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Chiral waveguides and exceptional points

A. De Corte[1], M. Besbes[2], H. Benisty[2], S.F. Koufidis[3], M.W. McCall[3], and B. Maes[1*]

[1] University of Mons, Micro- and Nanophotonic Materials Group, Research Institute for Materials Science and Engineering,
University of Mons, 20 Place du Parc, B-7000 Mons, Belgium
[2] Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Université Paris Saclay, 2 Av. Augustin Fresnel,
91127 Palaiseau Cedex, France
[3] Imperial College of Science, Technology and Medicine, Blackett Laboratory, Department of Physics, Prince Consort
Road, London SW7 2AZ, United Kingdom
*corresponding author: bjorn.maes@umons.ac.be

Abstract: In chiral waveguides with gain and loss, we report coupling between TE and TM modes leading to interesting dispersion patterns of avoided crossings and symmetry-broken zones. Additionally, even without gain and loss, we obtain backward modes via exceptional points in waveguides with a large chirality.

Photonic devices respecting parity-time (PT) symmetry have produced many interesting phenomena in recent years [1]. In waveguides e.g., under a certain gain-loss threshold, the modes are propagating, whereas above that threshold, called the exceptional point (EP), one mode is amplified and the other decays. This creates a mode dispersion with two characteristic 'forks', for the real and imaginary part, respectively, on each side of the EP (dashed lines in Fig. 1c). In addition, chiral materials are extensively studied due to their different response to left-handed and right-handed circularly polarized light [2]. We utilize material chirality with coupled waveguides to create novel guiding behaviors, first in coupled waveguides with balanced gain and loss separated by a chiral material (Fig. 1a), then by coupling a waveguide with large chirality to an achiral waveguide (Fig. 2a). We simulate these structures with the finite element method using the SimPhotonics software, a Matlab toolbox developed at the Laboratoire Charles Fabry.

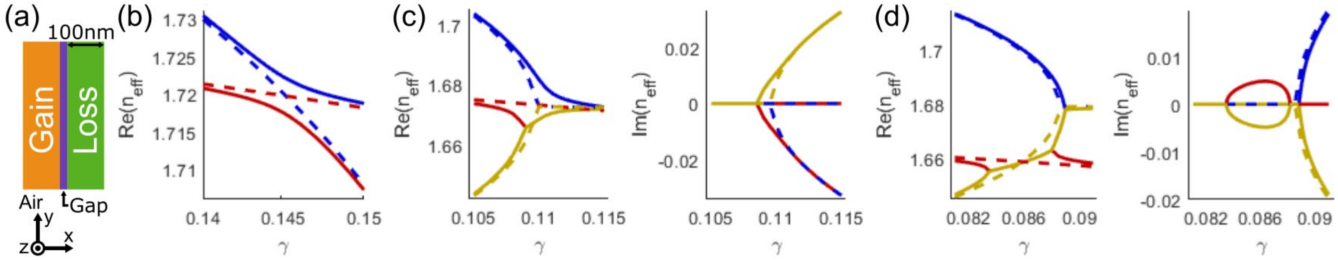

Figure 1: (a) PT-symmetric waveguides with a chiral gap. Dispersion for gap: (b) 12nm, (c) 32nm (d) 44nm. Dashed and solid lines refer to achiral and chiral gaps, respectively.

Two rectangular PT-symmetric waveguides are considered, one with gain and the other with loss (Fig. 1a), separated by a gap made of achiral or chiral material (purple in Fig. 1a) [3]. The mode dispersion is plotted by varying the gain-loss parameter γ. We focus our analysis on three modes: two modes of a TE-polarized PT fork and one mode of a TM fork. The introduction of chirality in the gap enables coupling between TE and TM modes when their dispersions cross (degeneracy). When the gap is narrow (<20nm) and achiral, a crossing occurs between the TM and TE mode (red and blue dashed lines in Fig. 1b). In contrast, an anti-crossing appears when chirality is introduced in the gap (solid lines in Fig. 1b). For medium-sized gaps (around 30nm), the TM mode crosses the EP for an achiral gap, where 2 TE modes coalesce (dashed lines in Fig. 1c). All three modes then interact under the effect of chirality, giving rise to a hybrid dispersion (solid lines in Fig. 1c). The anti-crossing width reaches values close to a homogeneous chiral medium, despite the narrowness of the gap. For a larger gap (>40nm), the TM mode crosses the lower TE mode (red and gold dashed lines in Fig. 1d). Interestingly, their chiral interaction leads to the appearance of a PT-broken zone, followed by a `symmetry recovery' zone (solid lines in Fig. 1d).

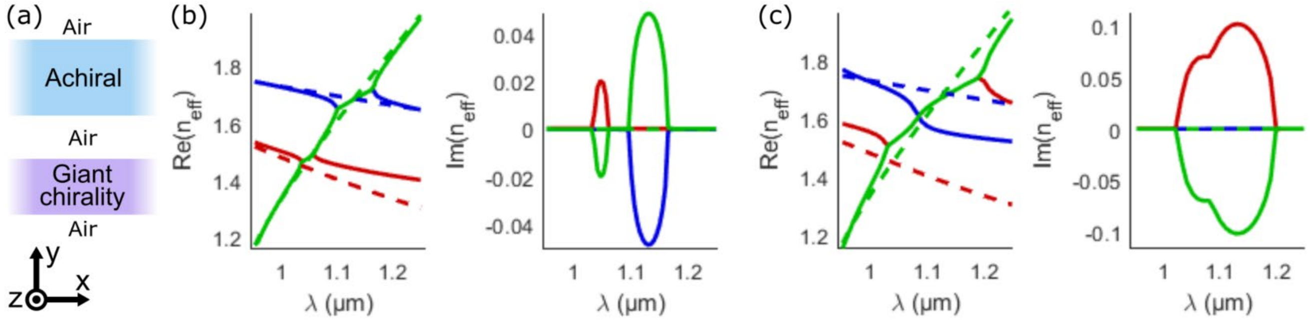

Figure 2: (a) Coupled chiral and achiral waveguides. Dispersion for gap of: (b) 200nm, (c) 100nm.

Exceptional points were recently achieved without gain or loss by coupling forward- and backward-propagating modes [4]. Furthermore, giant chirality can access negative refractive states, and thus backward mode propagation, without the necessity of simultaneous negative permittivity and permeability [5]. We combine these two approaches by examining the coupling between a slab with giant chirality and a thicker achiral waveguide (Fig. 2a). Their dispersion as a function of wavelength highlights important interactions. The modes of the achiral waveguide (red and blue dashed lines in Fig. 1b,c) are forward, while the chiral waveguide presents a backward mode (green dashed line). Figure 1b shows the dispersion for a 200nm air gap (solid lines). The interaction of forward and backward modes creates a PT-like 'broken zone' around each chiral-achiral crossing. When the gap is sufficiently small (e.g., 100nm, solid lines in Fig. 1c), the two zones merge to create one broken zone. Interestingly, the forward mode (blue) that crosses this large PT-broken zone gradually evolves from the higher order achiral mode (shorter λ) to the lower-order achiral mode (longer λ), by hybridizing with the broken modes during the transition.

Overall, chirality induces a rich variety of dispersion patterns with non-Hermitian features. On the one hand, with balanced gain and loss, chirality couples polarizations to create anti-crossings and broken zones. On the other hand, when a large-chirality backward mode interacts with a forward mode, an exceptional point appears in a device, intriguingly, without gain and loss.

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References

1. Feng, L., R. El-Ganainy and L. Ge, "Non-Hermitian photonics based on parity-time symmetry," Nat. Photonics, Vol. 11, 752, 2017.
2. M. Hentschel et al, "Chiral plasmonics," Sci. Adv., Vol. 3, No. 5, e1602735, 2017.
3. A. De Corte, M. Besbes, H. Benisty, B. Maes, "Chiral materials to control exceptional points in parity-time symmetric waveguides, " Phys. Rev. A, accepted.
4. T. Mealy and F. Capolino, "Exceptional points of degeneracy with indirect band gap induced by mixing forward and backward propagating waves," Phys. Rev. A, Vol. 107, 012214, 2023.
5. J. B. Pendry, "A chiral route to negative refraction," Science, Vol. 306, No. 5700, 1353, 2004.