Nonlinearity-Driven Broken Degeneracy and Nonreciprocity

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Nonreciprocal phenomena are at the basis of optical circulators and isolators, of fundamental importance for fundamental and applied photonics research and technology. Due to the weakness of magneto-optic effects in common materials, there has been recent strong interest in developing non-magnetic routes to nonreciprocity in photonic systems[1]. To date, most of these efforts have relied on temporal modulation schemes based on electro-optical phenomena, which are however restricted to moderate speeds, limiting the broad applicability of these ideas. Recently, we have shown that widely available nonlinear phenomena, suitably combined with degenerate resonances, can induce symmetry-breaking and nonreciprocity based on optical pumping, exploiting the handedness of circularly polarized (CP) light.

As a first route, we have explored a geometrically symmetric optomechanical cavity[2] supporting degenerate optical modes coupled to a mechanical resonance. A detuned pump field stimulates polarization conversion of a signal resonant with the cavity. A circularly polarized pump breaks time-reversal symmetry, such that only signals co-polarized with the pump engage the mechanical mode through radiation pressure (Fig. 1.a). As the pump intensity grows (Fig. 1.b), the effect becomes analogous to nonreciprocal Faraday rotation[3] of a linearly polarized input signal. By tailoring the properties of pump and cavity, it is possible to realize arbitrary polarization conversion of the input signals over the entire Poincaré sphere, opening opportunities for nonreciprocal polarization manipulation and isolation[3].

As a parallel approach, Faraday rotation may also be induced using instantaneous third-order nonlinear processes,[4] as in silicon or silicon nitride below the bandgap. In this scenario, we optically pump a nonlinear cavity, again supporting degenerate modes, with two CP signals of opposite handedness and a small detuning between them. Their interference results in a synthetic angular-momentum bias to the system, sustained by slowly varying nonlinear polarization currents that break degeneracy (Fig. 1.c) and enable nonreciprocal responses. In this scheme, the pump frequencies can be widely chosen since only their difference needs to be comparable to the cavity linewidth, hence even very slow pump frequencies can efficiently break degeneracy and reciprocity.

Both concepts can be straightforwardly combined with conventional optical components to realize free-space or waveguide-based magnet-free isolators and circulators, for instance using the setup shown in Fig. 1.d. These concepts open opportunities for integrated nonreciprocal devices and low-noise, low-loss, all-optical light control ideally suited for classical and quantum platforms.

1. D. L. Sounas, A. Alù, Nat. Photonics **11**, 774–783 (2017).
2. M. Aspelmeyer, et al. Rev. Mod. Phys. **86**, 1391–1452 (2014).
3. R. Duggan, J. del Pino, et al. Phys. Rev. Lett. **123**, 23602 (2019).
4. R. Duggan, et al. Optica **6**, 1152 (2019).

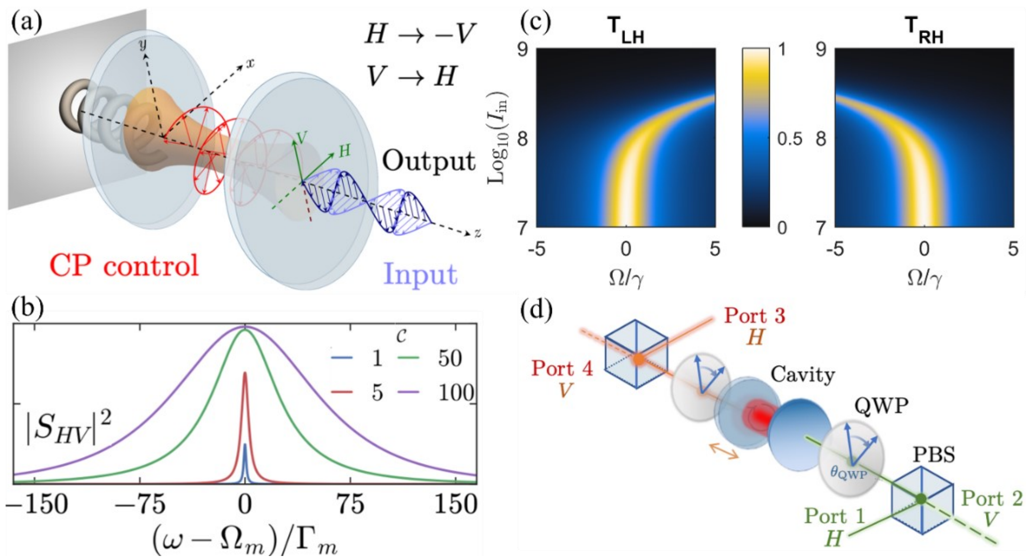

Fig. 1 (a) Fabry-Pérot optomechanical cavity driven with a CP pump beam. (b) Cross-polarized reflection coefficient as a function of the pump cooperativity. (c) Mode splitting for RH and LH modes in the dual-pumped χ^3 cavity manifested in transmission coefficients. (d) Optical setup to implement a circulator. (Adapted from [3,4]).