

Characterization of radiation pressure and thermal effects in a nanoscale optomechanical cavity

Ryan M. Camacho, Jasper Chan, Matt Eichenfield, and Oskar Painter

*Thomas J. Watson, Sr., Laboratory of Applied Physics, California Institute of Technology,
Pasadena, CA 91125*

opainter@caltech.edu

<http://copilot.caltech.edu>

Abstract: Optical forces in guided-wave nanostructures have recently been proposed as an effective means of mechanically actuating and tuning optical components. In this work, we study the properties of a photonic crystal optomechanical cavity consisting of a pair of patterned Si_3N_4 nanobeams. Internal stresses in the stoichiometric Si_3N_4 thin-film are used to produce inter-beam slot-gaps ranging from 560–40 nm. A general pump-probe measurement scheme is described which determines, self-consistently, the contributions of thermo-mechanical, thermo-optic, and radiation pressure effects. For devices with 40 nm slot-gap, the optical gradient force is measured to be 134 fN per cavity photon for the strongly coupled symmetric cavity supermode, producing a static cavity tuning greater than five times that of either the parasitic thermo-mechanical or thermo-optic effects.

© 2009 Optical Society of America

OCIS codes: (230.5298) Photonic crystals, (230.4685); Optical microelectromechanical devices, (230.5750); Resonators, (350.4855); Optical tweezers or optical manipulation, (270.5580); Quantum electrodynamics.

References and links

1. T. J. Kippenberg and K. J. Vahala, "Cavity Optomechanics: Back-Action at the Mesoscale," *Science* **321**(8), 1172–1176 (2008).
2. I. Favero and K. Karrai, "Optomechanics of deformable optical cavities," *Nat. Photonics* **3**(4), 201–205 (2009).
3. A. Dorsel, J. McCullen, P. Meystre, E. Vignes, and H. Walther, "Optical bistability and mirror confinement induced by radiation pressure," *Phys. Rev. Lett.* **51**(17), 1550–1553 (1983).
4. P. F. Cohadon, A. Heidmann, and M. Pinard, "Cooling of a Mirror by Radiation Pressure," *Phys. Rev. Lett.* **83**(16), 3174–3177 (1999).
5. S. Gigan, H. R. Böhm, M. Paternostro, F. Blaser, G. Langer, J. B. Hertzberg, K. C. Schwab, D. Bäuerle, M. Aspelmeyer, and A. Zeilinger, "Self-cooling of a micromirror by radiation pressure," *Nature* **444**, 67–70 (2006).
6. D. Kleckner and D. Bouwmeester, "Sub-kelvin optical cooling of a micromechanical resonator," *Nature* **444**, 75–78 (2006).
7. T. Corbitt, C. Wipf, T. Bodiya, D. Ottaway, D. Sigg, N. Smith, S. Whitcomb, and N. Mavalvala, "Optical Dilution and Feedback Cooling of a Gram-Scale Oscillator to 6.9 mK," *Phys. Rev. Lett.* **99**, 160801 (2007).
8. J. D. Thompson, B. M. Zwickl, A. M. Jayich, F. Marquardt, S. M. Girvin, and J. G. E. Harris, "Strong dispersive coupling of a high-finesse cavity to micromechanical membrane," *Nature* **452**(6), 72–75 (2008).
9. A. Schliesser, P. Del'Haye, N. Nooshi, K. J. Vahala, and T. J. Kippenberg, "Radiation Pressure Cooling of a Micromechanical Oscillator Using Dynamical Backaction," *Phys. Rev. Lett.* **97**, 243905 (2006).
10. M. L. Povinelli, M. Loncar, M. Ibanescu, E. J. Smythe, S. G. Johnson, F. Capasso, and J. D. Joannopoulos, "Evanescent-wave bonding between optical waveguides," *Opt. Lett.* **30**(22), 3042–3044 (2005).

11. M. Notomi, H. Taniyama, S. Mitsugi, and E. Kuramochi, "Optomechanical Wavelength and Energy Conversion in High- Q Double-Layer Cavities of Photonic Crystal Slabs," *Phys. Rev. Lett.* **97**, 023903 (2006).
12. M. Eichenfield, C. P. Michael, R. Perahia, and O. Painter, "Actuation of micro-optomechanical systems via cavity-enhanced optical dipole forces," *Nat. Photonics* **1**, 416 (2007).
13. M. Li, W. H. P. Pernice, C. Xiong, T. Baehr-Jones, M. Hochberg, and H. X. Tang, "Harnessing optical forces in integrated photonic circuits," *Nature* **456**(27), 480–484 (2008).
14. M. Eichenfield, R. Camacho, J. Chan, K. J. Vahala, and O. Painter, "A picogram- and nanometre-scale photonic crystal optomechanical cavity," *Nature* p. doi:10.1038 (2009).
15. G. Anetsberger, O. Arcizet, Q. P. Unterreithmeier, E. M. Weig, J. P. Kotthaus, and T. J. Kippenberg, "Near-field cavity optomechanics with nanomechanical oscillators," *ArXiv:0904.4051v1* (2009).
16. Q. Lin, J. Rosenberg, X. Jiang, K. J. Vahala, and O. Painter, "Mechanical oscillation and cooling actuated by the optical gradient force," *arXiv:0905.2716v1* (2009).
17. W. H. P. Pernice, M. Li, and H. X. Tang, "Photothermal actuation in nanomechanical waveguide devices," *J. Appl. Phys.* **105**, 014508 (2009).
18. E. F. Nichols and G. F. Hull, "A preliminary communication on the pressure of heat and light radiation," *Phys. Rev.* **13**, 307–320 (1901).
19. C. Höhberger and K. Karrai, "Cavity cooling of a microlever," *Nature* **432**(7020), 1002–1005 (2004).
20. B. Ilic, S. Krylov, K. Aubin, R. Reichenbach, and H. G. Craighead, "Optical excitation of nanoelectromechanical oscillators," *Appl. Phys. Lett.* **86**, 193114 (2005).
21. F. Marquardt, J. P. Chen, A. A. Clerk, and S. M. Girvin, "Quantum theory of cavity-assisted sideband cooling of mechanical motion," *Phys. Rev. Lett.* **99**(9), 093902 (2007).
22. I. Wilson-Rae, N. Nooshi, W. Zwerger, and T. J. Kippenberg, "Theory of ground state cooling of a mechanical oscillator using dynamical backaction," *Phys. Rev. Lett.* **99**(9), 093901 (2007).
23. P. T. Rakich, M. A. Popovic, M. Soljacic, and E. P. Ippen, "Trapping, coralling and spectral bonding of optical resonances through optically induced potentials," *Nature Photonics* **1**(11), 658–665 (2007).
24. J. Rosenberg, Q. Lin, K. J. Vahala, and O. Painter, "Static and Dynamic Wavelength Routing via the Gradient Optical Force," *arXiv:0905.3336v1* (2009).
25. J. Chan, M. Eichenfield, R. Camacho, and O. Painter, "Optical and mechanical design of a "zipper" photonic crystal optomechanical cavity," *Opt. Express* **17**(5), 3802–3817 (2009).
26. P. B. Deotare, M. W. McCutcheon, I. W. Frank, M. Khan, and M. Loncar, "Coupled photonic crystal nanobeam cavities," *arXiv:0905.0109v1* (2009).
27. S. S. Verbridge, J. M. Parpia, R. B. Reichenbach, L. M. Bellan, and H. G. Craighead, "High quality factor resonance at room temperature with nanostrings under high tensile stress," *J. Appl. Phys.* **99**, 124304 (2006).
28. C. P. Michael, M. Borselli, T. J. Johnson, C. Chrystal, and O. Painter, "An optical fiber-taper probe for wafer-scale microphotonic device characterization," *Opt. Express* **15**(8), 4745–4752 (2007).
29. C. K. Law, "Effective Hamiltonian for the radiation in a cavity with a moving mirror and a time-varying dielectric medium," *Phys. Rev. A* **49**(1), 433–437 (1994).
30. P. E. Barclay, K. Srinivasan, and O. Painter, "Nonlinear response of silicon photonic crystal microcavities excited via an integrated waveguide and fiber taper," *Opt. Express* **13**(3), 801–820 (2005).
31. J. T. Robinson, C. Manolatou, L. Chen, and M. Lipson, "Ultrasmall Mode Volumes in Dielectric Optical Microcavities," *Phys. Rev. Lett.* **95**, 143901 (2005).
32. C. Koos, P. Vorreau, T. Vallaitis, P. Dumon, W. Bogaerts, R. Baets, B. Esembeson, I. Biaggio, T. Michinobu, F. Diederich, W. Freude, and J. Leuthold, "All-optical high-speed signal processing with siliconorganic hybrid slot waveguides," *Nature Photonics* **3**, 216–219 (2009).
33. J. T. Robinson, L. Chen, and M. Lipson, "On-chip gas detection in silicon optical microcavities," *Opt. Express* **16**(6), 4296–4301 (2008).

Radiation pressure forces have recently been studied in the context of mechanically compliant optical microcavities for the sensing, actuation, and damping of micromechanical motion [1, 2]. A wide variety of cavity geometries have been explored, from Fabry-Perot cavities with movable internal elements or end-mirrors [3–8], to monolithic whispering-gallery glass microtoroids [9]. Nanoscale guided-wave devices have also been studied due to their strong optomechanical coupling resulting from the local intensity gradients in the guided field [10–16]. In addition to radiation pressure forces, there exists in each of these cavity geometries competing thermally driven effects [17], a result of optical absorption. Thermally induced processes include strain-optical, thermo-optical, and a variety of thermo-mechanical effects (early measurements of radiation pressure, for instance, were plagued by thermo-mechanical "gas action" effects [18]). In many cases (but not all [19, 20]), thermal effects can be neglected at

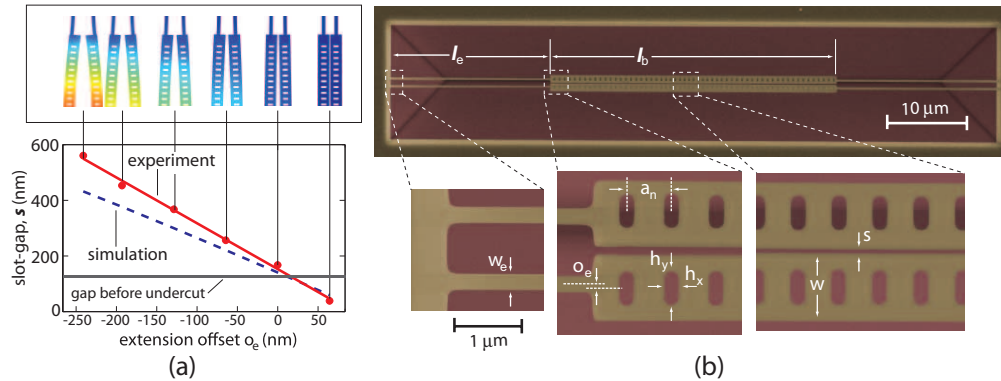


Fig. 1. (a) Slot width vs. extension offset, simulation and experiment. Support extensions placed near the outside of the beam width cause outward bowing, but inward bowing when placed near the inside. (b) Scanning electron microscope images of a device with support extensions placed just inside of center, causing slight inward bowing resulting in approximately a slot-gap of $s = 40$ nm at the cavity center. The device parameters that are common amongst all the devices tested in this work are: nominal lattice constant $a_n = 590$ nm, extension width $w_e = 211$ nm, hole width $h_x = 190$ nm, hole height $h_y = 416$ nm, beam width $w = 833$ nm, beam length $l_b = 18.4 \mu\text{m}$, extension length $l_e = 33.1 \mu\text{m}$. In order to vary the slot-gap size from 40-560 nm, the extension offset was varied between $o_e = 70$ to -235 nm.

the high frequencies associated with micromechanical resonances [9]; however, for static cavity tuning thermal effects may play a significant, if not dominant, role. Calibration of thermal effects is important not only in identifying the contribution of pure radiation pressure effects, but also in understanding the parasitic local heating processes, which in the realm of quantum optomechanics may limit optical cooling methods [21, 22], or for tunable photonics applications [13, 23, 24] where deleterious inter-device thermal coupling may arise.

In this work we describe the characterization of the low frequency (static) optical and thermal effects in a nanoscale photonic crystal cavity. This so-called zipper cavity [14, 25, 26] consists of a matched pair of Si_3N_4 nanobeams, placed in the near-field of each other, and patterned with a one-dimensional (1D) array of air holes. The resonant optical modes of the zipper cavity [25] consist of manifolds of even (bonded) and odd (anti-bonded) symmetry supermodes of the dual nanobeams, localized along the long-axis of the beams to a central *defect* in the photonic lattice. The strength of the gradient optical force applied to the beams is exponentially dependent upon the inter-beam slot gap (s) and is described by a dispersive coupling coefficient, $g_{\text{OM}} \equiv (\partial\omega_c/\partial\alpha)$, where ω_c is the gap-dependent optical cavity resonance frequency and α parametrizes the change in the inter-beam slot gap. Utilizing the connection between cavity mode dispersion and applied optical force, a pump-probe scheme is described below to accurately quantify the optomechanical, thermo-optic, and thermo-mechanical contributions to the static tuning of the bonded and anti-bonded modes versus internal cavity photon number.

The zipper cavity devices studied here were fabricated from optically thin ($t = 400$ nm) stoichiometric silicon nitride (Si_3N_4), deposited using low-pressure chemical vapor deposition on a silicon wafer. The deposition process results in residual in-plane stress in the nitride film of approximately $\sigma \sim 1$ GPa [27]. Electron-beam lithography is used to pattern zipper cavities with beams of length $l_b = 33.1 \mu\text{m}$, width of $w = 833$ nm, and an inter-beam spacing of $s = 120$ nm. The beams are clamped at each end using extensions with length equal to $l_e = 18.4 \mu\text{m}$ and width of $w_e = 211$ nm. The nanobeam and photonic crystal hole pattern are transferred into the Si_3N_4 film using a $\text{C}_4\text{F}_8/\text{SF}_6$ plasma etch. The underlying Si substrate is selectively etched

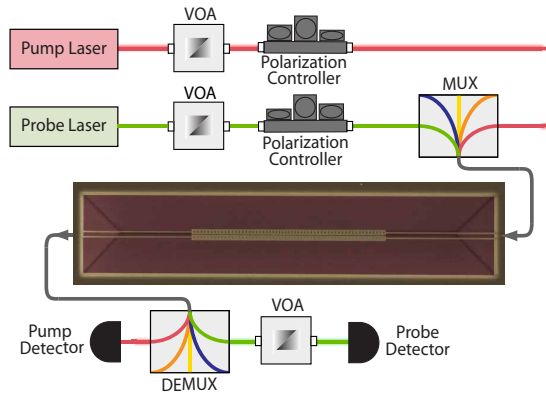


Fig. 2. Experimental setup for optical testing. Two separate lasers (pump and probe) with independent power control, via variable optical attenuators (VOA), and polarization control are combined into a fiber taper waveguide placed in the near-field of the photonic crystal cavity. Cavity transmission at both the pump and probe wavelengths are multiplexed and demultiplexed using a matched set of fiber-based filters and separately monitored using calibrated photodetectors.

using KOH, releasing the patterned beams. The devices are dried using a critical point CO₂ drying process to avoid surface-tension-induced adhesion of the nanobeams.

The internal stress of the Si₃N₄ thin-film is used to create a range of slot-gaps. This is achieved through misalignment of the support extensions and central nanobeams (Fig. 1(b)), breaking the symmetry of the internal stress along the length of the beams. As shown by the finite-element-method (FEM) simulations and device measurements plotted in Fig. 1(a), extensions placed near the outside edge of the beams cause outward bowing of the beams, while extensions placed near the inside edge cause inward bowing. By varying the lateral offset of the extension (defined as the difference between the center of the main beam and the center of the extension beam) from $o_e = 70$ to -235 nm, zipper cavities with slot-gaps at the cavity center ranging from 40-560 nm are created. Slot-gaps smaller than 40 nm could not be stably produced without the nanobeams sticking together at points of nanometer-scale roughness in the inner sidewall of the beams.

Optical spectroscopy of the zipper cavity modes is performed using the experimental setup shown in Fig. 2. In this setup, laser light from a bank of tunable external-cavity diode lasers covering the 1400-1625 nm wavelength band is coupled into an optical fiber taper nanoprobe. Using precision motorized stages, the tapered fiber can be controllably placed into the near-field of a zipper cavity [28], allowing for evanescent excitation and detection of resonant modes. Polarization of the laser field is adjusted using a fiber polarization controller, and optimized for coupling to the high- Q TE-like modes of the zipper cavity [25] (i.e., dominant electric field polarization in the plane of the device).

Figure 3(a) shows a series of wavelength scans from an array of nominally identical zipper cavities, each with slightly differing slot-gap due to variation in the lateral extension alignment. Scanning electron microscope images of the central region of each zipper cavity, from which the slot-gap is measured, are shown to the right of each wavelength scan. Even (bonded) and odd (anti-bonded) parity supermodes are identified by stepping the taper across the width of the zipper cavity and noting the lateral spatial symmetry of the mode coupling [14]. Three distinct pairs of modes are identified in the wavelength scans, with the fundamental longitudinal cavity

modes ($TE_{\pm,0}$) occurring at shorter wavelengths and the higher-order modes shifted to longer wavelengths (this is a result of the negative curvature of the photonic band-edge from which the modes originate [25]). Radio frequency (RF) spectra of the optical transmission intensity (see Fig. 3(b)) were performed to verify the presence of micromechanical oscillation and free movement of the nanobeams even for the smallest of slot-gaps.

Overlaid on the wavelength scan plots of 3(a) are theoretical dispersion curves generated using FEM simulations of the optical properties of the zipper cavity (a single in-plane scaling factor of 5% was used to match the $TE_{+,0}$ resonant wavelength for the largest (560 nm) slot-gap, which is within the accuracy of our SEM calibration). Figure 3(c) shows a plot of the measured and simulated splitting of the fundamental bonded and anti-bonded modes versus the SEM-measured slot gap. Good correspondence is found for all but the smallest (40 nm) slot gap, in which the theoretical curve shows significantly more dispersion for the bonded modes. The source of this discrepancy is not fully understood, but may be due to other effects such as the dispersive nature of the refractive index of the Si_3N_4 material itself (the frequency separation of the even and odd supermodes is more than 10 THz for the smallest slot-gap). As discussed below, the local sensitivity of each mode to beam displacement is consistent with the measured 40 nm slot gap.

In order to understand the various actuation methods of the zipper cavity, it is useful to consider the dispersive nature of the two supermode mode types, and their relation to the magnitude and direction of the optical force. In an adiabatic limit [10,29], the radiation pressure force can be related to the gradient of the internal optical cavity energy, $F_{OM} = -\partial(N\hbar\omega_c)/\partial\alpha = -N\hbar g_{OM}$, where N is the stored photon number and α is a displacement factor related to the movement of the nanobeams (here we choose α to be equal to one half the slot-gap size to be consistent with previous work in Refs. [14,25]). As can be seen in the measured and simulated dispersion curves of Figure 3(c), the symmetric bonded modes with large field strength in between the beams, tunes to the red with shrinking slot-gap (i.e., g_{OM} for the bonded mode is positive for $\alpha = s/2$). The direction of the optical force for photons stored in a bonded mode thus tends inwards, pulling the beams together (this is a result of the fact that in order to perform mechanical work on the beams, the stored photons must lose energy through a reduction in their frequency). In the case of the odd parity anti-bonded cavity modes, the resonance frequency decreases with increasing slot-gap, resulting in a negative g_{OM} and an optical force that pushes the beams apart.

Owing to the different dispersive character of the bonded and anti-bonded cavity modes, and the different directions in which cavity photons of each mode type apply forces to the two beams, pure radiation pressure effects actuate and tune the cavity modes in a unique and distinctive manner. This should be contrasted with thermo-optic and thermo-mechanical effects. The thermo-optic tuning of the cavity modes is related to the change in refractive index of the cavity material with temperature. For the Si_3N_4 zipper cavity studied here, the thermo-optic coefficient is known to be positive (and of magnitude $\partial n/\partial T \approx 1.9 \times 10^{-5} \text{ K}^{-1}$ [14]). The manifold of bonded and anti-bonded cavity modes thus tend to uniformly red shift with increasing temperature due to the thermo-optic effect (differences between modes in resonance frequency and modal overlap with the Si_3N_4 beams are insignificant). Increased temperature in the local cavity region of the beams, due to optical absorption, not only increases the refractive index of the clamped beams, but may also produce non-uniform thermal expansion and significant strain in the structure. Unlike the radiation pressure force, the resulting thermo-mechanical force is only dependent upon the temperature rise, and thus actuates the zipper cavity beams in the same manner independent of which cavity mode is being driven. Owing to the different dispersive nature of the cavity modes, however, the sign of the thermo-mechanical tuning will depend upon the type of supermode being considered.

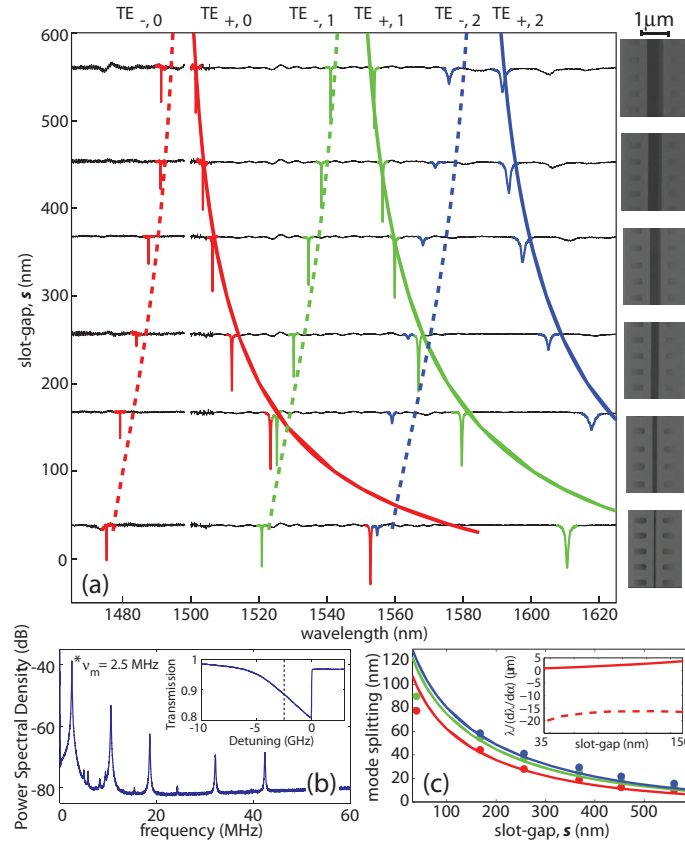


Fig. 3. (a) Experimentally measured optical transmission as a function of wavelength in an array of six devices (SEM images of the central cavity region on right), each with a different slot-gap. Overlaid are FEM simulations of the cavity mode dispersion versus gap size, where solid curves are for the bonded modes, dashed curves for the anti-bonded modes, and the color of the curve matches the highlighting applied to the different mode orders (red= $\text{TE}_{\pm,0}$, green= $\text{TE}_{\pm,1}$, blue= $\text{TE}_{\pm,2}$). (b) Measured RF spectrum of the $\text{TE}_{+,0}$ mode for the largest gap ($s = 560$ nm) zipper cavity. Inset shows the optical transmission as a function of detuning as the pump laser is swept across the cavity resonance (dashed vertical line indicates detuning for RF spectrum measurement). (c) Plot of the FEM-simulated and experimentally measured bonded and anti-bonded mode splitting versus slot-gap. The inset shows the effective optomechanical coupling length ($L_{OM} \equiv \lambda / (d\lambda/d\alpha)$) in the small slot-gap region (solid curve for bonded mode, dashed curve for anti-bonded mode).

We perform measurements of the different cavity mode tuning mechanisms using a two laser pump and probe scheme. In this scheme, a strong pump beam is coupled into either the fundamental bonded ($\text{TE}_{+,0}$) or anti-bonded ($\text{TE}_{-,0}$) cavity mode. In order to measure the self-mode tuning of a given mode the pump laser frequency is swept across the cavity mode resonance producing a bistability curve such as that shown in Fig. 3(b). A fit to the bistability curve yields the self-mode resonance tuning versus dropped power into the cavity for a fixed input power. The dropped cavity power is then converted into an internal photon number via the intrinsic Q -factor of the cavity mode [30] (measured to be $Q_i \approx 6 \times 10^4$ for both the fundamental bonded and anti-bonded modes using a calibrated fiber Mach-Zender interferometer). In order to ob-

tain the cross-mode tuning between bonded and anti-bonded modes the pump beam wavelength is stepped across the resonance of one of the modes. At each step in the pump wavelength a weak probe beam is scanned across the other mode. Converting the dropped pump power into a stored photon number (again using the intrinsic cavity Q -factor), and fitting a Lorentzian line-shape to the probe scan yields the desired cross-mode tuning curve. In these measurements a pump power of $\sim 300 \mu\text{W}$ and a probe power of $\sim 100 \text{nW}$ were used to ensure only the pump beam produces a significant tuning of the modes. The measured self and cross tuning curves of the smallest slot-gap (40 nm) zipper cavity, with the strongest optomechanical coupling, are shown in Fig. 4(a).

These measurements yield four tuning slopes $s_{ij} \equiv \Delta\omega_{ij}/N_i$, where subscripts $i, j \in \{e, o\}$ label the cavity mode (e for the even bonded mode, o for the odd anti-bonded mode), N_i is the stored cavity photon number of the pump mode, and $\Delta\omega_{ij}$ is the induced frequency shift in the j th mode due to the i th pump mode (note for self-tuning there is only one mode and laser; the j th mode is the same as the i th pump mode). For the limited model in which we consider optomechanical, thermo-mechanical, and thermo-optic sources of mode tuning, the induced frequency shift in a given mode can be separated into two components, one which is mechanical in nature and depends upon the reaction of a given mode to the deflection of the nanobeams, the other which is independent of the type of mode (bonded or anti-bonded) and is only dependent upon the intensity of the internal cavity field (photon number):

$$\Delta\omega_{ij} = \delta\alpha_i g_j + c_{to} N_i, \quad (1)$$

where $\delta\alpha_i$ is the induced beam deflection (change in the half-slot-gap extent) due to the i th pump mode, g_j is the optomechanical coupling coefficient of the j th mode, and here the intensity-dependent coefficient, c_{to} , is associated with the thermo-optic tuning of the cavity (other tuning mechanisms, such as due to the Kerr effect, are also included in this term but are expected to be negligible in comparison to the thermo-optic effect). The beam deflection can be related to the optically-induced forces acting on the nanobeams, $f_i = -\hbar(g_i + g_{tm})N_i$, where the first term is the i th mode radiation pressure force as described above, and the second term is due to general thermo-mechanical effects (parametrized by the constant g_{tm}). Here we assume that the thermo-mechanical forces depend only upon the photon number, and not the type of mode, which is a good assumption due to the negligible difference in the optical absorption (or generated heat) expected for the two mode types. Putting this all together, the tuning slopes can be related to the four coefficients describing the opto-mechanical, thermo-mechanical, and thermo-optic per-photon forces/dispersion:

$$s_{ij} = \left(\frac{f_i}{kN_i} \right) g_j + c_{to} = \left(\frac{-\hbar(g_i + g_{tm})}{k} \right) g_j + c_{to}. \quad (2)$$

where k is the spring constant associated with differential in-plane motion of the zipper cavity nanobeams (which must be determined self-consistently based upon our choice of “amplitude”, $\alpha = (1/2)s$).

Solving the set of coupled equations for the four cavity tuning coefficients yields (for $\alpha \equiv s/2$, i.e., $g_e > 0$, $g_o < 0$),

$$g_e = -\xi \sqrt{\frac{k}{\hbar}} \Delta_e, \quad (3a)$$

$$g_o = \xi \sqrt{\frac{k}{\hbar}} \Delta_o, \quad (3b)$$

$$g_{tm} = \xi \sqrt{\frac{k}{\hbar}} \Delta_c, \quad (3c)$$

$$c_{to} = -\xi^2 (s_{ee}s_{oo} - s_{eo}s_{oe}), \quad (3d)$$

where $\xi \equiv 1/\sqrt{-(\Delta_e + \Delta_o)}$, and we have defined relative tuning slopes $\Delta_e = s_{ee} - s_{oe}$, $\Delta_o = s_{oo} - s_{eo}$, and $\Delta_c = s_{eo} - s_{oe}$. From the measured and fit tuning slopes shown in Fig. 4(a), we extract the following values for the optomechanical and thermal coefficients of the smallest slot-gap zipper cavity: $\sqrt{\hbar/k}g_e = 1.44 \pm 0.04$, $\sqrt{\hbar/k}g_o = -0.083 \pm 0.021$, $\sqrt{\hbar/k}g_{tm} = -0.29 \pm 0.01$, and $\sqrt{-c_{to}} = 0.68 \pm 0.02$, all in units of $\sqrt{\text{MHz/photon}}$. The uncertainty in the measured coefficients is dominated by systematic error in the internal cavity photon number ($\sim 5\%$ due to uncertainty in cavity Q and optical input power).

The resulting contributions from this model to the cavity mode tuning are shown graphically in Fig. 4(b). Qualitatively, the resulting contributions to the measured mode tuning are consistent with expectations. In particular, the strong radiation pressure force and dispersive nature of the even bonded mode results in the most significant mode tuning when light is coupled into this mode (i.e., the “*ee*” configuration). In contrast, the weak dispersive nature of the odd anti-bonded mode means that when pumping on this mode not only is the radiation pressure force small, but any thermo-mechanical force is also transduced more weakly for this mode (resulting in the very small tuning in the “*oo*” configuration). The sign of the thermo-optic coefficient, which should result in a red-detuning of the mode, is found to be in accordance with expectations. The more difficult response to untuit, due to the thermo-mechanical effect, is found to result in an effective force that pushes the nanobeams apart with a magnitude in between that of the radiation pressure force of the even and odd supermodes of the zipper cavity.

A quantitative comparison of the measured and simulated contributions to the mode tuning and relevant forces can also be made. For an effective mechanical spring constant of $k = 13.18$ N/m (estimated from the mode-shape, motional mass $m_x \approx 53$ pg, and mode frequency $\Omega_M/2\pi = 2.5$ MHz for the fundamental in-plane mechanical mode of the zipper cavity structure [25]), the corresponding optomechanical coupling coefficients are $g_e/2\pi = 202.4 \pm 5.6$ GHz/nm and $g_o/2\pi = -11.63 \pm 2.9$ GHz/nm. These should be compared with the theoretical values estimated from FEM simulation at the SEM-measured slot-gap for this device ($s = 40$ nm), which are $g_e/2\pi = 208$ GHz/nm and $g_o/2\pi = -11.4$ GHz/nm. A similar zipper cavity structure was also tested that did not have the thin beam extensions and with ten times the mechanical spring constant. The resulting cavity tuning rate in this structure is dominated by the thermo-optic effect, and is measured to be -0.69 MHz/photon, similar to the pump-probe measured value of $c_{to} = -0.47 \pm 0.03$ MHz/photon for the device studied in Fig. 4. From measurements of the cavity tuning rate versus substrate temperature of the stiff structure (-1.87 GHz/K), the estimated temperature rise rate in the cavity of Fig. 4 (using the pump-probe measured c_{to}) is $\beta = 2.5 \times 10^{-4}$ K/photon. For the largest pump powers used here this corresponds to a maximum cavity temperature rise of about 14 K. FEM simulations of the thermo-mechanical properties of the cavity structure show an increase of the inter-beam slot-gap per Kelvin of temperature rise in the central cavity region equal to $\delta s_{tm} = 0.021$ nm/K. This yields a simulated change in beam displacement factor per cavity

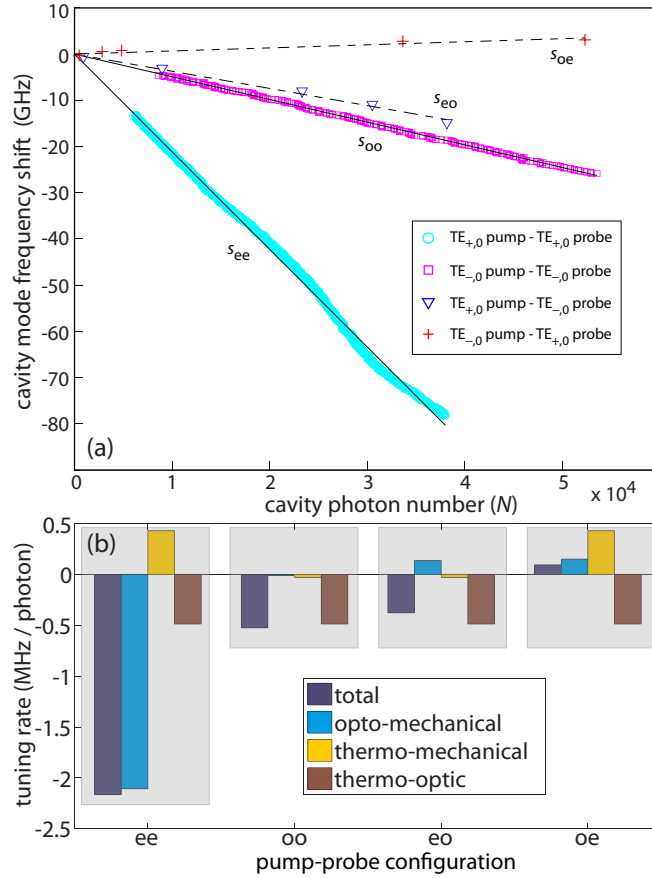


Fig. 4. (a) Measured tuning curves for the four pump-probe configurations. The solid (dashed) lines correspond to a linear fit to the self- (cross-) mode tuning data. (b) Opto-mechanical, thermo-mechanical, and thermo-optic tuning contributions as determined from a fit of the model coefficients.

photon of $\delta\alpha_{im} = (\delta s_{im}/2)\beta \approx 2.6$ fm/photon, or a thermo-mechanical force coefficient of $\tilde{g}_{im} = -(k/\hbar)\delta\alpha_{im} \approx -50$ GHz/photon, in good correspondence with the pump-probe measured value of $g_{im} = -40.8 \pm 1.4$ GHz/photon.

In conclusion, we have introduced a pump-probe method to completely characterize opto-mechanical, thermo-mechanical, and thermo-optic contributions to the static tuning of a zipper optomechanical cavity. Generally, this approach is useful for guided-wave devices in which near-field coupling between two (or more) elements is used to produce the optical gradient force, and for which the different supermodes of the composite structure introduce similar thermal and differing radiation pressure effects. We demonstrate the method experimentally using a strongly opto-mechanically coupled device, fabricated using a technique that allows for fine control over a nanoscale slot-gap which sets the magnitude of the optical gradient force. Using a device with a measured 40 nm slot-gap, we characterized all tuning mechanisms, and find in particular that the static tuning of the device is dominated by optical forces ($g_{OM} \approx 200$ GHz/nm equivalent to 0.13pN/photon). Beyond cavity optomechanics, the creation of ultra-small (tens of nanometer) slot gaps in photonic devices is interesting for cavity quantum electrodynamic-

ics [25, 31], nonlinear optics [32], and sensing [33], due to the extremely large per-photon electric field strengths that build up in such nano-slots.

Acknowledgements

This work was supported by a DARPA seed grant (grant no. HR0011-08-0002) and the National Science Foundation (EMT grant no. 0622246, MRSEC grant no. DMR-0520565, and CIAN grant no. EEC-0812072 through University of Arizona).