Mimicking the Faraday Effect with Temporal Modulations

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Time modulation has been intensively studied in recent years for a wide variety of purposes ranging from higher-dimensional physics to magnet-free nonreciprocity. For most nonreciprocal applications, the modulation is applied to synthesize an effective motion longitudinal to the wave propagation, which requires enough of a footprint for the traveling bias to create enough of a difference for waves tranveling in opposite directions.

In contrast, here we explore spatio-temporal modulation schemes that eneable nonreciprocity by effectively rotating the system in the transverse plane. We achieve this phenomenon by considering two oppositely handeded circularly polarized pumps in a resonator with a third-order nonlinearity, creating a synthetic rotation of the material at their difference frequency. A weaker probe field experiences a polarization rotation analogous to the Faraday effect due to the nonlinear interactions mediated by the pumping field. We discuss the dynamics of this interaction and the tradeoffs between different design parameters, in either waveguide or resonator settings.

Further, we discuss an extension of this synthetic Faraday effect to realize a nonreciprocal photonic topological insulator that supports inherently robust one-way propagation of electromagnetic waves along its boundary. Unlike conventional photonic topological insulators based on geometrical asymmetries but static in time, which are not immune to backscattering because of reciprocity, with our pumping scheme it is possible to establish ideal robustness to disorder or defects. Our approach also requires a single pumping field that can be uniform over the entire lattice, in contrast with other schemes to enable topological order that require individual control over each unit cell of the underlying lattice.

The same principles transfer from the spin-angular momentum to the angular momentum modes in a ring resonator, offering exciting opportunities to implement magnet-free integrated nonreciprocal photonic devices. We show that nonreciprocal detuning of a ring resonator can be achieved with all-optical biasing, opening a pathway towards miniaturization of isolators and circulators without the need for ferrites or garnets. Our modulation approach to mimic Faraday phenomena is therefore applicable to many different scenarios with exciting perspectives for several applications.