Exceptional points from giant chirality

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In non-Hermitian systems, exceptional points (EPs) are critical points of a system's parameter space where eigenvalues and eigenvectors coalesce. In photonic systems, this convergence of multiple eigenmodes into a single mode leads to remarkable dispersion relations near the merging point(s). In a structure comprising two coupled waveguides, EPs can be achieved by balancing gain and loss so that co-propagating modes combine in a parity-time-symmetric manner. Alternatively, coupling a standard waveguide with one exhibiting negative refraction enables interactions between counter-propagating modes, creating EPs without any gain or loss. Here, we adopt Pendry's chiral route to negative refraction, which does not necessitate the simultaneous negativity of the permittivity and permeability, by implementing giant chirality in numerically simulated photonic waveguides. We first consider a single waveguide with giant chirality where counter-propagating modes can coexist, creating an EP in a single, homogeneous waveguide. Secondly, we couple forward-propagating modes of a standard dielectric waveguide to a backward mode of a negatively refracting chirowaveguide, giving rise to two complex zones in the mode dispersion, each surrounded by two EPs. The latter geometry offers a control mechanism over the dispersion via the spacing between waveguides. Both structures open new pathways for integrated photonic applications.

Context

Eigenvalues and eigenvectors of a system can simultaneously coalesce at points in parameter space called exceptional points (EPs) [1]. In photonic coupled waveguides, EPs can arise by coupling either co-propagating or counter-propagating modes. The first method relies on non-Hermitian Hamiltonians, particularly in relation with those adhering to parity-time symmetry, with conventional coupling between waveguides exhibiting balanced gain and loss. The second mechanism does not require the use of gain or dissipation modulation, but rather a coupling of a standard guided mode with one exhibiting opposite directions of phase and energy propagation, called a backward mode. For a homogeneous waveguide, this behavior can be obtained by exploiting negative refraction. Although negative refraction is commonly achieved through simultaneously negative permittivity and permeability values (see, e.g., [2]), here, we access it via extreme values of optical chirality [3]. For weak values (compared to the average refractive index), chirality causes polarization rotation of propagating plane waves, but for extreme values it leads to negative refraction. This approach opens new avenues for photonic integrated devices since chirality offers an additional degree of freedom for light manipulation.

Coupled-wave theory

In reciprocal bi-isotropic media, using Tellegen's formalism, the constitutive relations read: $\mathbf{d} = \varepsilon\mathbf{E} + i\kappa\mathbf{h}$ and $\mathbf{b} = -i\kappa\mathbf{E} + \mu\mathbf{h}$, with all parameters being relative, and κ the chirality (or Pasteur) parameter. When introducing these equations in Maxwell's curl

relations for a monochromatic excitation, the supported eigenstates are two orthogonal circular polarizations, with corresponding wavenumbers $k_{\pm} = k_0(n \pm \kappa)$, where $n = (\varepsilon\mu)^{1/2}$. For extreme chirality, i.e., $|\kappa| > n$, the direction of phase propagation and handedness for one circular state changes, while the Poynting vector does not, resulting in a backward-propagating wave. In a dielectric chiral slab, surrounded e.g. by vacuum, the previous dispersion relation of unbounded media does not hold. Nevertheless, upon inspection of the dispersion relation of a chiral waveguide, as seen in Eq. (16) of [4], it is possible to show that when $\kappa = n$, one effective refractive index becomes zero. Numerical calculations (see next section) confirm that the dispersion curve changes sign at these zeros, suggesting the existence of backward modes in waveguides with giant chirality.
Assuming the presence of a forward- and a backward-propagating mode in the same waveguide structure, we express their interaction using coupled-wave theory. Considering a forward-propagating mode of amplitude a_1 and a backward-propagating mode of amplitude a_2, their perturbed propagation constants upon interaction with each other can be found by solving the following eigenproblem:

$$\frac{d}{dz}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} -ik_1 & C_{21} \\ C_{12} & -ik_2 \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

where C_{12}, C_{21} are given by overlap integrals between the unperturbed modes, and k_1, k_2 are the propagation constants of the unperturbed eigenmodes. It can be shown that the eigenvalues of this system – i.e. the propagation constants of the perturbed, coupled eigenmodes – and their corresponding eigenvectors coalesce simultaneously at certain dispersion points, creating EPs.

Single waveguide with giant chirality

Using a Matlab-based finite element mode solver (SimPhotonics), we first simulate a single slab waveguide with giant chirality, surrounded by vacuum, as depicted in Fig. 1(a). Most modes of this waveguide exhibit backward propagation (one example pictured in green in Fig. 1(d)), manifested as a negative group velocity (negative slope in ω(k)) and a negative z-component of the Poynting vector. Nevertheless, one forward mode is still allowed in the structure, and couples with one of the backward modes to generate parity-time-like dispersion features: the signature "forks" are present in Figs. 1(b) and (c). An EP occurs at $\lambda \approx 900$ nm where a forward-propagating mode (blue) and a backward-propagating mode (green) merge, as illustrated in Fig. 1(d). Such behavior is attained in a *single homogeneous* chirowaveguide when the chirality exceeds the refractive index, as expected from the theory (see previous section).

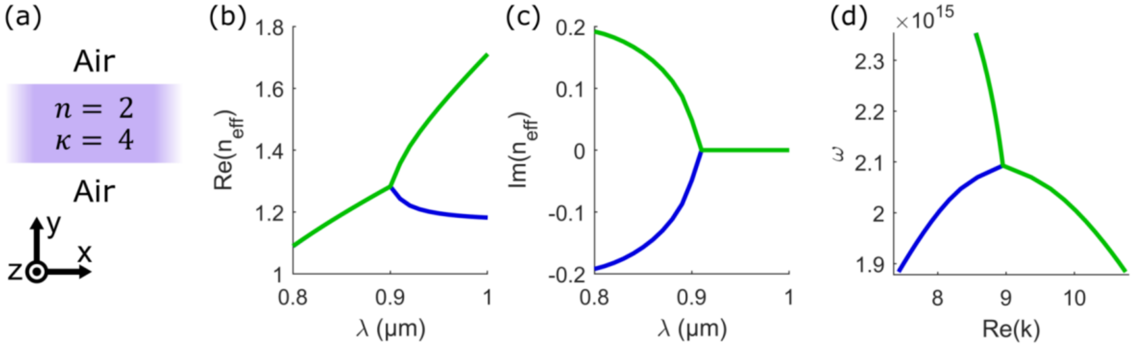

Figure 1 - (a) Schematic of a 150 nm-thick chirowaveguide with n = 2 and κ = 2n, embedded in vacuum. (b) Real and (c) imaginary effective index of two modes with an EP at around 900 nm. (d) Dispersion ω(k) of these same modes.

Coupled achiral and chiral waveguides

To deepen our analysis of the coupling between forward and backward eigenmodes, we next consider two waveguides (Fig. 2(a)): one achiral waveguide supporting forward-propagating eigenmodes, and one waveguide with giant chirality that sustains backward eigenmodes. Each forward mode (blue and red in Fig. 2(b) and (c)) interacts with a backward mode (green) by creating a complex zone at their crossing in the dispersion (around 1050 nm and 1150 nm), with EPs on each zone edge, similarly to parity-time-symmetric structures [5]. When the waveguides are brought closer together, the mode coupling grows which increases the size of these zones, so that they eventually merge into a single complex zone. The forward-propagating mode (blue in Fig. 2(d) and (e)) gradually evolves from lower-order achiral-dominated mode to higher-order achiral-dominated mode by hybridizing with the complex modes during the phase transition. These dispersion features are recreated using the coupled-wave theory developed above, with two complex zones for a wider gap and a single merged zone for a thinner gap.

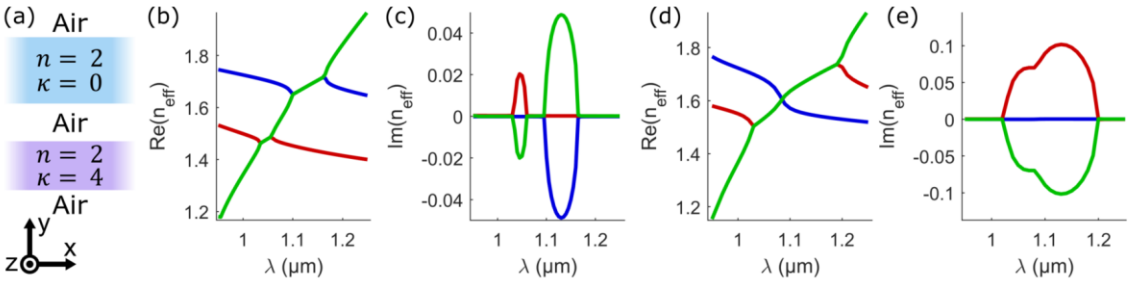

Figure 2 - (a) Schematic of a 300 nm-thick dielectric slab waveguide coupled to a 130 nm-thick chirowaveguide with giant chirality, separated and surrounded by air. (b) Real and (c) imaginary effective indices of three modes from the coupled waveguides separated by a 200nm air gap, showing four EPs. (d) Real and (e) imaginary effective indices of three modes from the coupled waveguides separated by a 100nm air gap, showing two EPs.

Conclusion

We numerically demonstrate backward propagation in waveguides with giant chirality, and achieve EPs by coupling backward and forward guided modes, thereby circumventing the need for gain/loss modulation, periodic gratings, or simultaneous negativity of the permittivity and permeability. In parallel, we devise a coupled-wave theory that gives insight into the forward-backward mode coupling while supporting our simulation results. With recent experimental demonstration in meta-media, giant controllable chirality unlocks a new range of photonic integrated devices.

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