Parity-time symmetric waveguides coupled through chiral materials

A. De Corte[1], M. Besbes[2], H. Benisty[2], and Bjorn Maes[1]

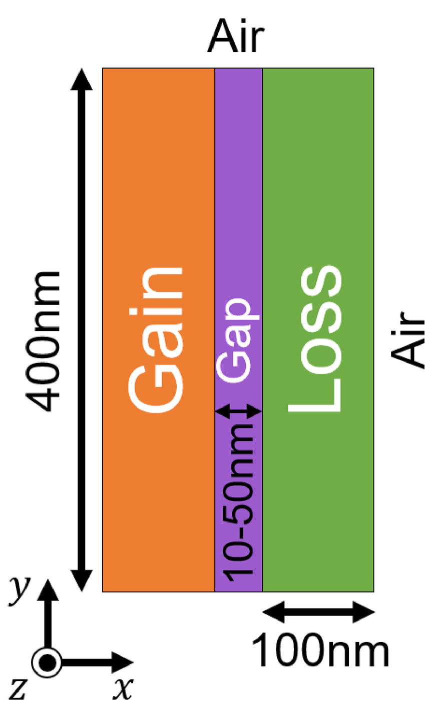
[1]Micro- and Nanophotonic Materials Group, Research Institute for Materials Science and Engineering, University of Mons, Belgium

[2]Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Université Paris Saclay, France

Abstract

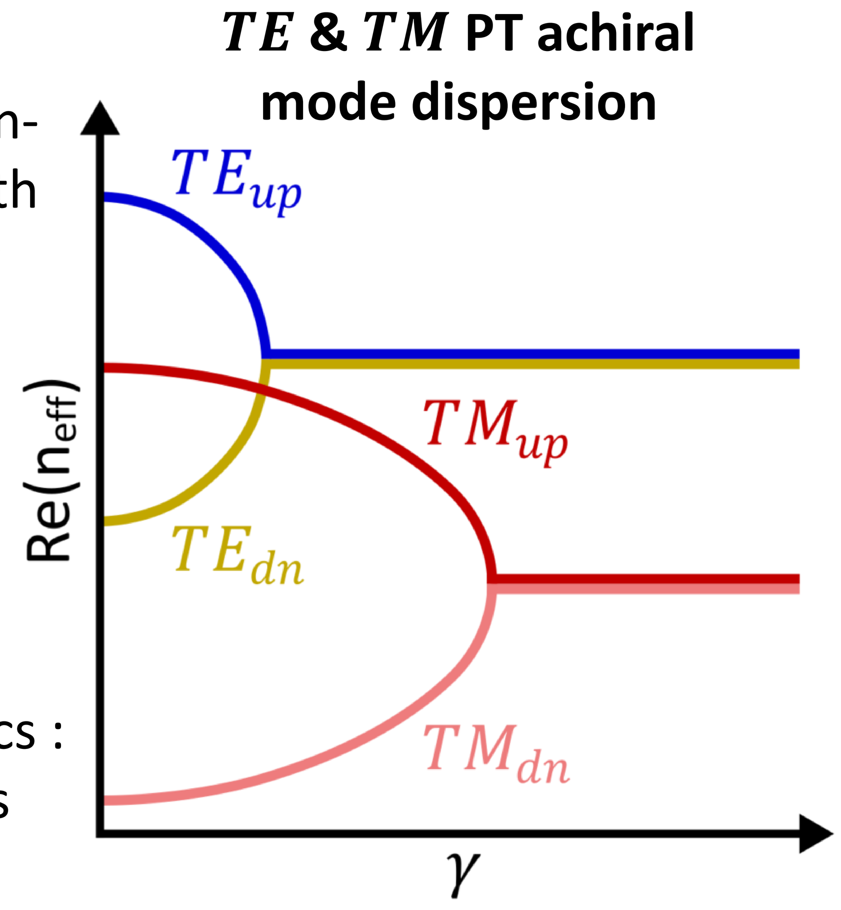
Parity-time (PT) symmetry can be achieved in a standard photonic structure formed by coupled waveguides with balanced gain and loss. It is characterized by a mode dispersion changing abruptly from propagating modes (PT-symmetric) to amplified/decaying modes (PT-broken), at a certain value of gain/loss called the exceptional point (EP). [1] We investigate the impact of inserting a material with chirality in the gap between two rectangular coupled PT-symmetric waveguides. At degeneracies between TE- and TM- polarized achiral modes, we observe a variety of avoided crossings dependent on the PT nature of the interacting modes.

Structure



- PT-symmetric rectangular waveguides with $n = 2 - i\gamma$ or $2 + i\gamma$
- Achiral/chiral gap

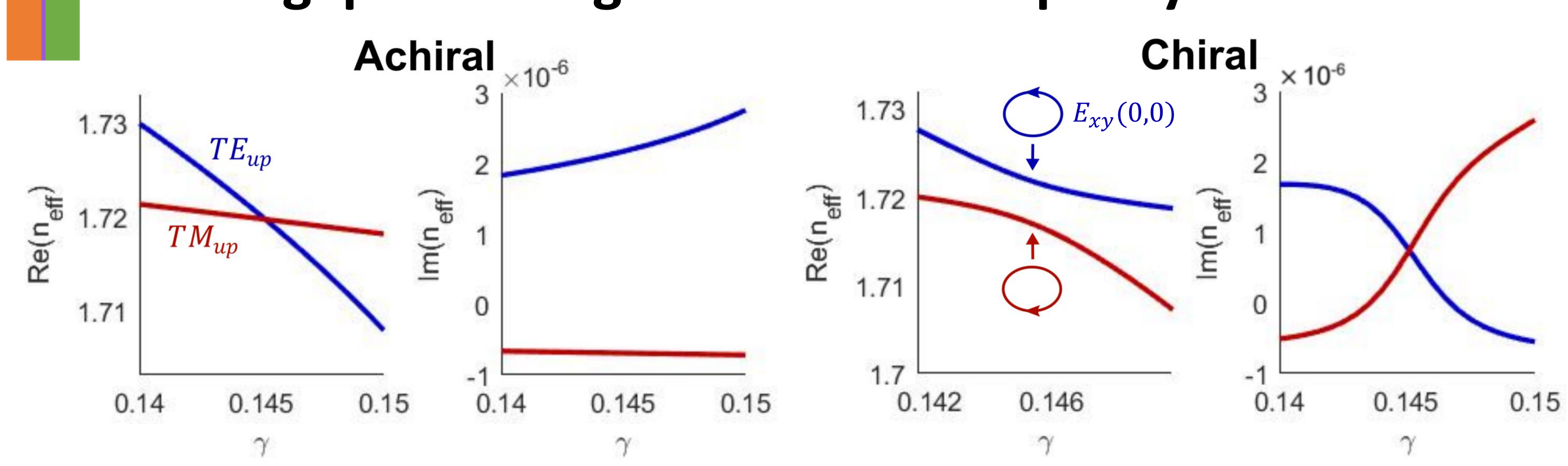
$$\vec{D} = \varepsilon\vec{E} - i\frac{\kappa}{c}\vec{H} \quad [2]$$
$$\vec{B} = \mu\vec{H} + i\frac{\kappa}{c}\vec{E}$$



Simulated via Matlab toolbox SimPhotonics : Finite Element Method Maxwell equations solver now able to model chirality

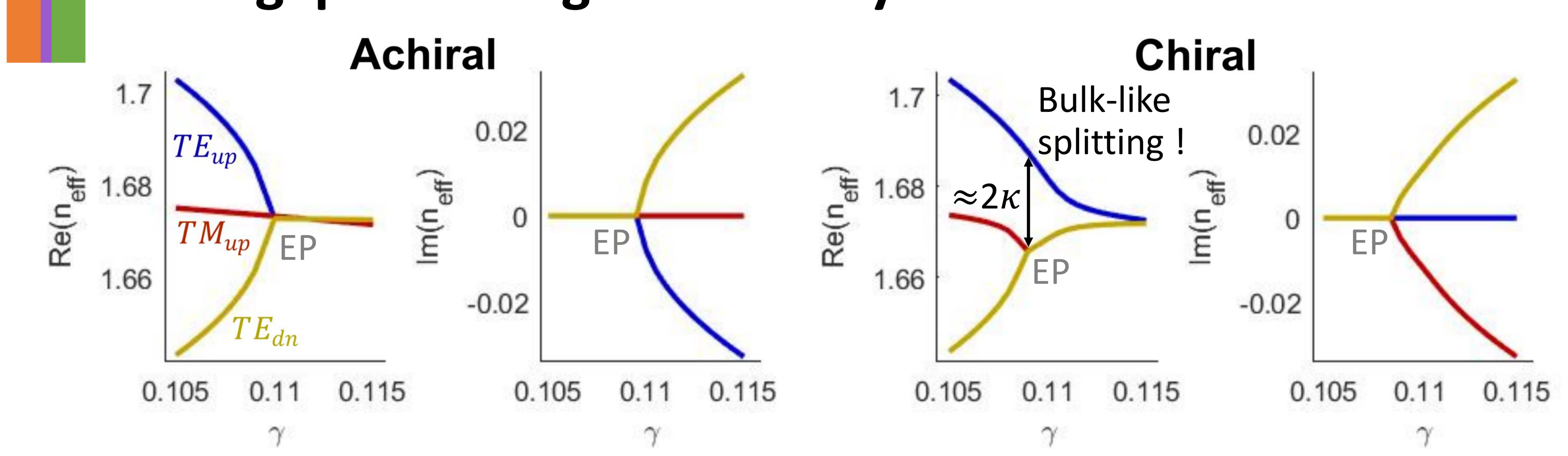
Chiral impact on the modes

12nm gap: Crossing between same-parity achiral modes



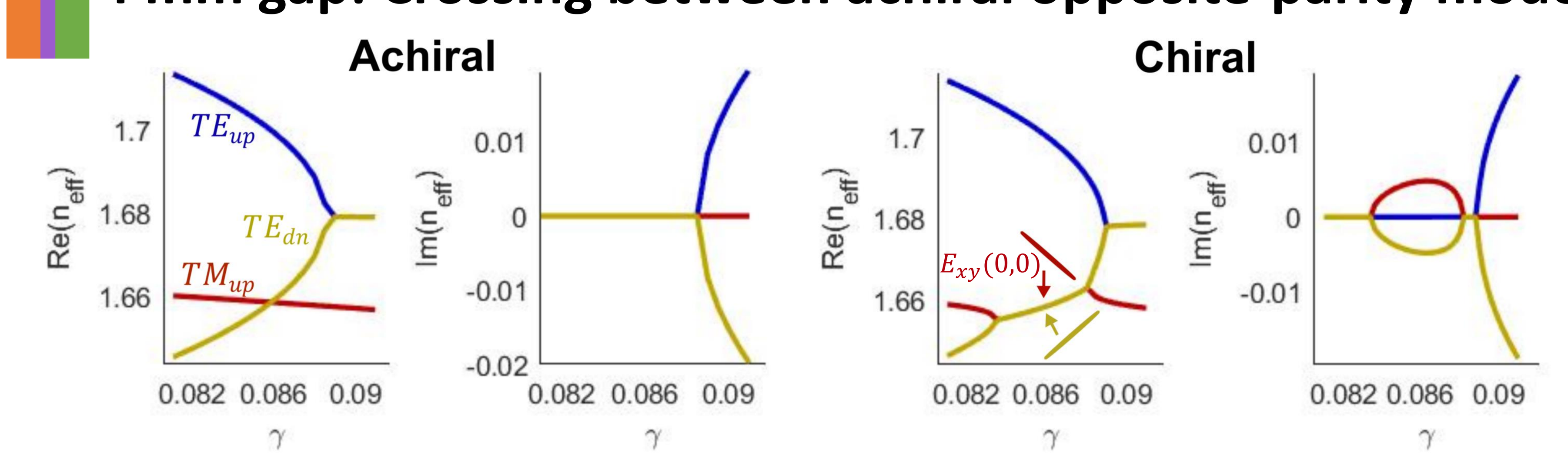
Chirality creates an anticrossing: Dispersions split and polarizations becomes strongly elliptical, with opposite phases.

32nm gap: Crossing between symmetric TM mode & TE EP



Chirality creates a trimodal anticrossing: Same-parity dispersions split and opposite-parity dispersions join. EP is displaced.

44nm gap: Crossing between achiral opposite-parity modes



Chirality creates a local PT-broken zone: Dispersions join in real space and split in imaginary space. Polarizations are tilted.

All avoided crossings are accurately reproduced by our model

Chiral coupled-mode equations

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

g=gain, l=loss

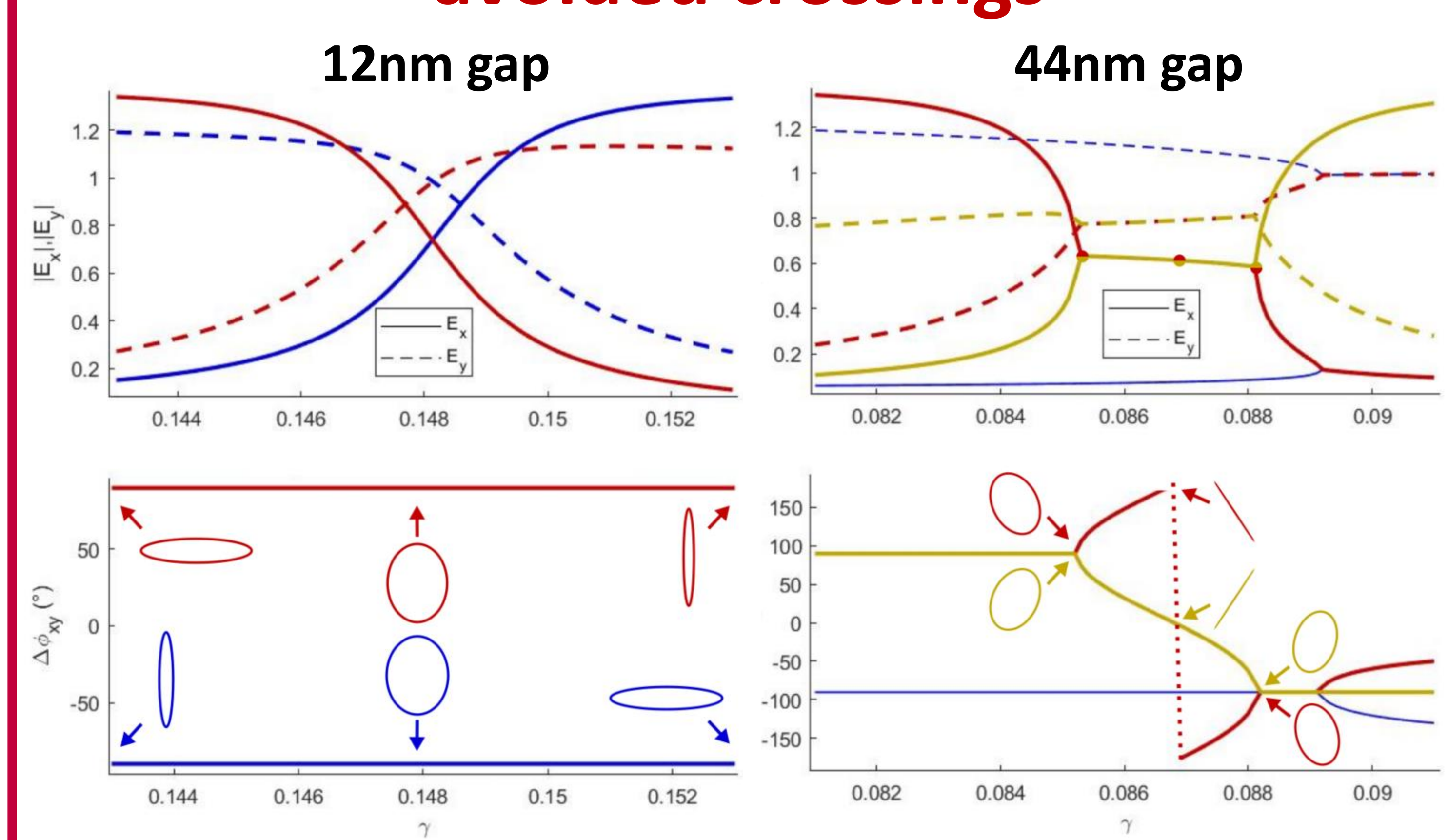
In supermode basis for $\gamma = 0$:

$$\frac{i}{k_0}\frac{d}{dz}\begin{pmatrix} TE_{up} \\ TE_{dn} \\ TM_{up} \\ TM_{dn} \end{pmatrix} = \begin{pmatrix} n_{TE} + A & 0 & \beta + \alpha & 0 \\ 0 & n_{TE} - A & 0 & \beta - \alpha \\ \beta^* + \alpha^* & 0 & n_{TM} + A & 0 \\ 0 & \beta^* - \alpha^* & 0 & n_{TM} - A \end{pmatrix}\begin{pmatrix} TE_{up} \\ TE_{dn} \\ TM_{up} \\ TM_{dn} \end{pmatrix}$$

with $C_{TE} = C_{TM} = C$ and $A = \sqrt{C^2 - \gamma^2}$

⇒ Without PT-symmetry, no up-dn chiral coupling

Eigenvectors evolution over avoided crossings



- Modes swap dominant field component ⇒ Quasi-TE and quasi-TM asymptotically
- 180° phase variation ⇒ ≈ ellipticity, ≠ handedness, $\Delta\phi$ = 0 or 180° in center

Conclusion

Introducing a chiral material in the gap of a pair of PT-symmetric waveguides results in a variety of avoided crossing patterns occurring at achiral degeneracies in the mode dispersion, accessible through modulation of the gap width. Fundamental differences are observed between same-parity and opposite-parity avoided crossings: splitting in the real versus imaginary dispersion, and elliptical vs linear polarizations. The coupled-mode model reproduces these features in much detail, enough to form the basis for quantitative designs and the study of novel geometries. It also shows that gain and loss are fundamental to obtain the local breaking effect.

Prospects

- Sensing with trimodal anticrossing bulk-like sensitivity
- Switching between linear and elliptical polarization in PT-broken zone

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[2] I. Katsantonis, S. Droulias, C. M. Soukoulis, E. N. Economou, T. P. Rakitzis and M. Kafesaki, *Chirality sensing employing Parity-Time-symmetric and other resonant gain-loss optical systems*, Phys. Rev. B, vol. 105 (2022),

Contact: alice.decorte@umons.ac.be