Exceptional points from giant chirality

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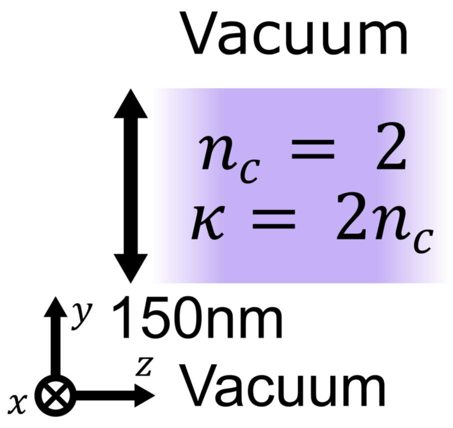
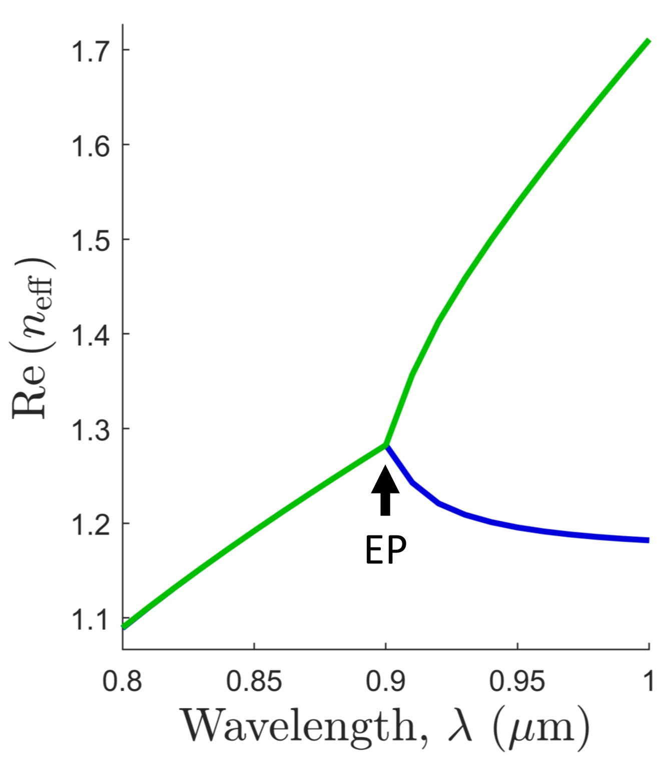
Abstract Exceptional points (EPs) are critical points of a system's parameter space where eigenvalues and eigenvectors coalesce. In coupled waveguides, EPs can be achieved by balancing gain and loss so that co-propagating modes combine in a parity-time-symmetric manner. Alternatively, coupling a standard waveguide with one exhibiting negative refraction enables interactions between counter-propagating modes, creating EPs without any gain or loss [1]. We adopt Pendry's chiral route to negative refraction [2], by implementing giant chirality in numerically simulated photonic waveguides. We first consider a single waveguide with giant chirality, then couple a dielectric waveguide to a chirowaveguide, giving rise to EPs and complex zones in the mode dispersion.

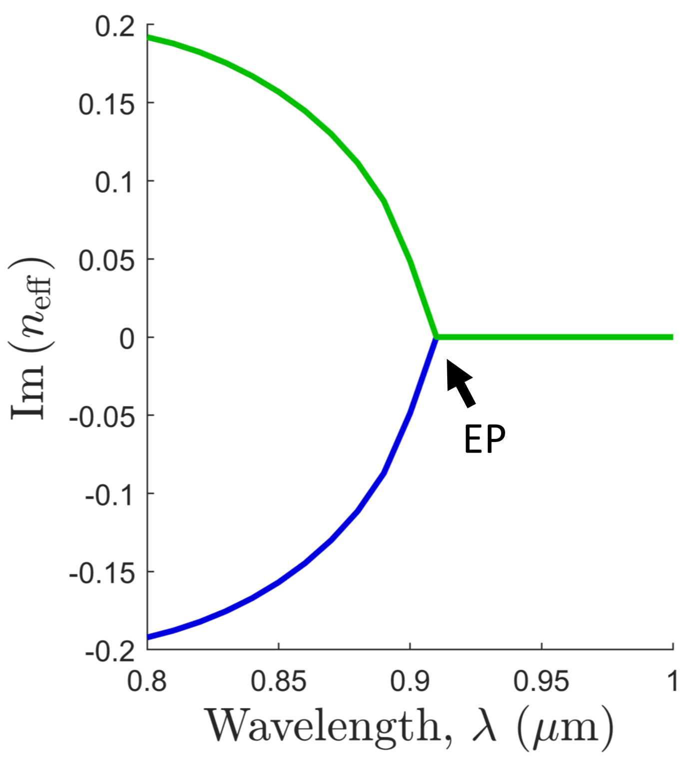
Single chirowaveguide

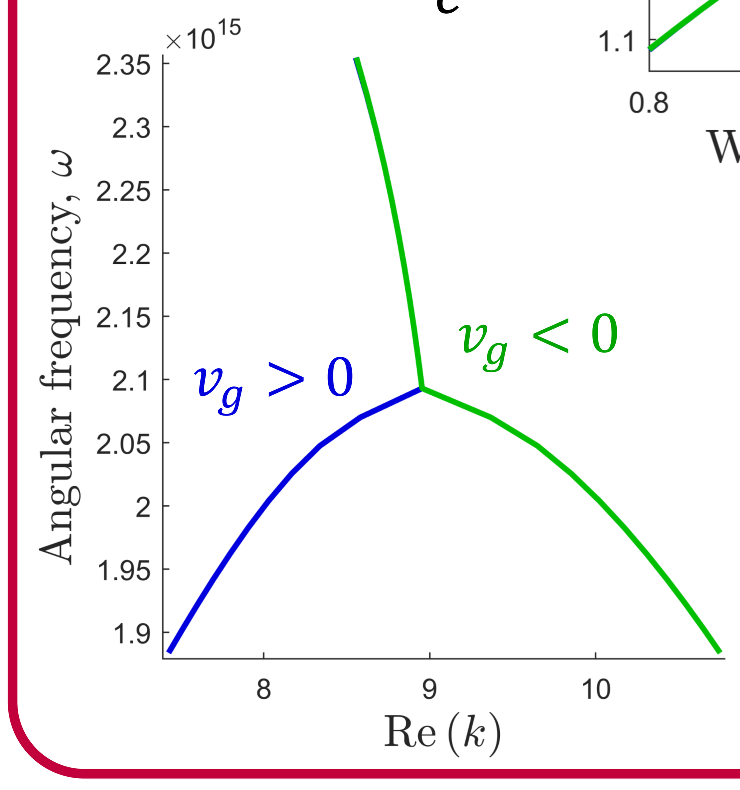


$$\vec{D} = \varepsilon\vec{E} - i\frac{\kappa}{c}\vec{H}$$

$$\vec{B} = \mu\vec{H} + i\frac{\kappa}{c}\vec{E}$$







Forward ($v_g > 0$) & backward ($v_g < 0$) modes interact: form an **EP**

- Before EP: Complex n_{eff} and fields with = magnitudes but >< phase
- After EP: Real n_{eff} and field with ≠ magnitudes but = phase

Coupled-mode theory

If a_1, a_2 = forward & backward mode amplitudes respectively, coupled modes resulting from forward-backward interactions are given by

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

where C_{12}, C_{21} = overlap integrals between unperturbed modes and k_1, k_2 = unperturbed eigenmodes propagation constants.

Eigenvalues: $\boldsymbol{k_\pm = \frac{k_1+k_2}{2} \pm \left[\left(\frac{\delta k_{21}}{2}\right)^2 - C_{12}C_{21}\right]^{1/2}}$

⇒ **EPs** when $\delta k_{21} = \pm 2(C_{12}C_{21})^{1/2}$

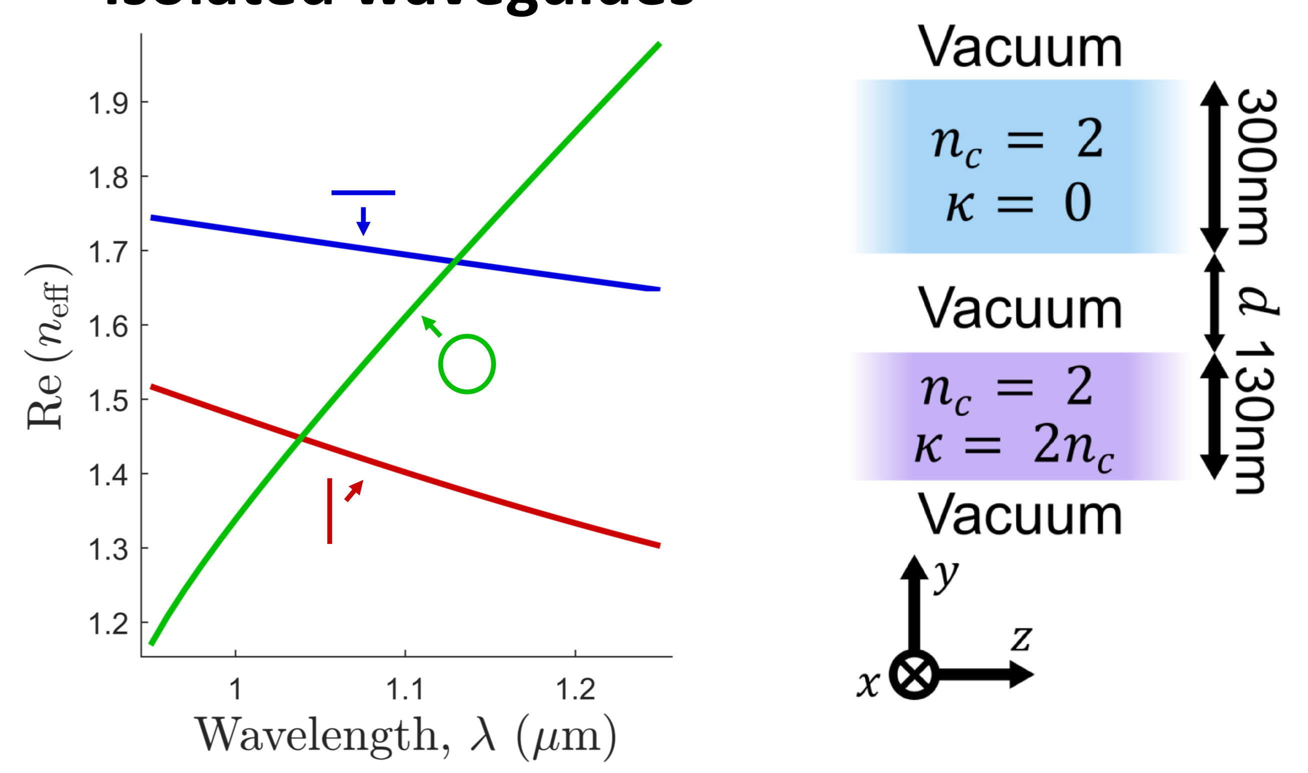
Theory reproduces coupled-waveguide dispersions.

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 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.

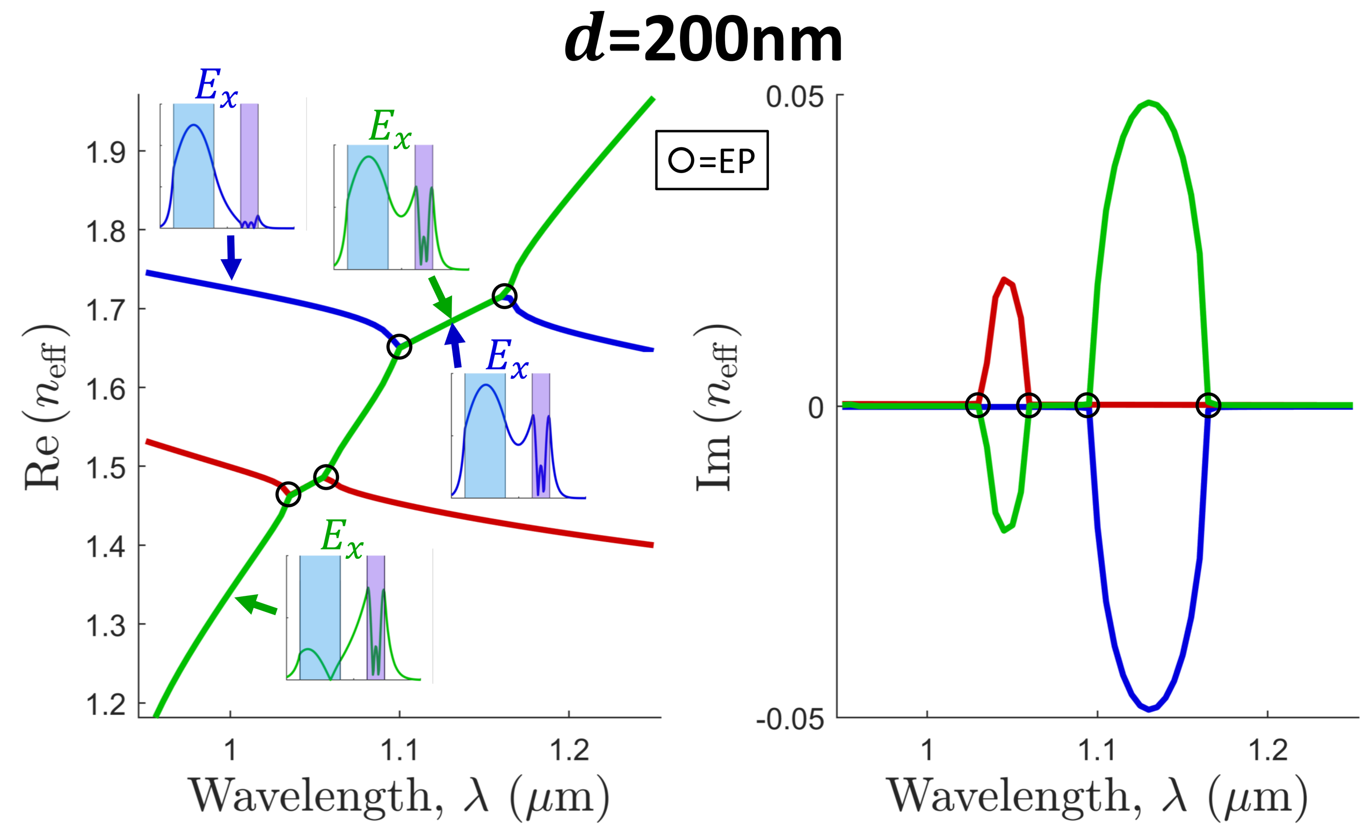
Coupled achiral and chiral waveguides

Isolated waveguides



- 2 achiral forward modes (blue & red)
- 1 chiral backward mode (green)

d=200nm

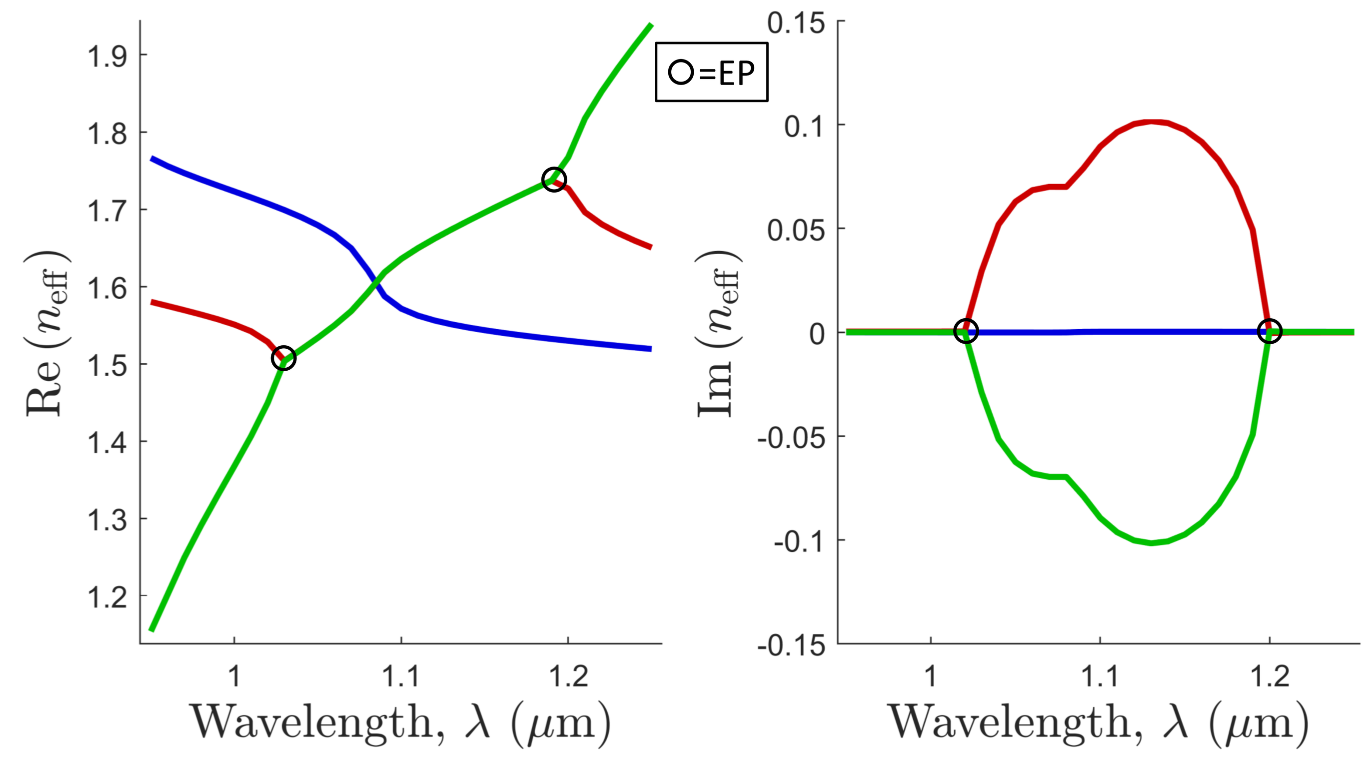


- Forward and backward modes interact

→ **Complex n_{eff} zones** around crossings

- 2 EPs per zone, one on each side
- Outside complex zones, modes ≈ isolated
- In complex zones, hybrid modes: chiral & achiral

d=100nm



Smaller gap ⇒ stronger coupling ⇒ complex zones widen and eventually merge

- 2 EPs disappear in the merging
- Non-complex, forward mode hybridizes with complex modes to gain higher order as λ ↗

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