>1GHz Optically Excited Vibrations of a Micron-Scale On-Chip Sphere

Tal Carmon and Kerry J. Vahala
Caltech
1200 E. California BLVD.
Pasadena, CA 91125 USA
tal@caltech.edu

Abstract— >1GHz optically-induced vibrations are demonstrated in an on-chip micron-scaled device in which radiation pressure of a (CW) optical input pushes the structure to mechanically oscillate. Many mechanical eigen-modes are investigated.

Radiation pressure (RP) can push the boundaries of an optical cavity to change its optical path [1, 2]. In doing this, RP also couples the optical and mechanical motion of the cavity. For this reason RP has been suggested as a mechanism for study of many quantum opto-mechanical applications [3-6] including quantum superposition of a macroscopic object [6]. Recently, radiation pressure of the light circulating in the cavity was demonstrated experimentally to excite mechanical vibrations [7-9]. These vibrations were demonstrated in the sub 100 MHz regime with a toroidal resonator hung on a thin ($2\mu\text{m}$) membrane. The next challenges are to excite such vibrations in cavities of rigid geometries (e.g. sphere) and to also demonstrate higher-order mechanical modes. More than exemplifying the universality of RP induced vibrations for various geometries, such avenues of study also allow for much higher eigen-frequencies.

Here we demonstrate experimentally excitation of the high-order mechanical modes of a spherical micro cavity. Vibration at frequencies above 1GHz is excited in a $24\mu\text{m}$ silica spheroid [10] on a silicon-chip platform. The simple experimental setup (fig. 1a) consists of a CW optical input coupled to a spherical cavity (fig. 1c) by means of tapered fiber [11, 12]. Radiation pressure created by the light circulating in the cavity excites vibrational modes of the sphere via a parametric instability as described in refs 7-9 for the case of toroidal devices. It is emphasized that the optical input here is CW and that no external modulation or feedback are used. When the input optical wavelength is tuned to optical resonance of the spherical oscillator and a threshold power is exceeded, mechanical vibration is excited in the spheroid and modulates the output optical power with a similar frequency. The equations that describe this dynamic are given in reference 7. Exciting high-order mechanical modes is done by shortening the lifetime of the optical-cavity photons, which, in practice, is done by changing the coupling. Oscillation here starts sinusoidal, but as optical power increases, higher harmonics of the eigen mechanical frequency appear in the optical spectra due to the nonlinear transfer function that relates the mechanical strain to optical-power. As many as 18 harmonics of the fundamental are

visible in the top panel of figure 2. As the exciting radiation pressure is axially symmetric, the excited mechanical modes are also axisymmetric. Such axisymmetric modes are calculated (fig. 2) and theoretical eigen-frequencies deviate only $\sim 3\%$ from the measured eigen-frequencies. As the frequency gets higher, the supporting silicon pillar also participates in the vibration. Of significance is the excitation of a vibrational mode with eigenfrequency 1.08 GHz (fig 2 RHS). The theoretical strain field for this mode shows that it

Fig. 1. (a) Schematic description of mechanical vibrations excited by CW input for a spherical cavity. (b) Micrograph of the spherical cavity. (c) Fabry-Perot analog.

contains many nodes.

To conclude, in analogy to optical spectroscopy as a tool to deduce the mechanical modes of a molecule, we have here studied the spectroscopy associated with the mechanical modes of a macroscopic object by measuring its interaction with radiation. Finally, the sustained trend in dissipation reduction and miniaturization of resonators suggests that vibrations excited by radiation pressure are expected to occur in other platforms, geometries and at yet higher frequencies.

Fig. 2. Measured optical-power oscillation with the corresponding calculated mechanical modes where colors represent log of the strain energy. Also calculated is the nodes geometry. The drawn deflection here is exaggerated.

REFERENCES

- [1] A. Dorsel, J. D. McCullen, P. Meystre, E. Vignes, and H. Walther, "Optical Bistability and Mirror Confinement Induced by Radiation Pressure," *Phys Rev Lett*, vol. 51, pp. 1550-1553, 1983.
- [2] V. B. Braginsky, M. L. Gorodetsky, V. S. Ilchenko, and S. P. Vyatchanin, "On the Ultimate Sensitivity in Coordinate Measurements," *Physics Letters A*, vol. 179, pp. 244-248, 1993.
- [3] L. Hilico, J. M. Courty, C. Fabre, E. Giacobino, I. Abram, and J. L. Oudar, "Squeezing with $\text{Chi}(3)$ Materials," *Appl Phys B-Photo*, vol. 55, pp. 202-209, 1992.
- [4] V. Giovannetti, S. Mancini, and P. Tombesi, "Radiation pressure induced Einstein-Podolsky-Rosen paradox," *Europhys Lett*, vol. 54, pp. 559-565, 2001.
- [5] S. Mancini, V. Giovannetti, D. Vitali, and P. Tombesi, "Entangling macroscopic oscillators exploiting radiation pressure," *Phys Rev Lett*, vol. 88, pp. -, 2002.
- [6] W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester, "Towards quantum superpositions of a mirror," *Phys Rev Lett*, vol. 91, pp. 130401, 2003.
- [7] T. Carmon, H. Rokhsari, L. Yang, T. J. Kippenberg, and K. J. Vahala, "Temporal behavior of radiation-pressure-induced vibrations of an optical microcavity phonon mode," *Phys Rev Lett*, vol. 94, pp. 223902, 2005.
- [8] H. Rokhsari, T. J. Kippenberg, T. Carmon, and K. J. Vahala, "Radiation-pressure-driven micro-mechanical oscillator," *Opt Express*, vol. 13, pp. 5293-5301, 2005.
- [9] T. J. Kippenberg, H. Rokhsari, T. Carmon, A. Scherer, and K. J. Vahala, "Analysis of radiation-pressure induced mechanical oscillation of an optical microcavity," *Phys Rev Lett*, vol. 95, pp. 033901, 2005.
- [10] D. K. Armani, T. J. Kippenberg, S. M. Spillane, and K. J. Vahala, "Ultra-high-Q toroid microcavity on a chip," *Nature*, vol. 421, pp. 925-928, 2003.
- [11] M. Cai, O. Painter, and K. J. Vahala, "Observation of critical coupling in a fiber taper to a silica-microsphere whispering-gallery mode system," *Phys Rev Lett*, vol. 85, pp. 74-77, 2000.
- [12] S. M. Spillane, T. J. Kippenberg, O. J. Painter, and K. J. Vahala, "Ideality in a fiber-taper-coupled microresonator system for application to cavity quantum electrodynamics," *Phys Rev Lett*, vol. 91, pp. 043902, 2003.