Cavity Optomechanics

Kerry Vahala

California Institute of Technology, Pasadena, California 91125
vahala@caltech.edu

Abstract Cavity enhancement of optical fields is providing a new way to couple light and mechanical motion. Its application to mechanical cooling and amplification, example implementations, and prospects for new science and technology are reviewed.

OCIS codes: (140.3320) (140.4780) (230.1150) (140.3945)

Cavity enhancement of optical fields is routinely used to strengthen the coupling of light with matter in nonlinear optics and cavity QED [1]. In recent years, however, cavity enhancement is also providing a way to modify the mechanical properties of the cavity itself, with important connections into many disciplines [2]. Related effects have been theoretically studied for decades in the context of the measurement of weak forces using interferometers (such as in the LIGO system). There, optical forces create quantum back-action on the mechanical motion of the interferometer mirror, helping to establish the so-called standard-quantum-limit [3]. Classically, cavity-enhanced optical forces also have a dynamical back-action effect on the mirror motion [4], which is now being studied experimentally to amplify [5] and cool [6-11] mechanical motion across a wide range of cavity designs (see figure 1). These phenomena have parallels in the world of atomic and ionic cooling [2], which, itself, has helped to enable remarkable new science and unprecedented leaps in metrology [12,13]. Moreover, the subject of cavity optomechanics is leveraging a surge in novel methods to fabricate high-optical-Q and high-mechanical-Q microstructures. This powerful confluence bodes well both for new science and for scalable, chip-based technologies.

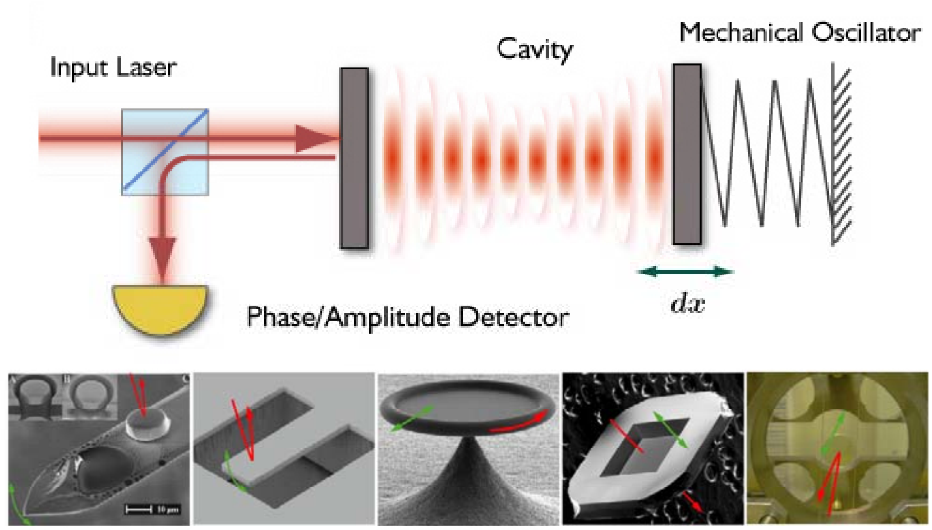

Figure 1: Upper panel: Simple representation of cavity opto-mechanical system in which a Fabry Perot interferometer is modified to include an end-mirror mechanical oscillator. Lower panel: a series of images of cavity opto-mechanical systems that are now being studied. From left to right: mirror on an AFM tip [8], mirror on a cantilever [7], microtoroid resonator [5,9], SiN membrane [11], and a gram-scale mirror [10]. (Upper panel is from ref. [2])

Experimental work is focused on dynamic back action for cooling and amplification of mechanical motion. The physics of this process can be understood by consideration of a Fabry Perot in which an end mirror is attached to a spring so as to function as a mechanical oscillator (Figure 1). The thermal oscillatory motion of the mirror induces (by way of Doppler shifts) Stokes and anti-Stokes sidebands on a pump laser field. Were the pump frequency exactly on resonance with the cavity, these sidebands would have equal amplitudes. However, with a detuned pump, the local density-of-modes will modify the scattering of power

978-1-55752-869-8/09/$25.00 ©2009 IEEE

into each of these sidebands. The detuning conditions illustrated in figure 2A and 2B represent cases where the power scattering is most asymmetric. In figure 2A, the pump wave is blue-detuned relative to the cavity resonance by an amount equal to the mirror oscillation frequency. The Stokes wave is therefore resonant with the cavity and experiences strong scattering enhancement. The complementary situation of a red-detuned pump is diagrammed in figure 2B. In each case, there is power imbalance when considering the incident optical power versus the total scattered power. Blue detuning causes a transfer of power from the optical wave to the mechanical oscillator mirror that can be shown to create amplification of the mirror motion; while a red-detuned, pump wave causes thermal power to be transferred from the mirror to the optical field, and thereby cools the mirror mode. The ability to amplify mechanical motion has lead to a new type of regenerative oscillator at microwave rates [5]. Back action cooling, on the other hand, is being pursued as a means to realize the quantum ground state of a macroscopic mechanical oscillator; the realization of which can enable numerous, long-anticipated studies of quantum opto-mechanical phenomena [14, 15], including even tests of quantum mechanics itself [16]. Recent progress in this field, including both advances in cooling and also demonstration of new micro and nano-cavity designs will be described. Also, possible future directions of research and the potential impact of this work on technology will be considered.

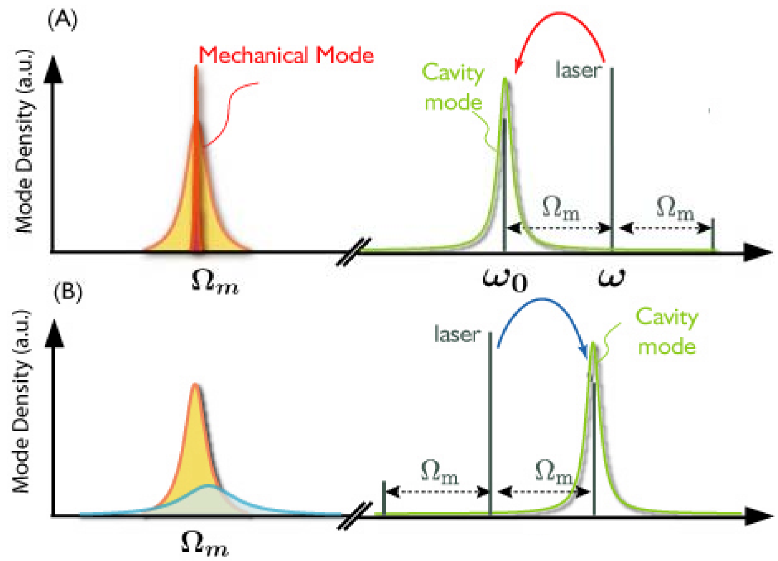

Figure 2: Spectral illustration of dynamic back action amplification (upper panel) and cooling (lower panel). On the right is shown the optical spectrum wherein a laser pump is blue detuned (above) or red detuned (below) relative to the cavity resonance by an amount equal to the mechanical eigen-frequency (Ω_m). The resulting power transfer amplifies (above) or cools (below) the mechanical mode (shown on the left). Cooling is also accompanied by damping which broadens the mechanical resonance as illustrated in the lower left panel (Panels from ref. [2]).

References

[1] Vahala, K. J., Optical microcavities. *Nature* **424**, 839-846 (2003).
[2] T.J. Kippenberg and K.J. Vahala, Cavity Optomechanics, *Science*, **321**, 1172, (2008).
[3] Caves, C. M. Quantum-Mechanical Noise in an Interferometer. *Physical Review D* **23**, 1693-1708 (1981).
[4] Braginsky, V. B. *Measurement of Weak Forces in Physics Experiments* (University of Chicago Press, Chicago, 1977).
[5] Kippenberg, T. J., Rokhsari, H., Carmon, T., Scherer, A. & Vahala, K. J. *Physical Review Letters* **95**, 033901 (2005); Carmon, T., Rokhsari, H., Yang, L., Kippenberg, T. J. & Vahala, K. J. *Physical Review Letters* **94** (2005); Rokhsari, H., Kippenberg, T. J., Carmon, T. & Vahala, K. J. *Optics Express* **13**, 5293-5301 (2005).
[6] S. Gigan, H. R. Böhm, M. Paternostro, F. Blaser, G. Langer, J.B. Hertzberg, K. C. Schwab, D. Bäuerle, M. Aspelmeyer, A. Zeilinger .*Nature* **444**, 67-70 (2006).
[7] Arcizet, O., Cohadon, P. F., Briant, T., Pinard, M. & Heidmann, A. *Nature* **444**, 71-74 (2006).
[8] Kleckner, D. & Bouwmeester, D. *Nature* **444**, 75-78 (2006).
[9] Schliesser, A., Del'Haye, P., Nooshi, N., Vahala, K. J. & Kippenberg, T. J. *Physical Review Letters* **97**, 243905 (2006).
[10] Corbitt, T., Ottaway, D., Innerhofer, E., Pelc, J. & Mavalvala, N., *Physical Review A* **74** (2006).
[11] J. D. Thompson, B. M. Zwickl, A. M. Jayich, Florian Marquardt, S. M. Girvin & J. G. E. Harris, *Nature* **452**, 72 (2008).
[12] R. Blatt and D. Wineland, *Nature*, **453**, 1008 (2008).
[13] K. Helmerson and W.D. Phillips, *Rivista del Nuovo Cimento*, **31**, 141 (2008).
[14] K. C. Schwab, M. L. Roukes, Phys. Today **58**, 36 (2005).
[15] Mancini, S., Giovannetti, V., Vitali, D. & Tombesi, P. *Physical Review Letters* **88**, 120401 (2002).
[16] Marshall, W., Simon, C., Penrose, R. & Bouwmeester, D. *Physical Review Letters* **91** (2003).