Exceptional points in waveguides with extreme chirality

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Exceptional points (EPs) are critical points of a system's parameter space where eigenvalues as well as eigenvectors coalesce [1]. They can be observed in non-Hermitian systems adhering to parity-time (PT) symmetry, as the transition point between complex and real eigenvalues. In photonic waveguides, structures designed to confine and guide light using a suitable combination of refractive indices, EPs result in the convergence of multiple eigenmodes – photonic eigenvectors – into a single mode. This leads to remarkable dispersion relations near the merging point(s). Placing two waveguides in close proximity causes their modes to interact. Coupling waveguides in this manner offers two potential methods for achieving EPs, using either co-propagating modes or counter-propagating modes. The first method relies on non-Hermitian Hamiltonians, particularly to those adhering to PT-symmetry, with conventional coupling between waveguides exhibiting balanced gain and loss. By contrast, as detailed in [1], the second mechanism does not require the presence of gain or dissipation modulation, but rather a coupling of a standard waveguide with one exhibiting backward propagating modes. For a homogeneous waveguide, such a behavior can be achieved by exploiting negative refraction, i.e. opposite directions of phase and energy propagation. Although it is customary to achieve negative refraction by making the permittivity and the permeability simultaneously negative (see, e.g., [2]), here, we access it via extreme values of optical chirality [3]. As a weak parameter compared to the average refractive index, chirality causes the polarization rotation of propagating plane waves, but for extreme values leads to negative refraction. Apart from eliminating the need for meticulous manufacturing, chirality also offers an additional degree of freedom for remarkable light manipulation.

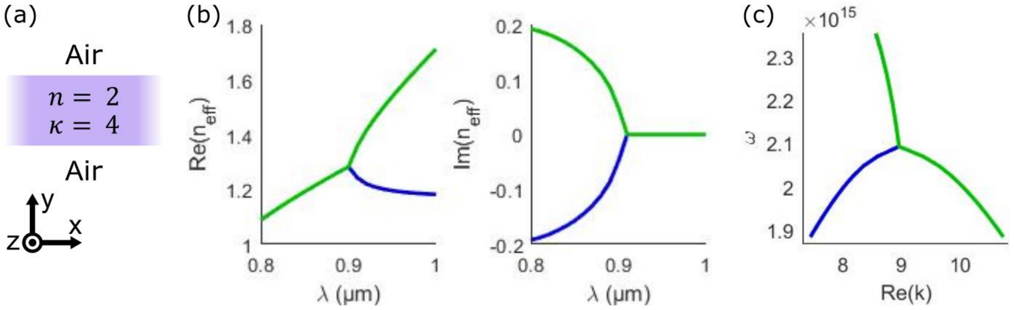

Figure 1 - (a) Schematic of a 150 nm-thick chirowaveguide, with n = 2 and κ = 2n, embedded in vacuum, (b) effective index and (c) dispersion of two modes with an EP at around 900 nm.

Using numerical simulations we first consider a single slab waveguide with giant chirality, surrounded by vacuum, as depicted in Fig. 1(a). Most modes of this waveguide exhibit backward propagation, manifested as a negative group velocity (negative slope in ω(k)) and a negative z-component of the Poynting vector. However, it appears that one mode still propagates forward in the structure, which couples with one of the backward modes to generate PT-like dispersion features: the signature “forks” of EPs are present in Figs. 1(b). An EP occurs at λ ≈ 900 nm where a forward-propagating mode (blue) and a backward-propagating mode (green) merge, as illustrated in Fig. 1(c). Such behavior is attained in a single homogeneous chirowaveguide when the chirality exceeds the refractive index.

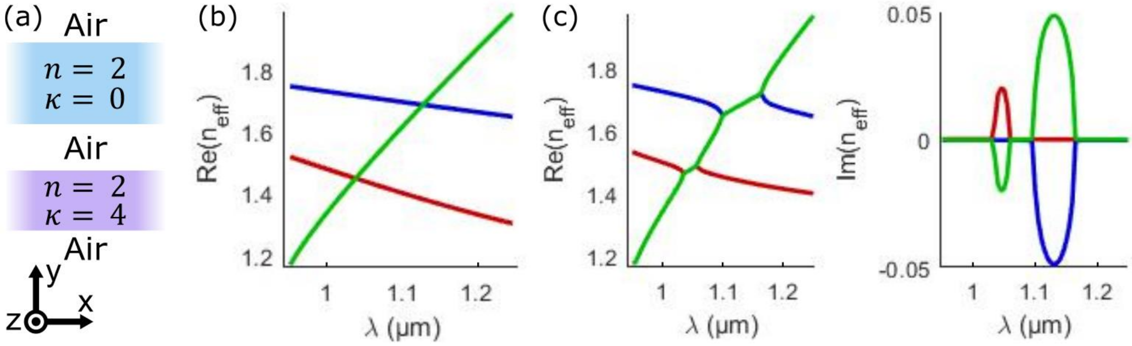

Figure 2 - (a) Schematic of a 300 nm-thick dielectric slab waveguide coupled to a 130 nm-thick chirowaveguide with giant chirality, separated and surrounded by air. (b) Effective indices of modes from the isolated achiral waveguide (blue and red) and chirowaveguide (green). (c) Effective indices of three modes from the coupled waveguides, showing four EPs.

To highlight the coupling between forward and backward eigenmodes, we examine two waveguides (Fig. 2(a)): one achiral supporting forward-propagating eigenmodes, and one chiral with giant chirality that sustains backward eigenmodes, as seen in Fig. 2(b) from their isolated dispersions. These modes interact when the waveguides are brought into proximity, by forming PT-like dispersion patterns as for the single waveguide, though more intricate. Broken PT-like zones [4] appear around each chiral-achiral crossing (around 1050 nm and 1150 nm in Fig. 2(c)), with EPs on each zone edge. The size of these zones increases with the mode coupling, controlled by varying the waveguide spacing, so that they eventually merge creating an atypical mode crossing.

Overall, we demonstrate backward propagation in waveguides with giant chirality, and achieve EPs and PT-like dispersion behaviors without resorting on gain/loss modulation or simultaneous negativity of the permittivity and permeability. Recent experimental demonstrations of meta-media with giant controllable chirality offer the necessary parameters, and thus exciting new-generation photonic devices appear within reach.

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