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PERSPECTIVE

The sandwich in the middle: using collective effects for stronger optomechanical coupling

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Optomechanics combines optical and mechanical degrees of freedom to enable new applications and to attain new parameter regimes. The simplest optomechanical system consists of only a single optical and a single mechanical mode. Such a system can serve as a quantum memory where an optical excitation is stored in the long lived mechanical excitation [1]. Conversely, the optomechanical interaction allows one to prepare quantum mechanical states of motion opening the door to the experimental exploration of quantum mechanics in massive system [2].

Over recent years optomechanical systems have gained in complexity, exploring multiple optical and/or mechanical modes. In those systems, mechanical degrees can mediate between different optical modes allowing to convert quantum excitations between the optical and the microwave domains [3]. On the other hand, the optical field can also couple dissimilar mechanical modes, which is useful for synchronizing the mechanical vibrations [4]. Now, Piergentili *et al* exploit a multimodal optomechanical system to increase the optomechanical coupling strength [5].

The paradigmatic case of an optomechanical system consists of a Fabry–Pérot cavity where one of the cavity mirrors is free to move around its equilibrium position. The mechanical motion couples dispersively to the cavity, that is, the cavity frequency is shifted by a displacement of the mechanical elements, leading to the optomechanical coupling $G_o = \omega_c/L$, where ω_c and L are the cavity frequency and its length, respectively.

Piergentili *et al*'s work [5] is based on a very successful variation of the paradigmatic Fabry–Pérot optomechanical cavity, where the end mirrors are fixed and a membrane is placed inside the cavity [6]. Even though the cavity length is constant, the optical path length depends on the position of the membrane along the cavity axis. This leads to an optomechanical coupling $G_o = \theta_m\omega_c/L$, where θ_m is the mode-overlap between the mechanical mode of the membrane and the optical cavity mode, which depends on the membrane refractive index and position. Thus, the optomechanical coupling increases for smaller cavities since the electromagnetic field is more concentrated and, consequently, microscopic cavities achieve the highest coupling strengths [7]. However, a small cavity comes with a faster cavity decay $\kappa \propto 1/L$ because the round trip time of photons in the cavity is proportional to its length.

An alternative strategy is to enhance the interaction by increasing the number of mechanical elements [8]. This allows one, for instance, to achieve a strong optomechanical interaction with ensembles of atoms, where the optomechanical interaction of each atom is rather small but the interaction of a collective mode of the ensemble is increased by a factor of $N^{1/2}$. A single atom is a weak scatterer and does not modify the cavity field. In contrast, a single membrane strongly modifies the cavity field and interference of the scattered fields can lead to an even stronger scaling $\propto N^{3/2}$ with the number of membranes [8], specifically in transmissive regime. Therefore, it was suggested that a stack of membranes instead of a single membrane could be used as an alternative path towards strong coupling. The optical properties of the stack depend on the spacing between the membranes in addition to the optical properties of the membranes themselves and one can think of the stack as a super-scatterer with an optical response that can be tailored by careful positioning of the individual elements. An intuitive way to understand the system is in the limit of high reflectivity and a stack of two membranes. The two membranes form an inner cavity of length q. This increases the coupling by a factor that is given by the ratio of lengths of the outer and inner cavities. Interestingly, the cavity decay time of the entire system is still given by the outer cavity, provided that the presence of the additional membranes does not introduce additional losses [9]. Thus, the ratio of coherent coupling rate to incoherent decay increases, which is desired for quantum coherent operation.

Piergentili *et al* present the first experimental extension of the membrane-in-the-middle geometry by replacing the single membrane sandwich with a stack of two membranes. The two membranes are mounted on piezo stages. This allows them to position the two membranes independently and characterize the optomechanical system for a variety of sandwich positions and distances between the membranes. The reflectivity of the membranes used in the experiment ($\mathcal{R}_m = 0.4$) is far from unity and the inner cavity formed by the membranes is not perfect. In this low reflectivity limit, the interference of the light that gets trapped between the membranes is expected to increase the optomechanical coupling by $1/(1 - \sqrt{\mathcal{R}_m}) \sim 2.72$ compared to a single membrane. Indeed the observed increase in the optomechanical coupling of 2.47 is close to the theoretical expectation. The difference is attributed to a small misalignment between the two membranes, which also increases the cavity loss when the membrane sandwich is present in the cavity. This should be improved in further experiments. Finally, they show that both membranes can be cooled simultaneously through the optomechanical interaction.

The sandwich-in-the-middle optomechanic platform is a valuable addition to the growing number of multimode optomechanical systems, which allow to study and exploit collective effects. Replacing the simple membrane with an optical elements with a more dramatic optical response has the potential to significantly increase the ratio of the optomechnical coupling to the cavity decay time, thus showing the way toward strong optomechanical coupling.

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