ICFO

Phd Thesis Defense: "Wave Propagation in Hyperbolic Metamaterial Waveguides"

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April 15, 2026

10:00

Auditorium

Low-loss waveguides are essential for energy-efficient photonic circuits, optical communications, and sensing applications. Over the past century, two lossless phenomena-Dyakonov modes and Bound States in the Continuum (BICs)-have been discovered in anisotropic waveguides, where permittivities differ but share the same sign. Hyperbolic metamaterials (HMMs) exhibit extreme anisotropy, with ordinary and extraordinary permittivities of opposite signs, enabling unconventional light manipulation. Their unique properties have attracted broad interest for applications including subdiffraction imaging, spontaneous emission control, and enhanced light-matter interactions. This raises a fundamental question: can extreme hyperbolic anisotropy support novel confinement mechanisms or new regimes of lossless propagation? Prior research on

HMM waveguides has been constrained to simplified models or propagation along principal axes, leaving systematic exploration of arbitrary propagation directions, and the phenomena they may reveal, as a critical gap.
To address this gap, this thesis develops a semi-analytical computational framework that combines a transfer-matrix formulation with a complex-plane Newton-Raphson root finder, enabling stable tracking of guided and leaky modes for arbitrary propagation directions. This tool allows systematic exploration of a wide range of parameters and configurations previously difficult to study.
This thesis provides the most comprehensive investigation to date of light propagation in planar HMM waveguides. For the first time, the work analyzes both type I and type II HMM waveguides across all in-plane propagation directions and with arbitrary optic axis orientations. The analysis reveals how hyperbolic anisotropy fundamentally influences polarization, confinement, polarization exchange between modes, mode ordering, radiation mechanisms, and slow light arising from topological transitions. This establishes general trends, identifies new guiding regimes, and maps the landscape of wave phenomena in these extreme anisotropic systems.
The exploration of leaky modes enabled a key discovery: Dirac points embedded in the Continuum (DECs), a novel class of topological degeneracy in non-Hermitian systems. DECs emerge when a symmetry-protected BIC and an interferometric BIC intersect linearly. At this intersection, the system exhibits a real eigenvalue, two orthogonal modes, and zero radiation loss-locally Hermitian behavior despite being embedded in a non-Hermitian system. The presence of both BICs suppresses Exceptional Points (EPs) and collapses the Fermi arc to a single point. Because DECs arise from universal BIC interactions rather than material-specific properties, this phenomenon extends beyond hyperbolic media, with implications in the fields of topological photonics and non-Hermitian physics.
This thesis demonstrates the framework's generality and reliability through application to anisotropic liquid-crystal waveguides, where predicted BIC trajectories match experimental observations, and to σ-near-zero metasurfaces, where the framework accurately reproduces published dispersion diagrams. These validations confirm its applicability beyond hyperbolic systems.
This thesis establishes a comprehensive theoretical and computational understanding of wave propagation in planar HMM waveguides for both type I and type II configurations and discovers DECs as a novel physical phenomenon with implications beyond hyperbolic media. By revealing how extreme anisotropy enables new guiding regimes and loss suppression, this work advances the understanding of light confinement in open, strongly anisotropic systems and provides new routes for designing low-loss photonic devices..

Wednesday April 15, 10:00 h. ICFO Auditorium

Thesis Director: Prof. Dr. David Artigas