17th International Congress on Artificial Materials for Novel Wave Phenomena - Metamaterials 2023
Crete, Greece, Sep. 11th - 16th 2023

Chiral Materials In Parity-Time Symmetric Waveguides

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***Abstract* – Coupled waveguides with balanced gain and loss form a standard photonic structure for the demonstration of PT-symmetry. We study the influence of chirality on the guided modes of this structure when inserting a chiral material between the waveguides. We observe a strong chiral impact at degeneracies, and elucidate how avoided crossings arise at exceptional points.**

I. Introduction

The unique properties of parity-time (PT) symmetry in photonics have sparked much interest in recent years. [1] A standard photonic structure for PT-symmetry features coupled waveguides, one made of a gain material and the other with an equal amount of loss. The imaginary part of the waveguides refractive index defines the gain/loss parameter γ, which determines the operating regime: PT-symmetric when the two modes propagate without gain or loss, and PT-broken when one mode is amplified and the other decays. The transition between these two regimes occurs at the exceptional point (EP) causing abrupt changes of propagation constants.

Chiral structures and materials respond differently to left-handed and right-handed circularly polarized light. This contrast is highly desired for enantiomer detection in chemistry and biology [2] and it has been shown that PT-symmetry can enhance it in a multilayer approach [3]. A chiral parameter κ can be defined using the constitutive equations of a chiral material [3].

In this work, we combine both approaches and insert a chiral material in the gap between PT-symmetric waveguides in order to study the influence of chirality on the waveguided dispersion.

II. Structure

Two rectangular PT-symmetric waveguides are considered, one with a gain material and the other with a lossy material, respectively defined by refractive index $2 - i\gamma$ and $2 + i\gamma$ (orange and green in Fig. 1). Both waveguides are 100nm-thick and 400nm-wide, and separated by a gap made of achiral ($\kappa = 0$) or chiral ($\kappa \neq 0$) material of refractive index 1.5 (purple in Fig. 1). The gain/loss parameter γ is varied to explore the different PT regimes and the gap thickness is tuned to obtain desired features in the modal dispersion. We simulate this setup with the finite element method using the SimPhotonics software, a Matlab toolbox developed at the Laboratoire Charles Fabry.

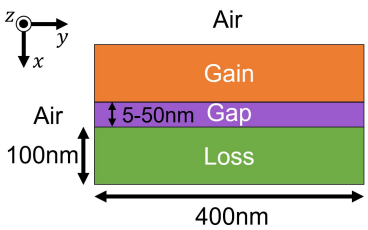

Fig. 1: PT-symmetric rectangular waveguides and chiral gap, infinite along z.

III. Three-Mode Coupling Model

We build a four-mode coupling model that helps elucidating the main features obtained from our numerical simulations (1). The model is written in the basis of isolated waveguide modes, i.e. guided TE and TM modes of the loss (l) and gain (g) waveguides. It features the usual PT coupling terms that occur between same-polarisation modes (TE or TM), with the refractive indices n, the classical couplings C and the gain/loss parameter γ. However, the presence of chirality introduces mixed TE-TM coupling terms, represented by coefficients α and β. To compare our simulation results to this model, n and C are determined by fitting achiral results while α and β are obtained from overlap integrals of achiral mode profiles.

$$\frac{i}{k_0}\frac{d}{dz}\begin{pmatrix} TE_g \\ TE_l \\ TM_g \\ TM_l \end{pmatrix} . = \begin{pmatrix} n_{TE}-i\gamma & C_{TE} & \beta & \alpha \\ C_{TE} & n_{TE}+i\gamma & \alpha & \beta \\ \beta^* & \alpha^* & n_{TM}-i\gamma & C_{TM} \\ \alpha^* & \beta^* & C_{TM} & n_{TM}+i\gamma \end{pmatrix}\begin{pmatrix} TE_g \\ TE_l \\ TM_g \\ TM_l \end{pmatrix} . \tag{1}$$

IV. Influence of Chirality on Dispersion

We observe that the introduction of chirality in the gap has the largest impact on modes when their real dispersions cross, i.e., they are degenerate. Various avoided crossing patterns can be witnessed under the effect of chirality, by spanning a range of γ. The structure supermodes in this section are denoted by TE_1, TE_2 for the TE PT-fork and TM_1, TM_2 for the TM PT-fork.

A. Anticrossing

When the gap is narrow (smaller than 20nm) and achiral, a crossing occurs between the dispersions of TM_1 mode and TE_1 mode (Fig. 2(a)). An anticrossing appears between these modes when chirality is introduced in the gap (Fig. 2(b)), whose width is proportional to the chiral parameter κ introduced in the gap. The obtained theoretical dispersion (Fig. 2(c)) achieves a very good match for the simulated dispersion.

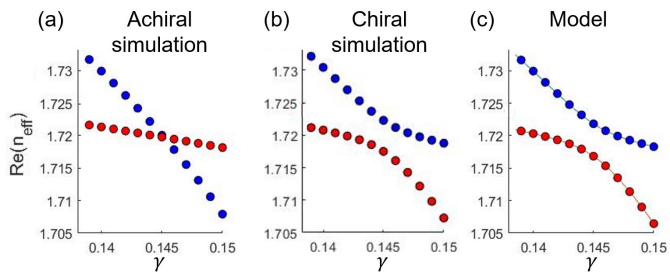

Fig. 2: (a,b) Dispersion of modes TE_1 (blue) and TM_1 (red) for a 12nm-thick gap (a) with achiral material (b) with chiral material. (c) Dispersion obtained from the coupling model using parameters fitted from achiral simulations.

B. Local symmetry breaking

For a larger gap (larger than 40nm), the achiral dispersion of the quasi-TM mode crosses the TE_2 mode (Fig. 3(a)). Their chiral interaction leads to the appearance of a PT-broken zone, followed by a 'symmetry recovery' zone (an 'inverted' EP, Fig. 3(b)). The same behavior is obtained with the coupling model (Fig. 3(c)) but only if the dispersion crossing takes place at $\gamma \neq 0$, as shall be discussed. PT-symmetry is thus essential in this case.

C. Trimodal interaction

For medium-sized gaps (around 30nm), a genuinely 3-moded intermediate situation arises: the TM_1 mode crosses the EP for an achiral gap (Fig. 4(a)), so chirality prompts a distinct trimodal interaction that generates a complex, hybrid dispersion (Fig. 4(b)). Whereas for small and large gaps two modes interact and the third remains

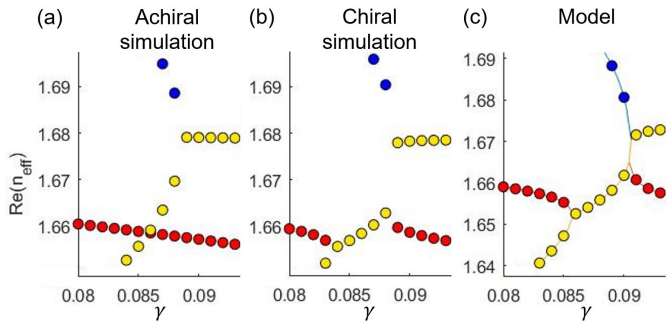

Fig. 3: (a,b) Dispersion of modes TE_1 (blue), TM_1 (red) and TE_2 (yellow) for a 44nm-thick gap with (a) achiral or (b) chiral material. (c) Dispersion obtained from the coupling model using parameters from achiral simulations.

practically unchanged, here the three modes are affected. The anticrossing width, which we define as the distance between the EP and mode TE_1, is again proportional to κ and reaches values surprisingly close to those expected for a homogeneous chiral medium, despite the narrowness of the gap — less than one sixth of the structure. This feature can be recreated quite accurately using the coupling model (Fig. 4(c)).

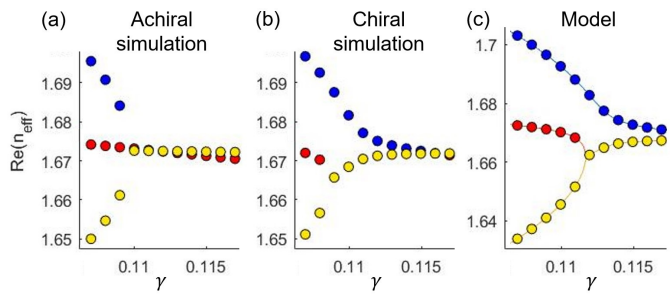

Fig. 4: (a,b) Dispersion of modes TE_1 (blue), TM_1 (red) and TE_2 (yellow) for a 32nm-thick gap with (a) achiral or (b) chiral material. (c) Dispersion obtained from the coupling model using parameters from achiral simulations.

V. Conclusion

Introducing a chiral material in the gap results in a variety of avoided crossing patterns, accessible through modulation of the PT landscape: an anticrossing for small gaps, a trimodal anticrossing for medium gaps and symmetry recovery for large gaps. These noticeable variations in the mode dispersion could be exploited in integrated chiral sensing applications, as medium-sized gaps appear to yield the same sensitivity as a fully homogeneous chiral medium.

Acknowledgement

This work benefits from the support of the French Community of Belgium with the financing of a FRIA grant.

References

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