Self-aligning "smart" microcavities and picometer-scale optomechanical control through optical forces and potentials

Peter T. Rakich[*], Miloš A. Popović, Marin Soljačić and Erich P. Ippen
Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, Massachusetts 02139
[*]e-mail: rakich@mit.edu

Abstract: We propose a new class of all-optical self-adaptive optomechanical circuits, enabling the manipulation of cavity resonances through resonantly tailored optomechanical potentials, leading to control of cantilevers with picometer precision and self-aligning microcavities.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (120.2440) Filters; (230.7370) Waveguides.

Optical forces resulting from interacting modes and cavities can scale to large values as optical modes shrink to nanometer dimensions [1-4]. Such forces can be harnessed in fundamentally new ways when optical elements are free to move and adapt to them [1-4]. Here, we propose the use of opto-mechanically coupled resonators as a general means of tailoring opto-mechanical potentials through the action of optical forces. We show that attractive and repulsive forces arising from opto-mechanically coupled cavity resonances can give rise to strong and highly localized opto-mechanical potential wells whose widths approach picometer scales. These potentials enable all-optical, self-adaptive behaviors such as the trapping and corralling (or dynamic-capture) of microcavity resonances with light [1]. As one example, we apply these concepts to the design of a novel resonator which dynamically self-aligns (or spectrally bonds) its resonance to an incident laser line all-optically ("passively"). Such "smart" resonators can adaptively track a laser-line through minimization of optomechanical energy [1]. Though these concepts are illustrated through dual-microring designs, broad extension to other photonic topologies is straightforward.

We explore these novel physical behaviors through coupled cavity systems such as the dual-microring resonator shown in Fig. 1(a). In this design, the lower ring and bus waveguide are assumed to be fixed while the upper ring moves unimpeded in response to optically induced forces generated by the guided light. Close approximations of this arrangement can be realized using membrane or cantilever structures to suspend the upper ring, and could be achieved using available fabrication techniques [5]. This geometry enables strong coupling between nominally degenerate ring modes creating symmetric and antisymmetric supermodes [see Fig. 1(b)-(d)] whose frequencies are remarkably sensitive to device geometry. Fig. 1(e) shows that as the waveguide coupling strength, κ(q), is increased (or distance q decreased) a linear resonance frequency splitting, in κ(q), (or exponential in q) occurs between the symmetric (blue) and antisymmetric (red) modes (4 µm radius assumed). Fig. 1(e) also reveals that strong coupling results in resonance crossings between adjacent orders. These give rise to fundamentally new means of manipulating optical resonances and mechanical structures when optomechanical forces and energy are considered.

Through open and closed system analyses of optomechanical energy, we show that the resonant excitation of the

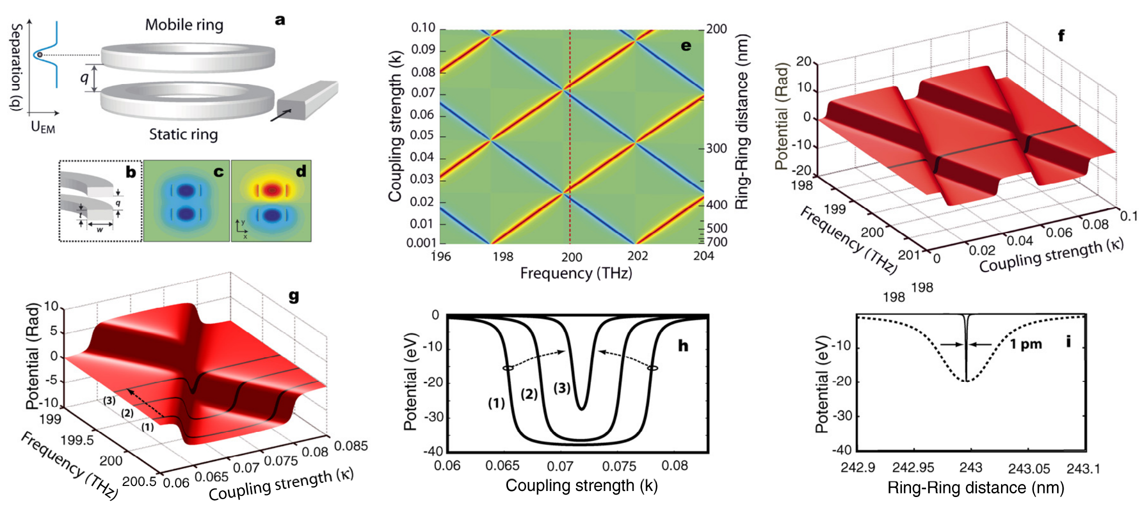

Fig 1. (a) Proposed dual-ring cavity (b) ring cross-section (w = 500 nm, t = 200 nm, q = 250nm) (c) symmetric and (d) antisymmetric guided modes. (e) computed resonance map and (f) optomechanical potential. (g) potential with three different laser excitations in black. (h) computed potential (eV) for 1mW power. (i) computed potential (1mW) as detuning from resonance crossing tends to zero.

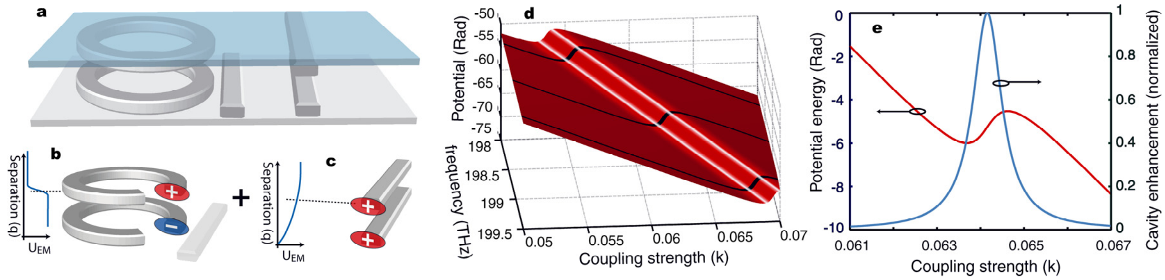

Fig 2. (a) Self-aligning cavity which combines resonant (b) and non-resonant (c) potentials. (d) computed optomechanical potential. (e) a plot showing the alignment of the potential minimum (red) with the resonant field enhancement within the cavity mode (blue).

symmetric ring system supermode results in attractive forces between the rings, while excitation of the antisymmetric mode results in repulsive forces [1-3]. Therefore, if the system is excited (via the bus waveguide) by a monochromatic laser-line of fixed frequency both the symmetric and anti-symmetric microring supermodes can be excited as the separation between the rings (q) is varied (due to the large frequency splitting afforded by this geometry). If, for instance, the system is excited by a fixed laser-line of 200 THz (represented by a vertical dotted line in Fig. 1(e)), resonant alignment of the cavity modes will be achieved at various positions, q, corresponding to different coupling strengths, $\kappa(q)$. Since both attractive and repulsive forces are generated by the symmetric and antisymmetric resonances excited along this trajectory of motion, nontrivial optomechanical potentials are created as well. For instance, the rigorously computed normalized effective potential (U_n) is shown in Fig. 1(f) corresponding to the (laser) frequencies and coupling strengths seen in Fig. 1(e) [here $U_n(q) = U_{eff}(q)/\hbar\Phi$, where Φ is the incident photon flux and $\hbar$ is Planck's constant]. The 200 THz laser frequency (shown as a vertical dotted line in Fig. 1(e)) can be seen as a solid projected line on the surface map of Fig. 1(f). Along this trajectory, two minima of optomechanical potential are seen, which result from resonant excitation of cavity modes of differing symmetries. These minima of potential indicate that the system can be trapped, effectively pinning the optomechanical system at positions, q, corresponding to placement symmetric and antisymmetric modes on either side of the laser-line.

Moreover, if a single laser-line is continuously swept toward the resonance crossing (over the trajectory shown by laser-lines indicated by the solid lines labeled (1)-(3) of Fig. 1(g)) one can adiabatically narrow the potential from a wide square-well to a δ-function, effectively allowing us to corral the system to one of several localized positions in space. The evolution of the potential for laser-lines (1)-(3) can be seen in Fig. 1(h) for a realistic guided power of 1 mW within the bus waveguide (or $\Phi \approx 10^{16}$ photons/sec). Furthermore, in the limit of small detuning from the resonance crossing, the spatial localization of the trapping potential scales to arbitrarily narrow values due to the existence a narrow linewidth supermode [1]. Finally, we note that for these modest powers the depth of the potential well is (~30 eV) far greater than k_BT, and the optically induced forces corresponding to this potential are 1-10μN in magnitude, which are sufficient to dominate in experimentally realistic situations [1,4].

From the potential map seen in Fig. 1(f)-(g), it is clear that the microcavity system's resonances – and its mechanical degree of freedom – can be manipulated in truly unique ways, all-optically. Of particular utility is the formation of a "resonantly-bound" optomechanical state, which can be used to stabilize a mechanical structure with remarkable spatial resolution, and tune the resonance over large frequency ranges through proper placement of one or more laser-lines [1]. In addition, these bound states can be made to adapt to the laser-line if resonant and non-resonant potentials are combined within a single device [Fig. 2(a)-(c)]. In this case, we will show that a localized optomechanical potential well can be formed which tends to pin the optomechanical system such that the cavity mode remains resonant with the laser line [e.g. see Fig. 2(d)-(e)]. Such self-adaptive (or "smart") optomechanical systems would have the remarkable ability to self-align with an incident laser line, and *follow it* to any wavelength to which it is tuned. These and similar self-adaptive optomechanical systems have the potential for far reaching impact in integrated photonic systems in part due to their ability to eliminate complex electronic feedback controls necessary to implement numerous optical functions.

Beyond the conceptual proposal in [1], we will expand on discussions of open-system energetics, stiction, discuss further practical physical implementations and explore configurations for experimental demonstration.

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