Exceptional points and large chirality in coupled photonic waveguides

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Abstract: In coupled waveguides, exceptional points can stem from the coupling of either counter-propagating modes or co-propagating modes. We utilize both methods, by implementing extreme chirality in a homogeneous waveguide, thereby realizing backward mode propagation, and by inserting a chiral material in the slot between waveguides exhibiting balanced gain and loss.

Exceptional points (EPs) are critical junctures in a system's parameter space where eigenvalues and eigenvectors coincide [1]. In waveguiding systems, EPs result in the convergence of multiple eigenmodes into a single mode, leading to remarkable dispersion relations nearby the merging point(s). In a photonic configuration comprising two coupled waveguides, EPs can be achieved in two main ways, using either counter-propagating modes or co-propagating modes. The first method relies on the coupling of a standard waveguide with one exhibiting negative phase velocity [1]. The second method utilizes non-Hermitian Hamiltonians, particularly those adhering to PT-symmetry, with conventional coupling between waveguides exhibiting balanced gain and loss [2]. Here, we harness giant values of chirality to achieve EPs using both approaches. First, we adopt Pendry's chiral route to negative refraction [3], coupling counter-propagating modes in waveguides made of homogeneous extremely chiral media [4]. Secondly, we alter the coupling between modes of PT-symmetric waveguides by varying the chirality of the material in the gap that separates them.

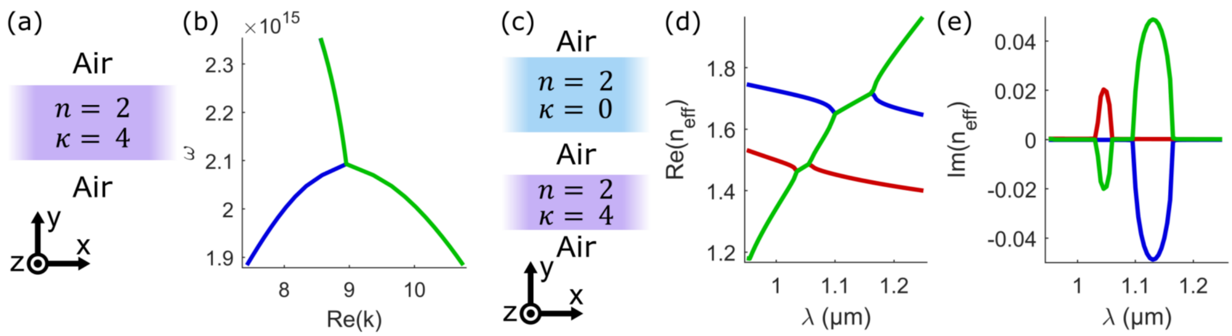

Figure 1. (a) Schematic of a 150nm thick chirowaveguide, with n = 2 and κ = 2n, embedded in vacuum, and (b) dispersion ω(k) of two of its modes. (c) Schematic of a 300nm thick dielectric slab coupled to a 130nm thick chirowaveguide, separated by 200nm, and (d) real and (e) imaginary parts of the effective indices of three modes [4].

Homogeneous chiral media, characterized by a chirality parameter κ, exhibit backward-propagating waves when their chirality reaches extreme values, i.e. $|\kappa| > n$, n being the medium's refractive index [4]. The phase velocity and power flow of these waves have opposite directions. Guided modes with these properties can be brought about in waveguides made of extremely chiral media, along with standard forward-propagating modes [4]. The interaction of counter-propagating modes, of great interest for EP generation, is numerically confirmed by simulating a single chiral slab surrounded by vacuum, as depicted in Fig. 1(a). A backward-propagating mode, characterized by a negative slope of ω(k) (green in Fig. 1(b)), couples with a forward-propagating mode (blue in

Fig. 1(b)) to create an EP ($\lambda \approx 900$ nm) and the signature "fork" dispersion of PT-symmetric structures. This coupling can also be observed between the counter-propagating modes of two distinct waveguides, one achiral and the other with giant chirality (Fig. 1(c)). Figs. 1(d,e) display the real and imaginary effective indices of two forward-propagating modes (blue and red) and one backward-propagating mode (green). Complex-index zones are brought about by the crossings of counter-propagating modes ($\lambda \approx 1.05$μm and 1.15 μm), with EPs at each end. The width and magnitude of these zones increase as the waveguide separation decreases, resulting in increased coupling, so that they can eventually merge.

EPs can also be achieved in PT-symmetric waveguides with balanced gain and loss. As the amount of gain and loss increase in the waveguides, controlled by a parameter γ, guided modes transition from a PT-symmetric regime with real effective indices to a PT-broken regime, with complex effective indices. The transition between these two regimes is the EP, that has previously been shown to be displaced by the introduction of chirality in the slot that separates these waveguides (configuration shown in Fig. 2(a)) [2]. We observe a similar behavior when chirality is increased to extreme values: the characteristic forks of PT-symmetric waveguides also appear for large chirality parameters κ, and their EPs are displaced as κ increases. For any κ, modes are PT-symmetric for small gain and loss ($\gamma < \gamma_{EP}$) and PT-broken beyond a gain-loss threshold ($\gamma > \gamma_{EP}$). For a fixed amount of gain and loss, this creates a succession of PT-symmetric and PT-broken regimes as κ varies (Figs. 2(b,c)).

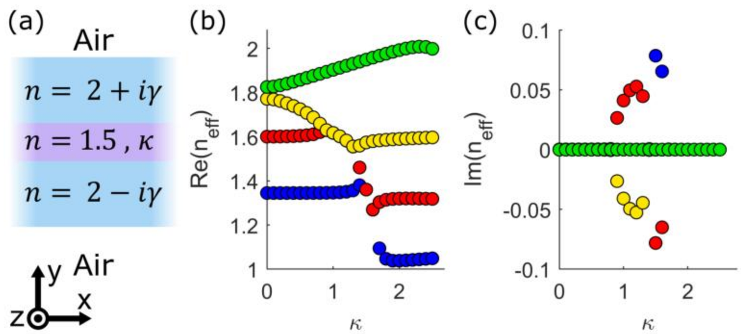

Figure 2. (a) Schematic of two 100nm thick achiral slab waveguides with gain and loss (2±iγ) separated by a 12nm thick chiral slab, and (b) real and (c) imaginary parts of the effective indices of four modes.

Meta-media advancements have enabled significant progress in accessing giant chiral values across various spectral realms [5], enabling giant controllable chirality. Utilizing these materials in coupled waveguide configurations provides an additional way of tailoring the mode dispersion, and in particular to manipulate the position of EPs, offering innovating perspectives for integrated photonics.

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References

1. Mealy, T. and F. Capolino, “Exceptional points of degeneracy with indirect band gap induced by mixing forward and backward propagating waves,” Phys. Rev. A, Vol. 107, p. 012214, 2023.
2. De Corte, A., M. Besbes, H. Benisty and B. Maes, “Chiral materials to control exceptional points in parity-time-symmetric waveguides, ” Phys. Rev. A, Vol. 109, p. 023531, 2024.
3. Pendry J. B., “A chiral route to negative refraction,” Science, Vol. 306, pp. 1353–1355, 2004.
4. De Corte, A., S. F. Koufidis, M. W. McCall and B. Maes, “Exceptional points in negatively refracting chirowaveguides due to giant chirality,” Phys. Rev. A, Vol. 110, p. 053513, 2024.
5. Katsantonis, I. et al., “Strong and broadband pure optical activity in 3D printed THz chiral metamaterials,” Advanced Optical Materials, Vol. 11, p. 2300238, 2023.