Optonanomechanical self-adaptive photonic devices based on light forces: a path to robust high-index-contrast nanophotonic circuits

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ABSTRACT

We describe a proposed new class of optonanomechanical integrated photonic devices that can have self-adaptive behavior and self-adaptive optical frequency response, through the use of optical forces to manipulate their movable parts. We propose applications for this technology, and show how such devices can address the enormous dimensional and thermal sensitivity present in nanophotonic structures. Through synthesis of the optomechanical potential, we propose to design and control either the effective optical, or the mechanical, properties of the nanostructure, such as a giant effective optical nonlinear response, nonlinear dynamics and memory. We show device designs that can trap desired states at picometer resolution. We also describe the design of a novel, self-tuning microcavity design whose moving parts adjust in response to light forces alone to always place the resonance at the wavelength of the incident light over a wide wavelength range. This device concept provides an athermal resonator design (temperature-independent resonance frequency), without use of materials with negative thermooptic coefficients. It could also address a major challenge with conventional strong-confinement (high-index-contrast) integrated photonics – their extreme sensitivities – through a self-locking filter bank and optical cross-connect proposal, that in principle can use arbitrarily low power to trim resonant filter passbands to a wavelength channel grid.

Keywords: Optomechanics, light forces, self-adaptive, self-tuning cavity, nanophotonics, nanomechanics, potential synthesis, athermal resonators, nanophotonic cross-connect, robustness.

1. INTRODUCTION

Light forces have a long history [8-11]. Optical forces resulting from interacting modes and cavities can scale to large values as optical modes shrink to nanometer-scale dimensions [1-7]. Such forces can be harnessed in fundamentally new ways when optical elements are free to move and adapt to them through exchange of optical and mechanical energy. In
Fig. 2. **Basic geometries for attractive and repulsive resonantly-enhanced optical forces.** An attractive optical force is present when bringing a perturbing object closer to a resonator causes a red-shift in resonance frequency: which can be realized by (a-b) a dielectric perturbing body with index larger than ambient, \( n_{\text{pert}} > n_{\text{amb}} \); or by (c) a perfect electric conductor (PEC) for a TM polarized excitation (motion assumed vertical). For repulsive forces, a blue shift is needed, calling for either (d-e) a dielectric perturbing body with smaller index than ambient (e.g. air), or (f) a PEC over a TE polarized mode. Since three of these four idealized situations aren’t practical in optics (c-f), we propose using a geometry based on dual coupled cavities, which by the image principle provide behavior equivalent to (c,f).

Recent work [1], we proposed the use of opto-mechanically coupled resonators as a general means of tailoring optomechanical 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]. Fig. 1 illustrates the basic device physics we propose to harness in the service of device design. The idea is that an optical driving signal, enhanced by the resonant optical response, gives rise to resonantly-enhanced optical forces; these forces act on movable nanomechanical parts of the photonic device; and the motion leads to a change in optical coupling between cavities, in the optical resonant frequencies of the system, and thus in turn to a change in the forces generated. The result is a form of feedback (Fig. 1a), or engineered nonlinear response. We approach engineering novel devices and functionality based on such physics through design of the optomechanical potential. Two important elements in design of such devices will be: (1) trapping the nanomechanical structure, through light forces, into a stable state; and (2) design allowing the optical input or device dynamics to manipulate the state of the device. These steps require the synthesis of trapping optomechanical potential wells, and their dynamical control.

In the first part of this paper (Sec. 2), we show [1] how practical devices realizing these capabilities may be designed, and explain the physics of their operation. As one example, we apply these concepts to the design of a novel, first-of-its-kind resonator which dynamically self-aligns (or spectrally bonds) its resonance to an incident laser line all-optically ("passively"). Such "smart" resonators can adaptively track the wavelength of a laser-line through minimization of optomechanical energy [1]. Though these concepts are illustrated through dual-microring-cavity designs, broad extension to other photonic topologies is straightforward. In the second part of this paper (Sec. 3–4), we propose some applications of this technology, and describe two already promising applications based on the self-tuning cavity concept. The first is an athermal (temperature-independent resonance frequency) optical resonator. The second is a nanophotonic...
Fig. 3. Synthesis of an optomechanical potential well using attractive and repulsive forces designed into the same resonant structure [1]: (a) dual-ring cavity geometry with movable top ring (weakly suspended in practice); (b) cross-section and the cross-sectional field distributions of the (c) symmetric (attractive) and (d) antisymmetric (repulsive) resonant supermodes; (e) optical force amplitude vs. wavelength and coupling strength (distance $q$) between the rings.

filter bank that, through intrinsic optonanomechanical feedback, can lock to an optical frequency reference signal, and eliminate sensitivity to dimensional variations, a major problem for scaling nanophotonic devices and circuits.

2. DUAL-MICROCAVITY UNIT CELL FOR OPTOMECHANICAL POTENTIAL SYNTHESIS

We explore these novel physical behaviors through coupled cavity systems such as the dual-microring resonator design shown in Fig. 1(a). This design results from a desire to obtain large resonantly-enhanced optical forces of either sign (attractive or repulsive), at practical optical driving signal powers. The rationale is explained in the following.

Some basic geometries allowing resonantly-enhanced optical forces are shown in Fig. 2. A perturbing structure, dielectric or metallic, that is moved within the evanescent field of a resonant cavity can greatly shift the resonant frequency [12]. A large shift in resonance frequency per unit distance of the motion corresponds to a large change in optical energy, and leads to a large force. If the perturbing structure is dielectric and has an index higher than the ambient (e.g. air) index (Fig. 2a,b), there is a red shift of the resonance when moving the structure closer to the resonator, so the force is attractive (no motion). On the other hand, it is not straightforward to extend this to obtain a repulsive force because the perturbing structure requires an index below that of air (Fig. 2d,e). However, a metallic perturbing structure (sheet) can produce both attractive and repulsive forces (Fig. 2c,f), using different polarizations with a perfect electric conductor (PEC). Both signs of force could in theory be obtained also in the same polarization, using alternately perfect electric and magnetic conductors (PEC and PMC). Since PMCs do not have a physical realization, and metals (that approximate PECs at low frequency) are highly absorptive at optical frequencies, the conductor approach does promise high-Q resonances needed to develop large optical forces. For this reason, we turn to theory of image charges: a perfect conductor is an electromagnetic “mirror”. Hence we use a dual-cavity geometry that is equivalent to having one cavity, with a perfect conductor at the half-way point between the two cavities. Symmetric and anti-symmetric supermodes correspond to the PEC and PMC cases, and provide attractive and repulsive forces.

Coupled microcavities were previously shown by Povinelli et al. [2] to allow both signs of force, but the geometry we propose is uniquely suited to developing very strong optical forces. In this design, the lower ring and bus waveguide are assumed to be fixed (e.g. on a silicon chip) while the upper ring is assumed to move unimpeded in the vertical direction 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 [13]. This geometry (of two co-propagating rings, Fig. 3a) enables strong coupling between nominally degenerate ring modes creating symmetric and antisymmetric supermodes [Fig. 3(b)-(d)] whose frequencies are remarkably sensitive to device geometry (and hence which allow large optical forces). Fig. 3(e) shows that as the waveguide coupling strength, $\kappa(q)$, is increased (or distance $q$ in Fig. 3b decreased) a resonance frequency splitting that
is linear in $k(q)$ (or exponential in $q$) results between the symmetric (blue) and antisymmetric (red) modes. Fig. 3(e), which shows the resonant optical force, also reveals that strong coupling results in crossings between adjacent longitudinal resonance orders. These crossings give rise to fundamentally new means of manipulating optical resonances and mechanical structures when optomechanical forces and energy are considered, as illustrated in the following subsections.

### 2.1 Picometer-Scale Positional Control via Trapping Optomechanical Potentials

Through open and closed system analyses of optomechanical energy [1], we can show that the resonant excitation of the symmetric ring system supermode results in attractive forces between the rings [shown in Fig. 4(a)], while excitation of the antisymmetric mode results in repulsive forces [1-3]. If the system is excited (via the bus waveguide) by a monochromatic laser-line 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, as shown in Fig. 3(e)).

We first show how practical optonanomechanical trapping can be designed using a realistic example based on silicon-core microring resonators with 5-micron diameter. If the system, shown in Fig. 3(a), is excited by a fixed laser-line at 200 THz, or 1500nm wavelength [represented by a vertical dotted line in Fig. 3(e)], resonant excitation of a cavity supermode will be achieved at various coupling strengths, $k(q)$, corresponding to different positions, $q$. Since both attractive and repulsive forces are generated (respectively) by the excitation of symmetric and antisymmetric resonances along this trajectory of motion, nontrivial optomechanical potentials are created. In particular, when attractive and repulsive resonant forces alternate as ring-ring distance is decreased, as in Fig. 3(e), a series of trapping optomechanical potential wells is created. Fig. 4(b) shows the rigorously computed normalized effective potential corresponding to the coupling strengths shown in the top half of Fig. 3(e), for three laser frequencies including 200 THz [1]. The potential for each of the three laser frequencies is a two-dimensional cut of the surface map in Fig. 4(b), shown as a thick, solid-line trace projected onto the surface plot. Along the shown trajectory, a minimum of optomechanical potential is seen, which results 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 a position, $q$, corresponding to the placement of symmetric and antisymmetric mode resonances at positions $q\pm\Delta q$ on either side of being resonant with the laser-line.

This design allows corralling or dynamic capture of the optomechanical system. That is, 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) in Fig. 4(b)] one can adiabatically narrow the potential from a wide square-well to a near $\delta$-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. 4(c) for a realistic guided power of about 1 mW within the bus waveguide (photon flux of $0 = 10^{10}$ photons/sec). For these modest powers the depth of the potential well ($\sim$30 eV) is far greater than $k_B T$, and the optically induced forces corresponding to this potential are 1 to 10μN in magnitude, which are sufficient to dominate in experimentally realistic situations [1,4].
2.2 Optically Tunable Position: Control of Equilibrium State of Optomechanical Potentials

In this section we show designs that allow the optical input signal to control and determine the position of the nanomechanical system, i.e. to tune the equilibrium state or optomechanical potential minimum. In the previous section we showed that the potential could be tuned from wide to narrow, to capture the mechanical system, by tuning the single excitation wavelength. But, the equilibrium position was fixed by the design (the cavity FSR, and spatial dependence of coupling). We show that using multiple wavelengths to excite the system allows a tunable-position potential well.

Fig. 5 shows the same system, excited simultaneously by two laser wavelengths. The total optomechanical potential (3), relevant for the mechanics, is the sum of the potentials [(1) and (2)] due to each wavelength shown in Fig. 5(b) in thick, solid line. If the two laser wavelengths [(1) and (2) in Fig. 5(b)] are detuned to the left and right of the crossing, and excited with equal intensity, one creates a potential well (2) and one a potential “hill” (1). If the wavelengths are equally detuned from the crossing, the potentials will add in cancellation to a nearly featureless, flat potential. However, if wavelength (1) is detuned less than wavelength (2), producing a narrower potential, their sum will produce two potential wells, at positions above and below the crossing.

If, furthermore, wavelength dependence of the coupling coefficient is accounted, only one potential well may be favored, as shown in Fig. 5(c). The position of this potential may be varied by simultaneously tuning both excitation wavelengths (in opposite directions) away from the crossing wavelength.

2.3 Bound Optomechanical States and Self-Aligning “Smart” Microcavities [1]

In this section, we describe the more complex design of a novel device we refer to as a self-tuning cavity, shown in Fig.

Fig. 6. (a) Proposed optonanomechanical self-tuning resonator [1]. Engineering a device that adjusts to always be resonant with the incident laser wavelength requires a combination of a resonant and a broadband optomechanical potential (e.g. due to coupled waveguides). (b) The potential map shows that the total (sum) potential has the same shape and simply translates the minimum (equilibrium state) position for different wavelengths (3 examples shown as black lines). (c) The antisymmetric resonance is at the right potential wall, so the cavity always moves to be resonant.
Ultrasensitivity of Silicon Resonators

Fig. 7. Major challenges in strong-confinement (high-index-contrast) nanophotonics circuits are strong dimensional and thermal sensitivity: (a) 1 angstrom error in the width or height of a waveguide cross-section that forms part of a microring resonator leads to tens of GHz shift in the resonance frequency; (b) standard thick-BOX SOI wafers used for silicon nanophotonics show several nanometers of thickness variation across the wafer; (c) silicon microring resonators shift as much as 10 GHz for a 1°C change in temperature (figures (a,c) from [14,15], (b) courtesy of T. Barwicz).

6(a). It achieves a tunable potential (mechanical position) using only a single laser wavelength excitation, giving rise to a unique “wavelength-to-position” converter. But, it also places the potential exactly at the location that makes it resonant with the incident line, producing a form of “spectral bonding” between the continuous-wave (CW) input light and the resonance frequency of the optomechanical system. The nanomechanical system adjusts to change in the optical input wavelength, resulting in all-optically (optomechanically) controlled ultra-wide tuning of the cavity resonance, potentially over 10’s and 100’s of nanometers, with extraordinary precision (subject to the width of the trapping potential well, and the stability and linewidth of the driving laser).

This device can be designed by combining a resonant and a broadband optomechanical potential. This is accomplished by starting with the dual cavity of the previous examples providing a resonant repulsive potential in this case, and adding a coupled waveguide pair that adds a broadband attractive potential. The waveguide pair is optically isolated from the cavities, but is mechanically coupled such that there is only one mechanical degree of freedom in the system [Fig. 5(a)]. The optomechanical potential is the sum of the resonant and the broadband potential as illustrated in Fig. 5(a). This leads to a total potential with a mostly monotonic slope and a local potential minimum introduced by the resonant potential of the cavity pair. This potential step always occurs at ring-ring displacement and wavelength combinations at which the antisymmetric resonance in resonantly excited, i.e. resonant at the driving wavelength. A consequence of this fact is that the system will modify position in response to optical forces until it is trapped in the potential minimum, and when it is at the potential minimum it is resonant (with a slight detuning) with the antisymmetric cavity supermode. Thus, the system adapts to make the antisymmetric mode’s resonance frequency coincide with the laser wavelength.

Fig. 5(b) shows a potential surface showing the optomechanical potential at three different excitation wavelengths. Thus the potential simply shifts to have its minimum at a different position for each wavelength. Fig. 5(c) compares the intracavity power and the optomechanical potential vs. displacement (i.e. coupling) showing that the supermode resonance is indeed near the potential minimum. Self-adaptive devices such as this self-tuning cavity design, that leverage optical forces to produce useful function and feedback, have the potential for major impact in nanophotonics.

3. APPLICATIONS: LIGHT-POWERED NANOMACHINES AND ALL-OPTICAL FEEDBACK

Optonanomechanical devices based on light forces can be used to produce optically-controlled optical properties, as illustrated in the previous examples, or optically-controlled mechanical properties. These and similar self-adaptive, “smart” optonanomechanical 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.

Strong-confinement nanophotonic circuits [16,17], due to their unique properties such as support for wavelength-scale, high-Q resonators, enable chip-scale solutions and unique functionalities for next-generation communication and...
computation technologies, including reconfigurable/tunable optical add-drop multiplexers for wavelength-routing optical networks, and scalable integrated photonic crossconnects for energy efficient manycore processor to memory communication for future supercomputers. Telecom-grade switchable and tunable filters [16], modulators [18] and other components have been demonstrated in this technology. However, strong-confinement (high-index-contrast) nanophotonic waveguides and resonators have been shown to have extreme intrinsic sensitivities (Fig. 7) – including subatomic dimensional tolerances [14,15,19] and sensitivity to temperature and waveguide wall roughness (optical losses). One of the principal challenges to unleashing the promise of strong-confinement photonics lies in taming these extreme sensitivities. For example, Fig. 7(a) shows that a 1nm error in the width or height of a conventional (e.g. 450x200nm cross-section) silicon microring resonator will lead to a 100-200GHz shift in resonance frequency. While relative dimensional control can be excellent in lithography thus allowing adjacent resonators to be at least resonant at the same wavelength, typical wafer-level thickness variations [Fig. 7(b)] would require thickness mapping to maintain device operation over larger areas. Even then absolute dimensional errors lead to absolute frequency errors that cannot be easily compensated in design.

One approach to solving this problem has been to introduce tuning capability (e.g. thermooptic) and feedback control electronics for each photonic element. However, such solutions become increasingly power hungry and complex with scaling of nanophotonic circuits to higher complexities where their greatest potential for impact lies. Optonanomechanics could address some of these problems by enabling a new family of nanophotonic device designs with physics-based, built-in feedback, such as the self-tuning cavity. Such designs may in principle approach no power consumption for tuning and stabilization.

In this section, we propose optonanomechanics based solutions to two important problems in nanophotonics: athermal resonators, and resonant filter banks and cross-connects impervious to dimensional errors. Solving these problems will have important implications for scalable nanophotonic integration, and its impact on applications from multicore computing, through photonic signal processing, to communication networks.

3.1 Athermal Optical Resonators

In this section, we describe how the self-tuning cavity design described can be used to achieve athermal resonator operation. An athermal resonator design refers to one whose resonance frequency is insensitive to temperature over a substantial range. This is an important problem, for example, in the future integration of nanophotonics with multicore processors, since on-chip temperature varies substantially (by 10’s of degrees) in space and in time. Thermooptic tuning would introduce substantial power use and require active electronic control to track dynamical temperature changes. The self-tuning cavity provides a conceptually simple, highly scalable approach, in principle free of power consumption, at the expense of inclusion of nanomechanical parts.

Fig. 8 illustrates the basic concept, based on the self-tuning cavity of Fig. 6. The basic idea is that an optical frequency reference is provided to drive the resonator at the wavelength desired to be the resonant wavelength of the cavity. The nanomechanical system will adjust in response to optical forces to become resonant with the driving optical signal. If a...
temperature change is introduced, this will result in a shift of the nominal resonance frequencies of the individual ring cavities. This means that for the ring cavity pair alone, the diagonal resonance contours in Fig. 3(e) will simply shift to laterally on that plot (e.g. left to lower frequency, if the temperature increases and the thermo-optic coefficient of the waveguides is positive). However, the potential of the entire system in Fig. 8 is shown in Fig. 6(b). Its lateral shift along the frequency axis will retain the same shape of potential, with the potential minimum position shifted (e.g. to a larger displacement, consistent with the example given here). Thus, the nanomechanical system will readjust in response to generated optical forces, but after settling into the new potential minimum, the system will still be resonant with the incident laser wavelength which remains unchanged. This behavior can remain valid over a large range of motion, and hence over large temperature ranges of several hundred degrees Celsius. Furthermore, energy is used from the optical driving signal during motion of the nanomechanical parts (since power = force*velocity), but when equilibrium is reached and the system is static, no optical power is used. Thus, as optical waveguides approaching low propagation losses, this approach approaches no power consumption for the stabilization.

3.2 Self-locking, Robust Nanophotonic Filter Banks and Cross-connects, Impervious to Dimensional Variations

In this section, we describe a new architecture for nanophotonic resonator-based filter banks for demultiplexers and cross-connects (Fig. 10). The architecture is based on a filter that is a more complex variant of the self-tuning cavity. Each filter comprises a narrowband self-tuning cavity and a wide bandwidth filter cavity. The self-tuning cavity will lock the device to a reference laser input signal, and the filter cavity will be used to form the passband for optical signal processing. A bank of such filters would be impervious to dimensional variations.

The problem of dimensional sensitivity in conventional nanophotonic filter banks is illustrated in Fig. 9. An example optical cross-connect/demultiplexer, shown in Fig. 9(a), is formed of an array of nodes each comprising an add-drop filter, for example based on microring resonators [Fig. 9(b)]. Dimensional variations, such as wafer-level thickness variations [Fig. 7(b)] will make the designed regular filter passband spacing in general irregular and not lined up with the grid of wavelength channels [Fig. 7(c)]. Furthermore, even without wafer variations, absolute dimensional control in lithography and etching is not good enough to line up the passband array with the channel grid (in an absolute wavelength sense) without external tuning. Power consuming tuning mechanisms and complex control are needed.

In the architecture we propose in Fig. 10, a reference laser is used to lock all filters to an absolute wavelength, or in accurate relation to it. The building block filter here is shown in Fig. 10(b). It uses a “master-slave” design, consisting of two, mechanically coupled parts: a self-tuning locking cavity (right) and a filter cavity (left). The self-tuning cavity (“master”) is the design of Fig. 6, and is designed to be as high-Q as possible (limited by intrinsic loss), to develop large forces and adjust to be resonant with the reference laser, that is guided to all filters in the array [Fig. 10(a)]. Such a linewidth cavity would be too narrow to operate on optical signals so the functions are separated by introducing the filter cavity pair (“slave”), that are designed to have a wide bandwidth (low Q) of 10’s of GHz to support modulated optical signals in the wavelengths channels. The mechanical coupling means that the locking cavity (“master”) adjusts the mechanical degree of freedom to become resonant with the reference laser, and the filter cavity (“slave”) follows. The filter cavity can be accurately spaced in frequency from the locking cavity because they are fabricated next to each other, and because relative dimensional control in nanofabrication is excellent. For example, the filters can be spaced from the locking cavities respectively by 100, 200, 300, 400… GHz, thus creating a filter bank with 100-GHz channel spacing. One way to produce the detuning in electron-beam lithography is by dose control [20].

The proposed architecture promises a major advance in filters because feedback is intrinsic to the device design, power consumption for the stabilization can approach very low values as waveguide loss is reduced through improvements in fabrication, and in addition locking in absolute wavelength is possible. This approach is highly scalable.

4. CONCLUSIONS

We have proposed a new class of light-powered nanomachines and all-optical self-adaptive optomechanical circuits that rely on the interplay between optically-induced forces and mechanical-motion-induced change in optical properties of a system. By synthesizing optomechanical potentials through the action of optical forces, unique designs result enabling all-optical operations on light that would be difficult to achieve by any other means. As first examples of how this concept could be applied, we have shown how all-optical self-adaptive photonic devices can be made to effectively corral and trap microcavity resonances and achieve dynamic self-alignment of a microcavity resonance to a single laser line over very large wavelength ranges. Such devices have the potential to provide many new and unique kinds of all-optical (optomechanical) functionality.
Conventional Nanophotonic Crossconnect/Demux based on Microring-Resonator Add-Drop Filters

DRAM Memory Banks

Add-drop filter

(a)

(b)

(c)

(d)

Fig. 9. Conventional filter bank suffers from enormous dimensional sensitivity in nanophotonic structures. (a) On-chip all-to-all wavelength routing network relevant for telecom and supercomputer applications; (b) each node may comprise a microring-resonator add-drop filter; (c) due to dimensional sensitivity, waveguide-layer thickness non-uniformity and lithographic variations the filter array is misaligned with respect to the evenly spaced multi-channel spectrum it is intended to operate on. Extreme sensitivities (Fig. 8) mean that in realistic silicon nanophotonic implementations the misalignment can be on the order of 500GHz.

Passively λ-Locked Crossconnect/Demux based Optonanomechanical Add-Drop Filters

(a)

(b)

(c)

(d)

Fig. 10. Proposed self-locking filter bank circumventing enormous dimensional sensitivity in nanophotonic structures: (a) the proposed self-locked on-chip optical cross-connect comprises a filter array, where each element (b) is an optonanomechanical photonic device comprising a self-tuning cavity to lock onto a reference wavelength, and a mechanically coupled add-drop filter that tracks wavelength with it. The filter is fabricated with a resonance frequency offset relative to the locking cavity, which can be very well controlled, because they are adjacent. (c) Without the reference laser excitation, dimensional sensitivity gives an unevenly spaced, misaligned filter bank spectrum, but with the reference laser excitation present, the filters lock to that wavelength. For low waveguide losses, the power consumed in the steady state, for this type of “trimming” approaches zero.

The new physics allows for new concepts of device design and control, and may provide an approach to eliminate the extreme dimensional and thermal sensitivities of strong-confinement photonic devices. The potential of optonanomechanics to lead to novel device concepts and applications has yet to be fully explored. Furthermore, the
unique functionality available through optomechanical energy coupling, the highly nonlinear behavior and possibilities available through the potential synthesis viewpoint make it desirable to develop a comprehensive design approach (a “circuit theory”) for the systematic design of all-optical optomechanical systems with prescribed desired properties. We have made initial steps in this direction [21].

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