Optical Nonreciprocity in Optomechanical Structures

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We demonstrate that optomechanical devices can exhibit nonreciprocal behavior when the dominant light-matter interaction takes place via a linear momentum exchange between light and the mechanical structure. As an example, we propose a microscale optomechanical device that can exhibit a nonreciprocal behavior in a microphotonic platform operating at room temperature. We show that, depending on the direction of the incident light, the device switches between a high and low transparency state with more than a 20 dB extinction ratio.

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Breaking the reciprocity of light on-chip can lead to an important new class of optical devices such as isolators, which are critical for the development of photonic systems. Traditional methods for creating nonreciprocal devices rely on magneto-optic media, optically active media, or photovoltaic electro-optic crystals [1–4]. Nonreciprocal behavior has also been studied in time varying media [5,6], bianisotropic media [7,8] (such as magnetoelectric media), and relativistic moving media [9]. However, the development of nonreciprocal devices for a microphotonic platform remains a challenge [6]. Hence, it is of great interest to pursue alternative mechanisms to break the reciprocity of light on a microscale platform. Here, we show nonreciprocity by exploiting a fundamental difference between forward and backward moving light: its momentum. Recent work in optomechanics [10], enabled by advances in optical microcavities [11] and nanoelectromechanical systems [12], has shown tremendous potential for a new class of microscale devices [13–16] and novel physical phenomena such as optomechanical cooling [17–19]. In this Letter, we show that when the dominant light-matter interaction takes place via momentum exchange, optomechanical devices can exhibit nonreciprocal behavior. This leads to optical spectral characteristics that are strongly dependent upon the direction of the incidence of light. We propose a silicon based micro-optomechanical device that exhibits a nonreciprocal behavior with a contrast ratio >20 dB.

An example of an optomechanical structure which interacts with light through linear momentum exchange consists of an inline Fabry Perot cavity with one movable mirror and one fixed mirror (Fig. 1). The emergence of nonreciprocity in such a system can be understood as follows [see Fig. 1(a)]: For a left-incident beam at the optical resonance frequency, the net momentum imparted per second on the movable mirror is $-[(2\eta - 1) - R]I/c$ (where η is the power buildup factor of the cavity, R is the power reflectivity of the Fabry Perot cavity, I is the incident power, and c the speed of light in vacuum, and the negative sign indicates that the direction of the force is away from the cavity). On the other hand, for a right-incident beam the net momentum imparted per second on the movable mirror is $-[(2\eta - 1) + R]I/c$. Hence the differential radiation force for left- and right-incident beams is $2RI/c$, which produces a direction dependent mechanical response from the mirror which leads to nonreciprocal optical transmission spectra.

To illustrate the nonreciprocal behavior in a realistic micro-optomechanical device, we describe a representative device which can be fabricated in a silicon material system. The device (Fig. 2) consists of a quasi-one-dimensional standing wave cavity formed by two quarter wave Bragg reflectors with one of the mirrors suspended via microcantilevers [20]. The mirrors forming the cavity are fabricated in a high index contrast system (the refractive indices of Si and SiO_2 are approximately 3.5 and 1.5, respectively). Spring constants spanning several orders of magnitude can be achieved (typically from 10^{-5} N m^{-1} to 1 N m^{-1} [21]) by varying the materials, geometry, and the arrangement of the cantilevers. We model the movable mirror as a vertical translation plate supported by four beams. Using the COMSOL [22] software package we compute the mechanical response of the structure by including material properties and boundary conditions into a finite element method based solver. No angular displacement is allowed because the beams are connected to the mirror which remains parallel to the substrate under small plate movements. The spring constant associated with four fixed beams is given by $4Ewt^3/l^3$ where E is the Young's modulus and w, t, and l are the width, thickness, and length of the silicon beams, respectively [20]. In a given material system, the cubic dependence of the spring constant on the aspect ratio (t/l) allows for a wide range of spring constants for this beam geometry. We consider a $10 \times 10\ \mu\text{m}^2$ mirror suspended using microcantilevers of thickness 110.5 nm [$\sim \lambda_c/4n_{\text{Si}}$ where λ_c is 1550.5 nm and n_{Si} (3.5) the refractive index of silicon], 10 μm length, and 100 nm width. The mass of the mirror is 165.26 pg. The spring constant for the chosen dimensions is $\sim$0.06 N m^{-1}. Using the finite element method software we calculate the mechanical displacement of the movable mirror for 666 pN ($2I/c$) applied force corresponding to a net radia-

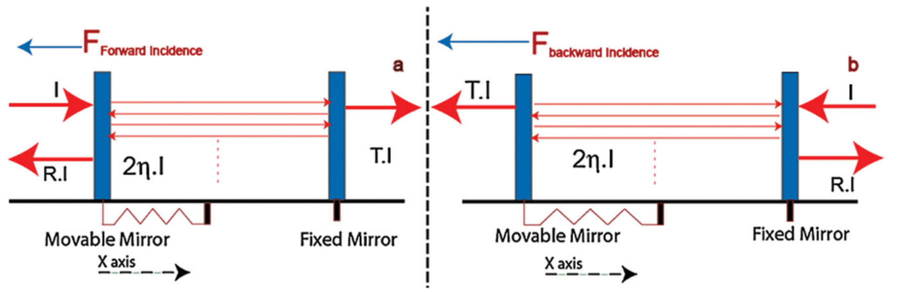

FIG. 1 (color). An optomechanical system with nonreciprocal response: cavity condition for (a) forward incident light and (b) backward incident light. Radiation force on the movable mirror is $-[(2\eta - 1) - R(\lambda, x, t)] * I/c$ for forward incidence and $-[(2\eta - 1) - R(\lambda, x, t)] * I/c$ for backward incidence.

tion force from a 100 mW beam reflected perfectly from the mirror (see Fig. 2) to be on the order of 10 nm. The bandwidth of the optical cavity formed by the mirrors is primarily determined by the reflectivity of the mirrors. We show the optical transmission characteristics of the device in Fig. 2(d). We consider quarter wave stacks on either side formed by alternating layers of Si and SiO_2 with 2 layers of deposited silicon and three layers of deposited oxide. The mirrors form an air filled cavity of length $\sim 50\lambda_c/2$. The quality factor of the cavity ($Q = \lambda_c/\Delta\lambda$) is $\sim$5200 centered at $\sim\lambda_c = 1550.5$ nm. The mirror layers have thicknesses of $21\lambda_{\mathrm{mirror1}}/4n_{\mathrm{Si}}$ and $21\lambda_{\mathrm{mirror2}}/4n_{\mathrm{Si}}$.

Nonreciprocal behavior in the proposed structure emerges due to the asymmetry of the radiation pressure on the movable mirror for forward and backward incident light. We model the cantilever dynamics by a driven second order differential system with a nonlinear driving function

$$\frac{d^2x}{dt^2} + \frac{b}{m_{\mathrm{eff}}}\frac{dx}{dt} + \frac{K}{m_{\mathrm{eff}}}x = \frac{F_{\mathrm{RP}}(\lambda, x, t)}{m_{\mathrm{eff}}}, \tag{1}$$

where radiation force on the movable mirror is

$$F_{\mathrm{RP}}(\lambda, x, t) = \begin{cases} -[(2\eta - 1) - R(\lambda, x, t)] * I/c & \text{for forward incidence} \\ -[(2\eta - 1) + R(\lambda, x, t)] * I/c & \text{for backward incidence,} \end{cases} \tag{2}$$

where I is the power of the incident beam η, R are the intensity buildup factor, and reflectivity of the cavity for wavelength λ and movable mirror position x. The position dependent reflectivity $R(\lambda, x, t)$ is given as a function of displacement x as

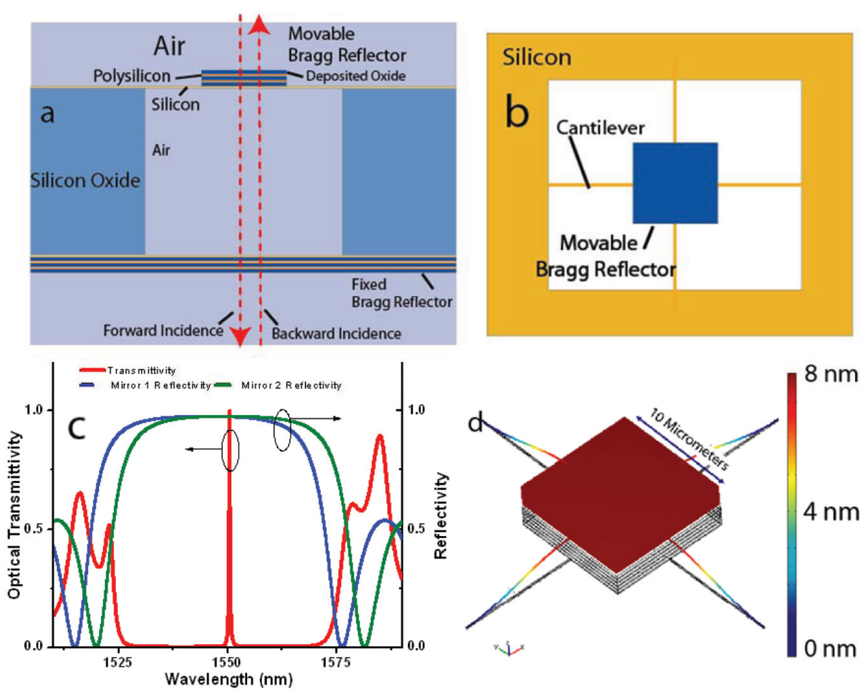

FIG. 2 (color). Proposed optomechanical device for realizing nonreciprocal transmission spectra. (a) Side view, (b) top view, (c) optical transmission through the device for low light intensities. Reflectivity spectra for the mirrors are shown in dotted lines. Layer thicknesses of the mirrors are slightly offset (5 nm) to allow for a pump-probe measurement. (d) Mechanical response of the suspended mirror for a radiation force corresponding to 100 mW incident power. An optional mechanical stop can be added near the movable mirror to minimize the insertion losses.

$$R(\lambda, x, t) = 1 - \left[\left(\frac{|t_1 t_2|}{1 - |r_1 r_2|}\right)^2 \times \frac{1}{1 + 4\left(\frac{\sqrt{|r_1 r_2|}}{1-|r_1 r_2|}\right)^2 \sin^2 \varphi(x)}\right]^{1/2}, \qquad (3)$$

where $\varphi(x)$ is the phase shift per round trip inside the cavity: $\frac{1}{2}\mathrm{Arg}[r_1 r_2 e^{i(2\pi/\lambda)(l-x)}]$ and r_1, r_2 and t_1, t_2 are the mirror reflectivities and transmittivities; l is the steady state cavity length. We assume a mass of 165.26 pg, spring constant of $0.06\ \mathrm{N\,m^{-1}}$ (corresponding to a $10 \times 10\ \mu\mathrm{m}^2$ Bragg mirror, see Fig. 2), and a net damping parameter of $10^{-6}\ \mathrm{kg\,s^{-1}}$. The damping mechanisms may include mass damping, stiffness damping, acoustic leakage at the anchors, and thin fluid squeezing [23]. The coupled optomechanical response is calculated at each time step ($1\ \mathrm{ns} \sim \boldsymbol{\tau}_{\mathrm{mechanical}}/16\,000$) by updating both the optical and mechanical state of the cavity. We also note that the photon lifetime ($\boldsymbol{\tau}_{\mathrm{photon}} = \lambda Q/2\pi c \approx 4.1$ ps) is much smaller than the mechanical rise time ($\boldsymbol{\tau}_{\mathrm{mechanical}} = m/b \approx 16\ \mu$s), which allows for the calculation of the optomechanical response iteratively. We neglect the quantum Langevin noise in calculating the optomechanical response. The transmission spectral characteristics exhibit the classical behavior of optical bistable systems. The transmission spectra of the device for forward and backward incident light are shown in Fig. 3. One can see the formation of a nonreciprocal transmission window at 1551.2 nm with a bandwidth of 0.25 nm and a forward to backward incident light extinction ratio of >16 dB. The transition time for backward to forward incidence (and vice versa) is on the order of $\boldsymbol{\tau}_{\mathrm{mechanical}}$ given by mechanical design of the movable mirror. With appropriate choice of damping ($b > \sqrt{4Km_{\mathrm{eff}}}$), the system response can be tuned to avoid oscillations during mechanical transitions.

The insertion loss through the device can be minimized by providing a mechanical stop for the movable mirror. To obtain a unity peak transmission, the Fabry Perot cavity needs to be perfectly on resonance with the incoming light. However, when the cavity is perfectly on resonance, the radiation force on the mirror passes through a maximum leading to instability [13]. A mechanical stop allows for peak resonance buildup while producing a nonreciprocal response. We describe a nonreciprocal optomechanical device to achieve low insertion loss (<0.1 dB) and high forward to backward incidence extinction ratio (>20 dB). In Fig. 4, we show the transmission spectra for forward and backward incident light of 100 mW power when the mirror is constrained to -30 nm displacement. One can see the formation of a nonreciprocal spectrum with a 0.25 nm bandwidth and a forward to backward light extinction ratio >20 dB. The insertion loss for the backward light is now <0.1 dB. The bandwidth of the nonreciprocal spectrum can be controlled by choosing the appropriate mirror reflectivity. We note that an important consideration for a mechanical stop is the effect of stiction force for mechanical objects in close proximity. However, earlier works have successfully demonstrated various methods to overcome stiction [24].

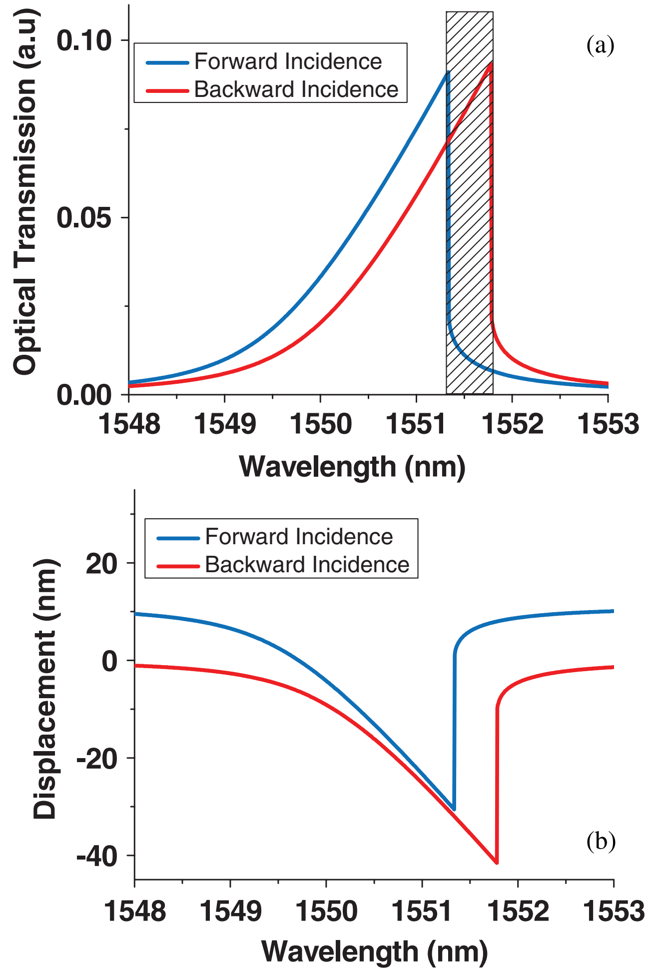

FIG. 3 (color). (a) Transmission spectra of the device for forward and backward incidence of light. (b) Steady state displacement of the movable mirror for forward and backward incidence of light.

The thermal equipartition noise imposes a minimum power condition for observing the nonreciprocal behavior. We estimate the optical power required for the radiation force displacement to exceed the mean square displacement of the mirror for a given spring constant. The minimum optical power required to overcome the thermal position noise is given by $I_{\mathrm{min}} = cK\Delta x$, where $\Delta x_{\mathrm{min}} = \sqrt{kT/K}$, k the Boltzmann constant, K the spring constant, and $T = 300$ K ambient temperature. Following the fluctuation dissipation theorem, this analysis takes into account the Langevin noise [25]. One can see that the net optical power contributing to the nonreciprocal behavior should be in the range of tens of mW to overcome the thermal equipartition noise. The optical power I_{min} can be lowered by lowering the spring constant. Even though thermal nonlinearity has traditionally been an important

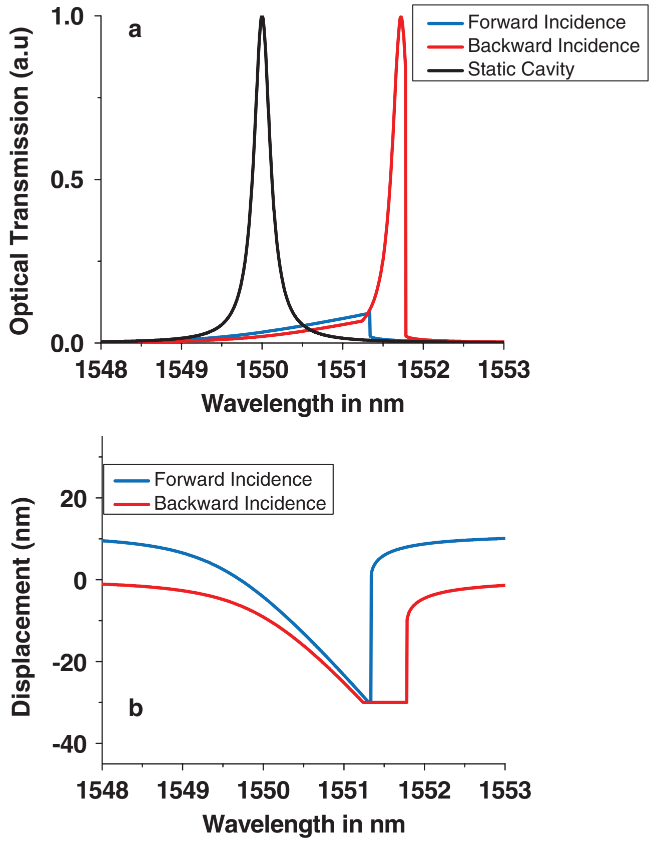

FIG. 4 (color). (a) Transmission spectra of the device for forward and backward incidence of light when the movable mirror is constrained at −30 nm displacement to achieve stability on resonance. (b) Steady state displacement of the movable mirror for forward and backward incidence of light.

constraint to microphotonic devices [26], we note that the effect of thermal nonlinearity will contribute to both directions of incidence. Traditionally strong thermal instabilities have been observed where the thermo-optic effect of the dielectric medium (silicon or silica) plays a significant role [26]. In the device described here these effects are further suppressed since the cavity is formed in air and the reflectivity from the broadband Bragg gratings is temperature insensitive. The general principles described here for creating devices with nonreciprocal transmission spectra can be extended to in-plane geometry by employing suspended resonators [15] as frequency selective reflectors [27]. This class of devices with nonreciprocal spectra can enable new functionalities for integrated optical systems.

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