x_M(t)$ and $\alpha(t)$ can be found (Marquardt et al. 2006; see also Ludwig et al. 2008). The two parameters of the solution, the amplitude A and the average displacement $\bar{x}$, can be determined from two balance conditions: For any periodic solution the total force should average to zero during one cycle,

$$\langle \ddot{x}_M \rangle \equiv 0 \quad \Leftrightarrow \quad m\omega_M^2 \bar{x} = \langle F_{\mathrm{rad}} \rangle = \frac{\hbar g}{m x_{\mathrm{ZPF}}} \left\langle |\alpha(t)|^2 \right\rangle . \tag{2}$$

This yields an implicit equation for $\bar{x}$, since $\langle F_{\mathrm{rad}} \rangle$ is a function of $\bar{x}$ and A. Furthermore, the work performed by the radiation pressure balances on average the frictional losses,

$$\langle F_{\mathrm{rad}} \dot{x} \rangle = \Gamma_M \left\langle \dot{x}^2 \right\rangle . \tag{3}$$

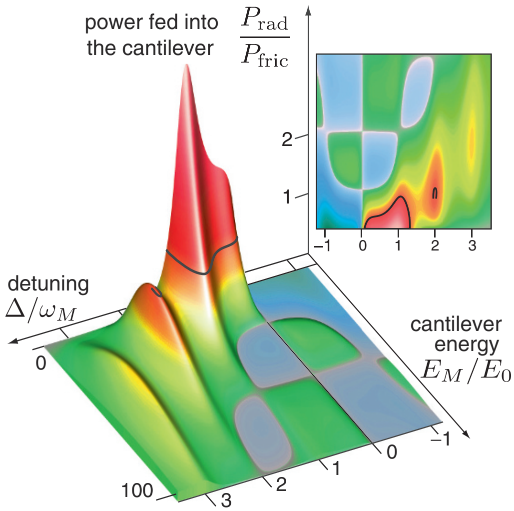

Figure 2. The power fed into the cantilever motion by the radiation force, as a function of oscillation amplitude and laser detuning. This can be used to construct the possible attractors for the elf-induced oscillations (indicated by thick lines)

Eliminating $\bar{x}$ by use of (2) we can plot the ratio between radiation power input and frictional loss, the two sides of the last equation, as a function of the oscillation amplitude A. Such a plot is shown in Fig. 2, where we chose the detuning Δ as a second variable, while other parameters are fixed. The condition of (3) is fulfilled if the ratio $P_{\mathrm{rad}}/P_{\mathrm{fric}} = 1$, as indicated by the horizontal cut in Fig. 2. A solution will be stable only if an increase of the amplitude is accompanied by a decrease of $P_{\mathrm{rad}}/P_{\mathrm{fric}}$. By that reasoning the final attractor diagram is constructed, as indicated by the thick black lines in Fig. 2.

Important general features of the dynamics of the coupled system can be seen in Fig. 2. Self-induced oscillations appear for sufficiently strong driving around integer multiples of the cantilever frequency, $\Delta \approx n\omega_M$. Such oscillations appear for a positive detuning Δ, while for red detuned laser light ($\Delta < 0$) the stationary solution, $x_M(t) = \text{const.}$, is stable. Note that stable solutions with large amplitude do exist even for $\Delta < 0$.

The most striking feature, however, is the coexistence of several stable solutions with different finite oscillation amplitudes for a fixed set of system parameters. This dynamical multi-stability, first discussed in this context in Marquardt et al. (2006) and also seen in similar systems (Rodrigues and Armour 2007), is visible in Fig. 2b, while for the parameters of Fig. 2a we find coexistence of a stationary and a finite amplitude solution around $\Delta \approx 2\omega_M$.

These multi-stabilities could be utilized for ultra-sensitive "latching" measurements, as argued in Marquardt et al. (2006).

Self-induced oscillations in an optomechanical system have already been observed in experiments with bolometric forces (Höhberger and Karrai 2004; Metzger et al. 2008) and in microtoroidal structures where radiation pressure dominates (Carmon et al. 2005). Recently, a more detailed comparison of theory and experiment revealed interesting effects due to higher order mechanical modes that get involved in the nonlinear dynamics (Metzger et al. 2008).

4. Quantum Theory of Optomechanical Systems

The prospect of reaching the quantum mechanical ground state of a "macroscopic" mechanical object is currently one of the main goals in the field of micro- and nanomechanics. Impressive progress has been made in a series of experiments (Cohadon et al. 1999; Höhberger-Metzger and Karrai 2004; Arcizet et al. 2006; Gigan et al. 2006; Schliesser et al. 2006; Kleckner and Bouwmeester 2006; Corbitt et al. 2007; Thompson et al. 2008), though the ground state has not yet been reached at the time of writing. In the classical picture derived above, we found that a properly detuned laser beam will cool the cantilever by providing extra damping. According to the classical theory, the cantilever can be cooled down to an effective temperature $T_{\text{eff}} = T\,\Gamma_M/(\Gamma_{\text{opt}} + \Gamma_M)$, apparently arbitrarily close to absolute zero for sufficient drive power and low mechanical damping. However, quantum mechanics sets the ultimate limit for optomechanical cooling.

Starting from an intuitive quantum picture of the cooling process, we will present in the next subsection a quantum noise approach to cooling. Quantum effects on the self-induced oscillations can be described numerically within a quantum master equation discussed in the following subsection, which allows studying the classical-to-quantum crossover.

4.1. QUANTUM NOISE APPROACH TO COOLING

In the quantum description, a photon impinging on the cavity will emit or absorb a phonon of the mechanical cantilever motion and change its frequency accordingly, in a Raman-like process. A photon that is red detuned from the resonance will absorb a phonon of energy $\hbar\omega_M$ from the cantilever, so that it is scattered into the cavity resonance, leading to cooling. Detuning to a "sideband" of the cavity at a frequency $\omega_{\text{cav}} - \omega_M$ will be particularly effective.

For a quantitative approach the radiation field of the cavity will be considered as a "bath" acting upon the "system," the cantilever degree of freedom $\hat{x}_M$, via the coupling term, $-\hat{x}_M\hat{F}$, in the Hamiltonian. The influence of the

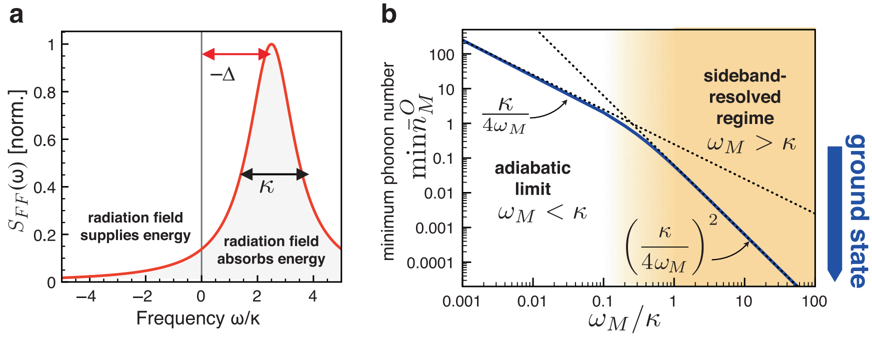

Figure 3. (**a**) Power spectrum for the radiation pressure force. (**b**) Quantum-mechanical cooling limit

bath is then characterized by the power spectrum of the force, $\hat{S}_{FF}(\omega) = \int dt \exp(i\omega t)\left\langle \hat{F}(t)\hat{F}(0)\right\rangle$. In particular, Fermi's golden rule links the net optical damping rate of the cantilever to the possibility of the cavity to absorb/emit a quantum of energy $\hbar\omega_M$ from/to the bath, $S_{FF}(\pm\omega_M)$, as

$$\Gamma_{\text{opt}} = (x_{\text{ZPF}}/\hbar)^2 \left[S_{FF}(\omega_M) - S_{FF}(-\omega_M)\right] . \tag{4}$$

The power spectrum S_{FF} is directly related (Marquardt et al. 2007) to the spectrum of photon number fluctuations due to shot-noise (see Fig. 3). Crucially, the asymmetry of the power spectrum (which is set by the laser detuning) determines whether the cavity will more readily absorb or emit energy, setting the sign of the net optical damping rate Γ_{opt} [cf. (4)].

One finds (Marquardt et al. 2007; Wilson-Rae et al. 2007) a simple limit on the minimal occupation number, $\bar{n}_M^O = [\kappa/(4\omega_M)]^2$, which can be reached for optimal detuning $\Delta = -\omega_M$ in the resolved-sideband limit $\omega_M \gg \kappa$, for $\Gamma_{\text{opt}} \gg \Gamma_M$. In general, the reachable occupation number $\bar{n}_M$ of the mechanical mode will depend on the initial occupation $\bar{n}_M^T$ (hence, starting from cryogenically precooled samples is advantageous) and the mechanical and optical damping rates, as $\bar{n}_M = (\Gamma_{\text{opt}}\bar{n}_M^O + \Gamma_M\bar{n}_M^T)/(\Gamma_{\text{opt}} + \Gamma_M)$, which reduces to the simple classical expression for the effective temperature given above for $\bar{n}_M^T \gg 1$. As shown in Fig. 3 ground state cooling is most advantageously pursued in the resolved-sideband regime with high finesse cavities and high frequency resonators. With various groups working on a variety of setups further progress and final success in approaching the quantum limit is expected in the very near future.

The strong coupling regime, where $\Gamma_{\text{opt}} > \kappa$, needs a more sophisticated analysis and gives rise to new features (Marquardt et al. 2007, 2008).

4.2. QUANTUM DESCRIPTION OF SELF-INDUCED OSCILLATIONS

For a full quantum description (Ludwig et al. 2008) of the self-induced oscillations, we have to consider the reduced density matrix $\hat{\rho}$ of the system consisting of cantilever and cavity mode. Mechanical damping and photon decay out of the cavity are treated using a Lindblad master equation,

$$\frac{d}{dt}\hat{\rho} = \mathcal{L}\hat{\rho} = -\frac{i}{\hbar}\left[\hat{H}_{\text{cav+cant+drive}}, \hat{\rho}\right] + \Gamma_M \mathcal{D}[\hat{c}] + \kappa\mathcal{D}[\hat{a}] \quad (\text{for} \quad T = 0), \tag{5}$$

where $\mathcal{D}[\hat{a}] = \hat{a}\hat{\rho}\hat{a}^\dagger - \frac{1}{2}\hat{a}^\dagger\hat{a}\hat{\rho} - \frac{1}{2}\hat{\rho}\hat{a}^\dagger\hat{a}$ is of the standard Lindblad form.

The stationary state of the system is found as the eigenvector of the Liouvillian $\mathcal{L}$ for eigenvalue zero. This problem can be solved numerically for a restricted, but sufficiently large number of cavity and cantilever states. From the eigenvector, the density matrix $\hat{\rho}_f$, all quantities of interest, for instance, the average kinetic energy of the cantilever motion, can then be calculated.

Before comparing the results of this quantum mechanical description to the classical approach, it is instructive to quantify the degree of "quantumness" of the system. Using the dimensionless parameters $\mathcal{P} = 8\,|\alpha_L|^2\, g^2/\omega_M^4$, characterizing the driving strength, and $\zeta = g/\kappa$, the Hamiltonian is written as

$$\hat{H}_{\text{cav+cant+drive}} = \hbar\left\{\left[-\Delta - \kappa\zeta(\hat{c} + \hat{c}^\dagger)\right]\hat{a}^\dagger\hat{a} + \omega_M\hat{c}^\dagger\hat{c} + \frac{\sqrt{2\mathcal{P}}\omega_M^2}{4\kappa\zeta}(\hat{a} + \hat{a}^\dagger)\right\}. \tag{6}$$

The master (5) then contains only dimensionless quantities, if time and the remaining energy/frequency variables are written in terms of the mechanical oscillation frequency ω_M. Four of the dimensionless parameters in this equation, Γ_M/ω_M, κ/ω_M, Δ/ω_M and $\mathcal{P}$ do also appear in the classical equations of motion, while

$$\zeta = \frac{g}{\kappa} = \frac{x_{\text{ZPF}}}{x_{\text{FWHM}}} \propto \sqrt{\hbar} \tag{7}$$

does not. The so-defined "quantum parameter" ζ constitutes a measure of the quantum nature of the system and vanishes in the classical limit $\hbar \to 0$. It is defined as the ratio of the quantum mechanical zero point fluctuations of the cantilever to a classical length scale, namely the resonance width x_{FWHM} of the cavity.

The quantum master equation allows studying the quantum-to-classical crossover of the system dynamics by changing the numerical value of the quantum parameter ζ. Classical results are recovered for small ζ, while for $\zeta \gtrsim 1$ quantum fluctuations tend to smear out the sharp features of the

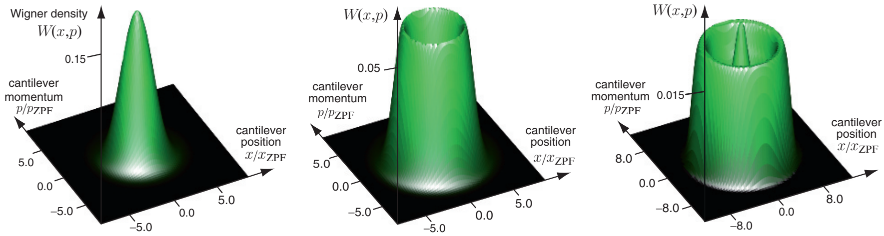

Figure 4. Wigner densities for the cantilever under the influence of the radiation force, for varying detuning, displaying the optomechanical instability (middle and right panels)

classical result and favour the occurrence of self-induced oscillations below the classical onset, a feature which can also be deduced from the quantum noise approach introduced above (see Ludwig et al. 2008 for details and figures). Note that to some extent the effects of quantum fluctuations can be mimicked by introducing quantum zero-point fluctuations into the classical equations of motion (Ludwig et al. 2008).

The existence of classical bi- or multistable solutions can be seen by considering the Wigner density of the cantilever. As illustrated in Fig. 4, the Wigner density shows characteristic features corresponding to (a) a single stationary classical solution (broad peak in phase space), (b) a single finite amplitude classical solution (ring structure – the phase of the oscillatory solution is undetermined), or (c) the coexistence of a classical stationary and finite amplitude solution (peak with superimposed ring structure).

We find that most optomechanical experiments are well in the classical regime, in the sense that the quantum parameter remains small (e.g. $\zeta \approx 10^{-3} \ll 1$ in the Bouwmeester setup, Kleckner and Bouwmeester 2006). In two recent setups, however, combining standard optomechanics with cold-atom physics (Gupta et al. 2007; Murch et al. 2008; Brennecke et al. 2008), ζ is of the order of one. In these experiments a cloud of cold atoms is placed in an optical cavity, so that the collective motion of the cloud couples to an optical mode of the cavity, replacing the cantilever motion.

5. Towards Fock-State Detection

Linked inextricably to the race towards ground state cooling is the question how to confirm the quantum nature of the final state. Measurement of the displacement quadratures is possible via optical readout (Clerk et al. 2008). However, probably the most straightforward demonstration would be to observe the quantum jumps from the ground state to progressively higher energy eigenstates (Fock states), as the system heats up again. Such quantum jumps between different Fock states have been observed in the mechanical motion of an electron in a Penning trap (Peil and Gabrielse 1999). In optomechanics such quantum jumps might eventually be observed for the mechanical motion of a truly macroscopic object, consisting of billions of atoms.

Recently, the Yale group of Jack Harris introduced a novel optomechanical setup (Thompson et al. 2008; Jayich et al. 2008), where a thin dielectric membrane is placed in the middle of a cavity with two fixed, high finesse mirrors. Beside the technological advances offered by this setup, it also leads to a different coupling of the mechanical displacement of the oscillating membrane to the cavity, which is advantageous for the aim of Fock state detection. To find the structure of the coupling term in the Hamiltonian, consider first the limit of a perfectly reflecting membrane at some position x in the middle of the cavity. Moving the membrane will change the frequencies of resonances in the left and right halves of the cavity in opposite directions, which would lead to a resonance crossing at some displacement x_{cross}. A finite transmission of the membrane, however, produces an anti-crossing, with $\omega(x) - \omega(x_{\mathrm{cross}}) \propto x^2$ near the degeneracy point. In rotating wave approximation the coupling is then of the form $\propto (\hat{c}^\dagger \hat{c} + \frac{1}{2})\, \hat{a}^\dagger \hat{a}$, so that $\left[\hat{H}_{\mathrm{cant+cav+drive}}, \hat{c}^\dagger \hat{c}\right] = 0$, allowing non-destructive measurement of the phonon number. Detecting the phase of the transmitted beam driving the cavity at resonance frequency then constitutes a direct quantum non-demolition (QND) measurement of the phonon number.

Shot noise in the transmitted beam can be overcome by time averaging, which, however, is restricted by the life time of Fock states due to finite damping and temperature. Optimal averaging times and strategies, how best to distinguish classical from quantum fluctuations, even when the QND readout time is comparable to the state's life time, have been explored in Jayich et al. (2008).

6. Conclusions

Optomechanics is a new research topic that has been established in the past four years, with strong progress being made through a tight interplay of theory and experiment. Even the classical nonlinear dynamics of these systems is far from being fully explored: For example, chaotic motion has been observed at strong drive (Carmon et al. 2005), but not yet analyzed systematically. In the quantum regime, ground-state cooling and creation of nonclassical states (e.g. entanglement) are interesting challenges. New setups expand the applicability of these concepts, e.g. in superconducting microwave circuits or with cold atoms.

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