Photonic crystal paddle nanocavities for optomechanical torsion sensing

Marcelo Wu[1,2], **Aaron C. Hryciw**[2], **Behzad Khanaliloo**[1,2], **Mark R. Freeman**[2,3], **John P. Davis**[3], **Paul E. Barclay**[1,2]

1: Institute for Quantum Information Science, University of Calgary, 2500 University Drive NW, Calgary, AB, T2N 1N4, Canada

2: NRC-National Institute for Nanotechnology, 11421 Saskatchewan Drive NW, Edmonton, AB T6G 2M9, Canada

3: Department of Physics, University of Alberta, Edmonton, AB T6G 2E1, Canada

Abstract: Photonic crystal nanocavities with suspended central elements suitable for optomechanical detection of torsional forces are designed and fabricated. This "floating" low mass nanocavity may be mechanically coupled to nanomagnetic structures.

OCIS codes: (350.4238) Nanophotonics and photonic crystals; (120.4880) Optomechanics

Optomechanical cavities [1] provide an integrated platform for sensitive detection and control of mechanical displacements and forces by enhancing the interaction between light and its surrounding mechanical environment. Recent groundbreaking applications of cavity optomechanics include measurement of resonator mechanical motion with sensitivity near the standard quantum limit [2, 3], optical cooling of a resonator into its quantum ground state [4], and sensitive evanescent detection of mechanical oscillator [5] and cantilever [6] motion.

Nano- and microphotonic optomechanical devices can also function as sensitive detectors of non-optical forces and fields, for applications such as magnetometry of external fields [7], and nanoscale magnetic systems [8]. In these applications magnetic excitations couple to mechanical degrees of freedom, which are transduced by the optical cavity. To increase sensitivity, mechanical oscillators with both strong optomechanical cavity coupling *and* efficient coupling to magnetic moments, such as those associated with magnetic vortices in nanomagnetism, are desirable. Here we present a photonic crystal optomechanical cavity whose suspended central element is designed to support low effective mass torsional and flexural mechanical modes suited for probing nanomagnetic torques.

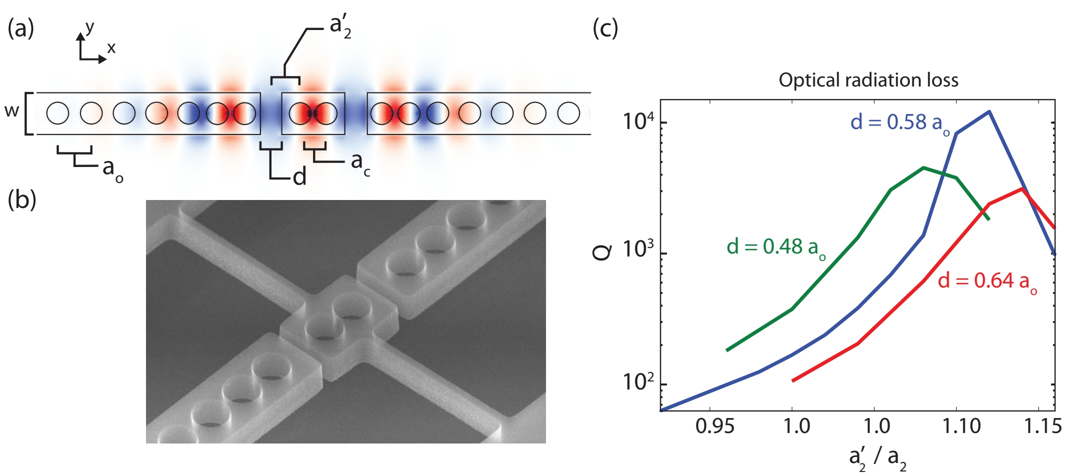

Fig. 1. (a) Photonic crystal paddle nanocavity design and simulated field profile, $E_y(x,y,z=0)$, of the high-Q TE-like mode supported by this structure (top view). Air holes (radius $r = 145$ nm) are patterned in a free standing silicon nanowire ($n_{\mathrm{Si}} = 3.5$, thickness $t = 250$ nm, width $w = 600$ nm). The nominal hole spacing varies quadratically over six periods from $a_c = 350$ nm to $a_o = 450$ nm. The two second closest holes to the cavity center are replaced with gaps in the nanowire of size $d = 0.58a_o$, and center position $a_2' = 1.12a_2$ where a_2 is the nominal spacing between the first and second hole of the uncut structure. (b) Scanning electron microscope image of a device fabricated from a Si membrane using design parameters similar to those in (a). (c) Simulated radiation Q of the photonic crystal paddle nanocavity mode as a function of gap position a_2', for varying gap size d. All other parameters are equal to those in (a). Calculated using three dimensional finite difference time domain simulation software (MEEP).

The photonic crystal paddle nanocavity studied here is shown in Figures 1(a,b), and consists of a modified silicon nanobeam photonic crystal nanocavity [9]. Two of the nanocavity holes have been replaced with gaps passing through the nanobeam, creating a floating or "suspended" central nanocavity paddle. In general, the gaps reduce the maximum attainable Q of optical modes supported by the nanocavity. However, as shown in Fig. 1(c), by tuning the gap size, d, and the gap position, a_2', TE-like modes with radiation loss limited $Q > 10^4$ can be supported by this structure. At the optimal d and a_2' values the "local" waveguide bandedge associated with the unit cell encompassing the gap is aligned with that of the removed hole unit cell. A typical mode profile is shown in Fig. 1(a) for parameters supporting a mode with $Q \sim 12000$ and resonant wavelength ~ 1650 nm. Additional enhancement to Q may be possible by further optimizing other nanocavity parameters. In a fabricated device, thin supports are necessary to suspend the nanocavity paddle, as shown in Fig. 1(b); the simulations in Figs. 1(a,c) do not include these supports. Additional simulations indicate that a 25 nm wide (250 nm thick) support similar to that shown in Fig. 1(b) does not degrade the maximum attainable nanocavity Q, although it reduces the optimal values of a_2' and d. Preliminary simulations indicate that introducing 50 nm wide supports should also be feasible without spoiling Q.

The optomechanical properties of the suspended nanocavity paddle can be optimized for specific functions through careful design of the paddle supports. Two types of mechanical resonances of particular interest are shown in Figs. 2(a,b). In the presence of an external magnetic field, these torsional and flexural resonances may be excited by magnetic moments from nanomagnetic materials attached either to the nanocavity paddle, or to mechanical structures connected to the supports. To date, optical readout of this type of magnetic-mechanical coupling has relied on free space interferometry [8]. In comparison, the photonic crystal optomechanical paddle nanocavity presented here has a lower effective mechanical mass ($\sim$ 100 fg), and higher optical Q. In addition, the nanocavity's small optical mode volume ($V \sim 0.3(\lambda/n_{\mathrm{Si}})^3$, defined by the peak per-photon electric field), and the strong overlap between the mechanical mode and optical mode peak field suggests that the optomechanical coupling strength, g_{OM}, may be large. However, due to the symmetry of the paddle with respect to the symmetric nanocavity mode, the optomechanical coupling will be quadratic in nature for the mechanical resonances shown in Fig. 2. To break this symmetry and obtain a linear optomechanical coupling, a geometry in which the paddle is offset from the field maximum may be used. On-going studies are focused on experimental characterization of photonic crystal paddle nanocavities, and optimizing the optomechanical properties of this device geometry for ultra-sensitive optical magnetometery.

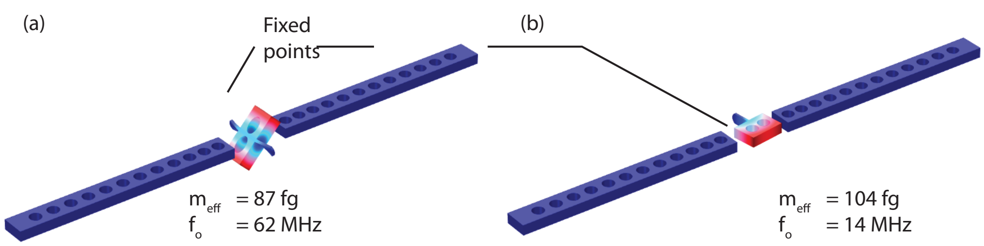

Fig. 2. (a) Torsional and (b) flexural mechanical resonances of the photonic crystal paddle optomechanical cavity. The length and width of the paddle supports are 500 and 50 nm, respectively. In a real device these supports are attached to the surrounding silicon wafer; see Fig. 1(b). The support dimensions can be adjusted to tune the mechanical resonance frequencies.

References

[1] T. J. Kippenberg and K. J. Vahala, "Cavity Opto-Mechanics," Opt. Express **15**, 17 172–17 205 (2007).

[2] O. Arcizet, P.-F. Cohadon, T. Briant, M. Pinard, A. Heidmann, J.-M. Mackowski, C. Michel, L. Pinard, O. Français, and L. Rousseau, "High-Sensitivity Optical Monitoring of a Micromechanical Resonator with a Quantum-Limited Optomechanical Sensor," Phys. Rev. Lett. **97**, 133 601 (2006).

[3] A. Schliesser, O. Arcizet, R. Rivière, G. Anetsberger, and T. Kippenberg, "Resolved-sideband cooling and position measurement of a micromechanical oscillator close to the Heisenberg uncertainty limit," Nature Physics **5**, 509–514 (2009).

[4] J. Chan, T. P. M. Alegre, A. H. Safavi-Naeini, J. T. Hill, A. Krause, S. Groblacher, M. Aspelmeyer, and O. Painter, "Laser cooling of a nanomechanical oscillator into its quantum ground state," Nature **478**, 89–92 (2011).

[5] G. Anetsberger, O. Arcizet, Q. Unterreithmeier, R. Rivière, A. Schliesser, E. Weig, J. Kotthaus, and T. Kippenberg, "Near-field cavity optomechanics with nanomechanical oscillators," Nature Physics **5**, 909–914 (2009).

[6] K. Srinivasan, H. Miao, M. Rakher, M. Davanço, and V. Aksyuk, "Optomechanical transduction of an integrated silicon cantilever probe using a microdisk resonator," Nano letters **11**, 791 (2011).

[7] S. Forstner, S. Prams, J. Knittel, E. van Ooijen, J. Swaim, G. Harris, A. Szorkovszky, W. Bowen, and H. Rubinsztein-Dunlop, "Cavity Optomechanical Magnetometer," arXiv:1110.2271 (2011).

[8] J. Davis, D. Vick, D. Fortin, J. Burgess, W. Hiebert, and M. Freeman, "Nanotorsional resonator torque magnetometry," Applied Physics Letters **96**, 072 513 (2010).

[9] M. W. McCutcheon and M. Lončar, "Design of an ultrahigh Quality factor silicon nitride photonic crystal nanocavity for coupling to diamond nanocrystals," Opt. Express **16**, 19 136 (2008).