Editorial

Focus on optomechanics

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Abstract

We provide a brief overview of the various topics addressed in this 'focus on' collection on optomechanics.

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1. Introduction

Optomechanics is a rapidly developing field of research that explores the interaction between light and mechanical motion. The combination of modern nanofabrication techniques for mechanical devices and ultralow dissipation optical cavities has enabled an explosion of experimental progress in the past few years. The principles of optomechanics show promise for both applications and fundamental investigations. Optomechanical systems (figure 1) are advancing the art of precision measurement of small displacements, forces and masses, with all these functionalities now available on-chip thanks to integrated platforms. Optomechanical systems are considered to be prime candidates for realizing quantum interfaces between solid-state quantum bits and photons, with applications in information storage and processing envisioned. Finally, due to the comparatively large masses of the mechanical objects involved, it has been proposed that generating superposition states and entanglement of mechanical
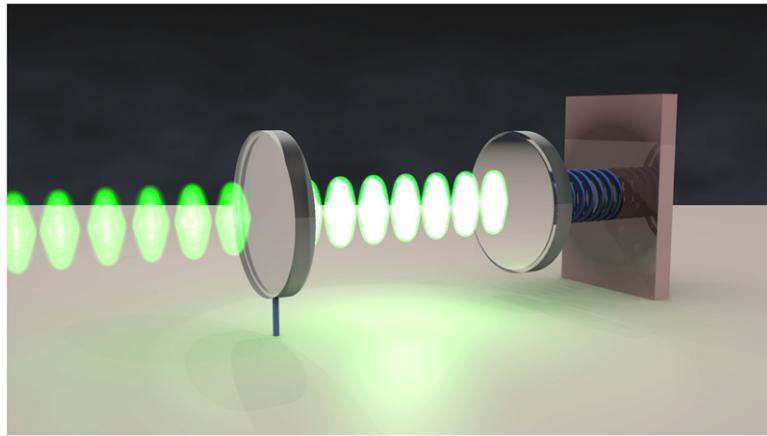
Figure 1. Three-dimensional representation of a standard optomechanical cavity with a spring mirror. Image courtesy of C Baker.

motion and light may test foundational questions of quantum physics, at a mesoscopic mass scale where gravity may play a role.

At present, the field is in the middle of an exciting phase. After a period of rapid experimental progress, since 2011 several experiments have exploited laser-cooling to reach down to near the quantum ground state of mechanical motion in cavity-optomechanical systems. This opens the door to true quantum experiments. At the same time, other aspects such as nonlinear dynamics, single-photon operation, the electrical control of optomechanical systems, as well as their multimode and collective behaviour, are beginning to be explored. Many different novel experimental settings have been introduced, each with its own particular advantages. The field now spans systems with several orders of magnitude in mass, frequency and size, and it covers systems as diverse as clouds of cold atoms, superconducting microwave setups, optical microcavities and microspheres, vibrating membranes, levitating nanospheres and magnetic bodies, cantilevers, nanotubes, graphene and nanophotonic devices.

This 'focus on' collection aims to collect original research contributions from many of the leading groups worldwide. We hope that it will give an overview of the richness of current activity and provide inspiration for pushing forward the frontiers of this interdisciplinary area, at the intersection of mesoscopic condensed matter physics, nanophotonics, electrical engineering and quantum optics.

In the following, we present briefly the various contributions in this 'focus on' collection. Their variety demonstrates the vigour and breadth of the field. For more background, the reader may also consult a number of review articles on the topic which have been published in the past few years [1–9].

2. Optical sensing of mechanical motion: new applications

Optomechanical coupling allows precise optical read-out of mechanical motion. This was recognized early on as having great potential for sensing applications. Doolin *et al* [10] explore this route with an integrated MEMS sensing device perspective. They fabricate and measure silicon-based optical microcavities detecting the in-plane and out-of-plane displacement of AFM-like vibrating levers positioned in their near-field.

In the same spirit but with slightly better performances, Miao *et al* [11] also show how optomechanical concepts can be used to improve the performance of MEMS devices. They present a novel platform that separates the optical and mechanical components, with a micron-scale ring coupled to both a mechanical membrane and a waveguide, and they demonstrate readout sensitivity approaching the standard quantum limit.

Homodyne measurements are a standard tool in quantum optics to measure the different quadratures of the electric field. Kaufer *et al* [12] use this tool to characterize the output of a Michelson–Sagnac interferometer containing a thermally excited membrane.

Bringing optomechanics to the interface with fluidics, Bahl *et al* present a detailed study of mechanical modes supported by bubble silica capillary resonators [13]. They discuss how to increase the coupling of these modes with light stored in the bubble, in order to optomechanically measure fluids injected into the capillary.

3. Membranes

The paper by Jayich *et al* [14] shows 400mK cryogenic operation of a silicon-nitride membrane-in-the-middle optomechanical setting reaching the good-cavity regime.

With a similar membrane-in-cavity approach, but with different technical choices including a very monolithic cooled setting, Purdy *et al* [15] report on low phononic occupation numbers, bringing silicon nitride membranes near the quantum regime.

A membrane also forms the centerpiece of the experiment reported by Karuza *et al* [16], who characterize optomechanical cooling in their setup. They were able to observe the mechanical frequency shift that is expected when the quadratic terms are retained in the dependence of optical frequency on the mechanical displacement.

Differing from this membrane-in-the-middle approach, Kemiktarak *et al* introduced the concept of a membrane with a grating structure [17] to reduce mechanical mass and engineer optical reflectivity. They utilize the membrane as back mirror of a Fabry–Pérot geometry and demonstrate efficient optomechanical cooling.

In the context of optomechanics, high-frequency mechanical modes would offer the advantage of straightforward access to the quantum regime even without laser cooling. Borkje *et al* [18] show how a dilatational mode of a thin membrane, with frequencies of several GHz up to tens of GHz, could be exploited in this manner. Due to the high frequency, a phonon from this mode could scatter a photon between different longitudinal optical cavity modes.

4. Optomechanical circuits and arrays

Going from one mechanical mode to many, Schmidt *et al* propose a quantum model where a common optical mode driven by a laser couples to a whole set of vibrational degrees of freedom [19]. By modulating the laser amplitude, the authors show that a controlled quantum interaction between two distinct mechanical modes can be mediated by photons, generating quantum state transfer, squeezing and entanglement.

Coupled mechanical modes are the subject of the paper by Yamaguchi *et al* [20]. Following a series of experiments reported by them on a dual-mode doubly clamped beam, the authors now propose an elastic model that explains subtle features of the parametric coupling between different mechanical modes of the beam.

In another paper addressing optomechanical circuits, Habraken *et al* [21] point out how to route phonons in such a circuit and how to implement circulators for phonons, based on an optomechanical setup. They also explain how the problem of a finite thermal occupation in the phonon waveguides can be overcome by a cooling scheme that works for the continuum of modes in a waveguide, instead of the usual single mechanical mode.

An important class of optomechanical setups consists of one or several nanomechanical resonators inside a cavity (e.g. a nanowire or a membrane). In their analysis, Xuereb *et al* [22] show how a scattering approach provides a more refined description of the radiation forces, going beyond the often-used approximation of coupled cavity modes.

Photonic circuits that include optomechanical components are very promising for applications ranging from sensing to quantum communication. While silicon photonics has provided a very successful platform, some challenges remain and could be overcome by introducing new material platforms. Xiong *et al* [23] demonstrate aluminum nitride as the basis for low-loss high-bandwidth circuits. Moreover, this material has the added benefit of a second-order optical nonlinearity, and the authors show first nonlinear optical effects in this platform.

5. Introducing nonlinearities: two-level systems and single photons

The quantum interaction of a single spin with a mechanical oscillator is the topic of the work by Bennett *et al* [24]. Following their experiments employing a NV center coupled to a magnetic vibrating cantilever, the authors now analyze the limits of their measurement scheme, both in the classical case relevant to current experiments and in the quantum domain of future realizations to come.

An interesting twist on the general theme of optomechanics is generated when the optical cavity resonance is replaced by an internal resonance, e.g. an excitonic resonance of a quantum dot. Wilson-Rae *et al* [25] show how such a resonance inside a carbon nanotube can couple parametrically to the nanotube vibrations, and they demonstrate that this can give rise to a huge coupling constant.

Two promising routes of introducing nonlinearities at the quantum level into any quantum-optical system are: single-photon sources and single-photon detectors. Basiri-Esfahani *et al* [26] describe a system where a single photon is injected into a combination of two optical cavities, effectively generating a photonic qubit, which is then coupled to a mechanical resonator. The quantum states of the resonator can then be engineered by exploiting photon counting.

6. Quantum state manipulation and foundations

State transfer between electromagnetic modes at different frequencies (e.g. microwave and optical) is likely to become an important component of quantum information processing networks. Therefore, mechanically-mediated quantum state transfer may become one of the primary applications of optomechanics. Wang *et al* [27] present a new hybrid scheme that combines the best elements of previous proposals, and they display a 'phase diagram' that indicates the optimal transfer scheme depending on the experimental parameters.

Both squeezed and entangled states can be produced by parametric driving, i.e. time-dependent modulation of frequencies or coupling constants. In their analysis, Mari *et al* [28]

show how to engineer suitable time-periodic modulation to obtain large degrees of entanglement between a mechanical resonator and a radiation mode.

New possibilities arise when a quantum system is both driven and measured at the same time. Szorkovszky et al [29] show in their theoretical work how a combination of detuned parametric amplification and continuous quantum measurement can be employed to generate squeezed mechanical quantum states.

Regarding foundational quantum mechanics experiments, one of the earliest proposals deals with an optomechanical which-way experiment where a photon leaves behind a trace in one arm of an interferometer, in the form of a vibrational excitation. In a follow-up to this idea, Pepper et al now propose the use of two nested optical interferometers to produce 'macroscopic' superposition states of mechanical oscillators [30]. Nested interferometry now allows to come closer to experimental implementation. The paper focuses on experimental requirements and decoherence.

7. Controlling mechanical dissipation and noise

One of the big challenges in nano- and micro-optomechanics is to engineer smaller mechanical dissipation. This is important particularly in the quantum regime. Chang et al [31] propose to optically trap tethered membranes inside an optical cavity. This has the advantage of storing most of the potential energy inside the optical field, suppressing the mechanical losses connected to intrinsic dissipation mechanisms.

Theoretical proposals of levitating silica nanospheres as ultra-low dissipation mechanical resonators have emerged in recent years. In their paper [32] Monteiro et al elaborate further on this idea and make it more concrete by measuring experimentally the dynamics of a sphere trapped inside an optical dipole potential and the optomechanical coupling behaviour. They discuss how the strong coupling regime of optomechanics might be attained with this approach.

Adopting a different kind of levitation approach, Druge et al [33] provide the first detailed experimental observations on a magnetic object levitated above a superconductor. In particular, they characterize its damping and the non-linearity.

Thermal fluctuations of mechanical resonators limit the sensitivity of precision experiments, such as in gravitational wave interferometers. A contribution that is particularly important at low frequencies is connected with internal friction, i.e. structural damping. In their experiment [34], Neben et al analyze the fluctuations at low frequencies due to this mechanism, for a gram-scale mirror, and point out how to improve the design to overcome this challenge.

Laser noise can be an important factor in the analysis of cavity quantum optomechanics experiments. In this collection, three papers specifically address this question, each with a different perspective. Safavi-Naeini et al [35] propose an extended model, together with careful laser noise measurements, that helps to clarify their past experiments and the level of control needed for true quantum optomechanics experiments. Kippenberg et al [36] measure the noise of typical external cavity diode lasers and point towards potential interpretation mistakes when cooling at the quantum limit. The topic of classical laser noise is also addressed by Jayich et al [14], this time with a focus on avoiding possible mistakes in interpreting side-band thermometry experiments.

8. New approaches to optomechanical coupling

While much of the discussion in optomechanics focusses on radiation pressure forces, some systems display much stronger photothermal effects, and these can also be exploited for cooling. Xuereb *et al* [37] provide a theoretical model to explain the recent experimental results on photothermal cooling of a GaAs membrane.

In conventional optomechanics, the mechanical displacement modulates the optical cavity frequency. Some authors have analyzed in the past how the cavity decay rate can be modulated as well, leading to a situation sometimes called dissipative optomechanics. Here Weiss *et al* [38] go one step further and show how these dissipative effects manifest themselves in the strong coupling regime of optomechanics, and give birth to unconventional behaviours.

Optomechanical concepts have in the past been shown to also apply to deep sub-wavelength sized mechanical elements. Gil-Santos *et al* [39] report here on singly clamped silicon nanowires addressed by a simple optical fibre-cavity. They analyze the relative importance of photo-thermal (bolometric) and radiation pressure effects in these wires.

Every optomechanical system can undergo an instability, where it settles into a state of self-sustained mechanical oscillations. The physics of this is analogous to that of a laser or maser, and Khurgin *et al* [40] make this analogy quantitative by discussing the phonon lasing instability in terms of concepts known from laser theory. They also present experimental results for photo-thermally driven self-oscillations in a Si waveguide.

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