Optomechanical nonreciprocity

Ewold Verhagen and Andrea Alù

The two-way symmetry of electromagnetic wave propagation, known as Lorentz reciprocity, can now be effectively broken with the help of radiation pressure. This enables compact and versatile devices to route photons in remarkable ways.

Symmetries dictate the laws of physics, and constrain response and function of natural systems. As a remarkable example in wave propagation, from sound to light, time-reversal symmetry and reciprocity ensure the familiar concept that signal transport is two-ways symmetric. Breaking this symmetry has proven extremely useful, enabling protection for sensitive sources, better use of information capacity in communication technology, and fundamental building blocks of logical networks and quantum information systems[1,2]. A direct way to break reciprocity is to bias the propagation channel through a static quantity that does not reverse with time, such as a d.c. magnetic field. For electromagnetic waves, this solution however requires magneto-optic materials, which are inherently difficult to integrate and miniaturize. As such, a vibrant search for alternative biasing gauges, such as directional parametric time modulation, has sprung up.

While the idea of nonreciprocity through temporal modulation is rather old[3], recent opportunities in nanofabrication and optoelectronics have fostered the field of magnet-less parametric nonreciprocal devices[4,5]. In this context, optomechanical coupling offers a versatile platform to engage temporal modulations effectively. In engineered optical cavities, radiation pressure couples light to mechanical resonators[6], with powerful opportunities in quantum control and sensing of motion. It also allows controlling light with light – by inducing temporally modulated cavity deformations – in unique ways, including the possibility of nonreciprocal optical transmission in compact, on-chip systems.

A universal mechanism: directional optomechanical mode conversion

Various systems that couple micro- or nanomechanical motion to optical cavity modes have been recently shown to exhibit nonreciprocity. Optomechanical ring resonators showed asymmetric spectra for probe beams detuned from a stronger control beam by about one mechanical resonance frequency[7-10]. The fact that such spectral features, known as optomechanically-induced transparency, can be nonreciprocal was predicted by Hafezi and Rabl[11]. Similar effects were observed in suitably driven photonic crystal nanobeams coupling multiple localized optical and mechanical modes[12]. Superconducting LC resonators with vibrating capacitor plates showed nonreciprocal transmission for microwave signals[13,14]. Careful measurements quantified two-way transmittance in these systems[9,10,12-14], proving that tens of dBs of isolation is possible with low insertion loss and over a wide range of probe powers. The linearity, potential of low noise, high degree of reconfigurability and small system size are exciting benefits of this optomechanical approach to magnet-less nonreciprocal integrated devices.

Even though experimental realizations take quite different guises (see Fig. 1a-c), their operation can be described by the same underlying mechanism. When two resonators of different frequency are coupled through a field oscillating at their difference frequency, the phase of that field is imprinted on up or down transitions in opposite fashion[15]. In a cavity optomechanical system, this effect is naturally realized by optical control fields, which induce a linear coupling between optical and mechanical resonant modes. Detuned from cavity resonance, it provides the energy difference between a cavity photon and a mechanical phonon, and its strength controls the coupling rate[6]. If two control fields couple two optical modes to a single mechanical mode (Fig. 1d), a path from mode 1 to 2 via the mechanical resonator will acquire an overall phase that is equal to the phase difference of the two control fields, whereas mode conversion in the opposite direction acquires opposite phase[16,17]. This directional phase delay is the equivalent of Peierl's phase for charged particles in a (magnetic) gauge potential, and can be interpreted as a synthetic magnetic flux. The optical control beams synthesize the gauge potential, providing inherent reconfigurability to the system.

Synthetic gauge fields and momentum biasing

Nonreciprocity always requires breaking spatial symmetry. This is guaranteed by working with two optical modes coupled to the output ports with different phase and/or amplitude. Mechanically-mediated mode conversion implies that (at least) two optical modes are necessary. This can be achieved in distinct cavities (Fig. 1b), but also in a single ring resonator (Fig. 1a), in which even and odd modes are populated by a control beam incident through a waveguide. The two modes are then inherently excited with a $\pi/2$ phase difference, which maximizes the nonreciprocal response[9]. In rings, it is obvious that directionality – i.e., the imparted momentum – of the control beam breaks symmetry. In fact, such momentum biasing can be recognized in *any* nonreciprocal system: creating a Peierl's phase requires driving two modes of different symmetry in quadrature, thus imparting an effective momentum to the total field in the system. Indeed, this reveals a deep connection between explanations of nonreciprocity based on synthetic gauge fields[9,12,16,17] or momentum-biased potentials[7,8,10,11], which transcends optomechanical systems[5,18,19].

Gyration, isolation, circulation

Once nonreciprocity is enabled through biasing control fields, several functionalities are possible, depending on the way the modes are coupled to each other and to the input and output ports[5,19,20]. In the simplest case – two cavities each coupled to one port – the mechanically-mediated mode conversion leads to a nonreciprocal phase transmission from port to port, enabling the functionality of a gyrator. To induce isolation, interference with another path is needed, such that the paths constructively interfere in one direction. Light traveling in the other direction is dissipated, experiencing an engineered, one-way reservoir[19]. The bath in which energy is dissipated can be controlled through the mode-to-port coupling: mechanical dissipation allows isolation for low control powers, whereas dissipation through optical absorption allows larger bandwidths[20].

Efficient nonreciprocal operation requires optical linewidths smaller than the mechanical frequency[11], and tuning of optical modes. The required level of degeneracy is rather straightforward in high-quality ring resonators[7-10]. Photonic crystal nanocavities have also been successfully tuned[12]. Moreover, nonreciprocal effects can be established between different-frequency ports, as demonstrated in microwave experiments (see Fig. 1e)[13,14]. Recently, the important function of circulation was reported in both microwave and optical domain[21,22], by expanding the number of ports and modes and controlling interference conditions.

Bandwidth, noise, and many-body physics

Optomechanics provides an exciting playground for on-chip nonreciprocity, but how does it compete with other parametric systems, such as modulated devices relying on other forms of nonlinearity[23,24,25]? Bandwidth, power consumption, linearity and noise are crucial metrics to watch closely as these systems continue to be improved. Bandwidth appears fundamentally limited by the mechanical frequency, which can be extended to several GHz[6,12]. Limited-bandwidth applications may have interesting opportunities for filtering, duplexing, and source protection. For widespread application, the need to drive a continuous control beam may be detrimental in terms of power consumption. Yet, noise, optical real-time reconfigurability, and inherent compactness are clear advantages of this approach to nonreciprocity, particularly appealing for routing quantum information.

Optomechanical cooling can help to suppress noise and increase bandwidth. This is especially true for red-detuned control fields, which naturally cause sideband cooling of motion. Noise levels can be suppressed to the single-quantum level over the full isolation bandwidth under the same condition as mechanical ground state cooling. Development of high-frequency, strongly-interacting systems is thus beneficial. Moreover, the ability to continuously tune optical cavity modes over a wide range can effectively enhance the operation bandwidth for some applications.

Extending the number of interacting modes may allow channeling noise in directions where it does least harm[5,13,14], and enhance bandwidth. The ultimate extension of optomechanics to mode *continua* corresponds to (stimulated) Brillouin scattering in waveguides[26]. Other intriguing possibilities in many-mode optomechanical implementations include exploiting nonreciprocal phases in the mechanical response[16], and realizing topological insulators for photons and phonons[27]. In presenting minimal systems that show the required symmetry breaking, the recent developments provide a promising start to exploring such rich many-body physics for photons and phonons.

Ewold Verhagen is in the Center for Nanophotonics at AMOLF, Amsterdam, The Netherlands. Andrea Alù is in the Department of Electrical and Computer Engineering, The University of Texas at Austin, USA. E-mail: verhagen@amolf.nl.

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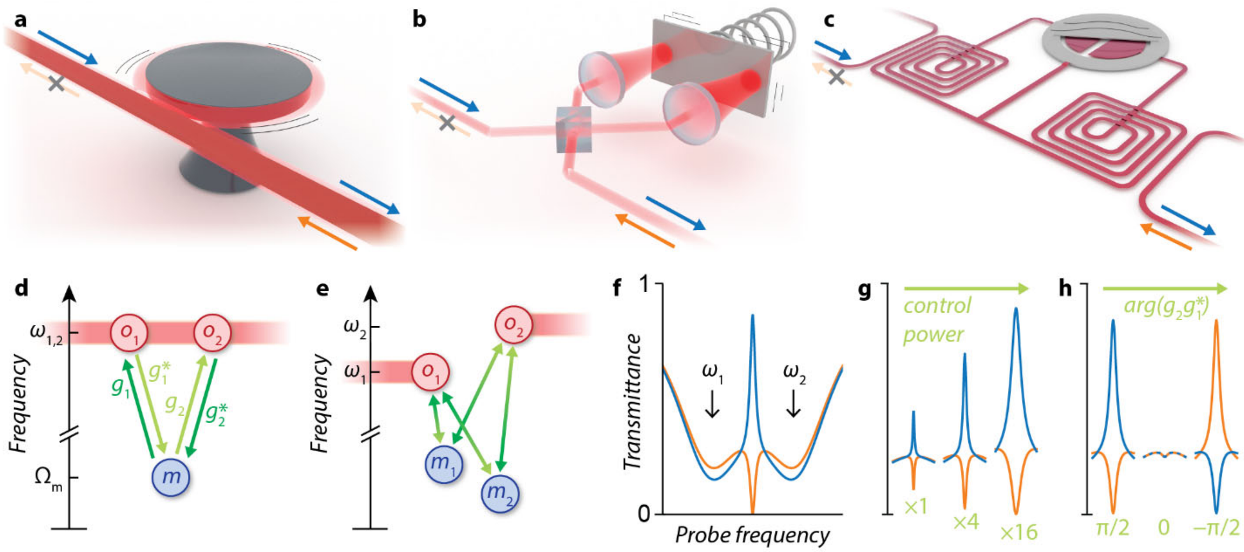

Figure 1. One-way transmission in optomechanical systems. Various geometries support nonreciprocal response by coupling optical and mechanical modes, such as (**a**) even and odd optical modes in a ring resonator coupled to breathing motion, (**b**) Fabry-Pérot cavities coupled to a shared mirror displacement, and (**c**) two microwave LC resonators coupled to a vibrating capacitor plate. (**d**) Control fields mediate the coupling between optical modes o_j and mechanical mode m. The phases of the induced coupling rates g_j induce nonreciprocal mode conversion from o_1 to o_2. Interference with a direct path then creates isolation. A similar mechanism allows one-way frequency conversion (**e**). (**f**) In this example, the transmittance spectra of a forward (blue) and backward (orange) probe beam show the signature with nearly degenerate optical modes, separated by one cavity linewidth. A nonreciprocal transmission window is opened when the probe frequency is equal to the sum of the control and mechanical frequency. Nonreciprocity can be tuned through the power (**g**) and phase difference (**h**) of the control fields.

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