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**Nonlinear effects in light propagation in periodic structures with
spectral singularities**

Dr. Ilya Vitebskiy (AFRL / RYDHC)

AFOSR PO: Dr. Arje Nachman

This is a (nonlinear) part of my Lab Task 24RYCOR008 entitled
Wave propagation in 1D and 2D periodic arrays with spectral singularities

Key Collaborators:

AFRL/RX: Drs. Ricky Gibson, Carl Pfeiffer, Igor Anisimov, Vlad Vasilyev

AFRL/RX: Dr. Robert Bedford (co-PI)

AFRL/RD: Drs. Brad Hoff, Martin Hilario, Anthony Baros

Academia:

- Prof. Andrey Chabanov (University of Texas, San Antonio)
- Prof. Tsampikos Kottos (Wesleyan University)
- Prof. Filippo Capolino (University of California, Irvine)

Effects of Weak Nonlinearity on Wave Propagation in Periodic Waveguides Supporting Exceptional Point Degeneracy

1) Nonlinear wavepacket dynamics in proximity of a stationary inflection point.

S. Landers, A. Kurnosov, I. Vitebskiy, and T. Kottos. Phys. Rev. B 109, 024312 (2024)

2) Unidirectional amplification in the frozen mode regime enabled by a nonlinear defect.

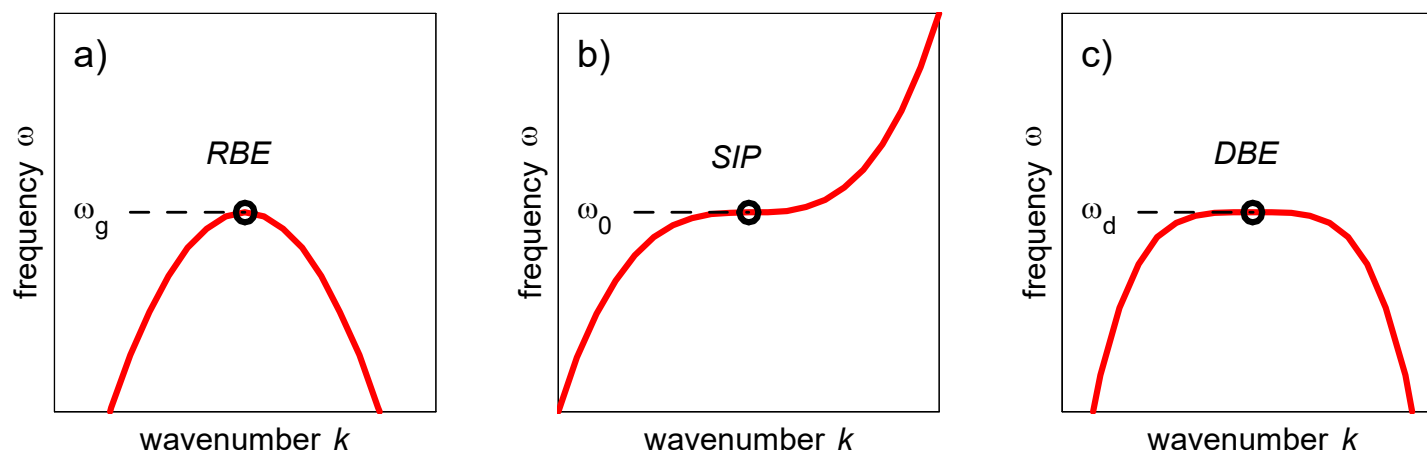
S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Optics Lett. 49, 4967 (2024)

3) Robust nonlinear isolators based on the frozen mode exceptional point degeneracy.

S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Phys. Rev. Res. 7, 013110 (2025)

Exceptional Point Degeneracy (EPD) Associated with Vanishing Group Velocity

Three examples of Bloch dispersion relations with a stationary point corresponding to vanishing group velocity $\omega'(k) = 0$



In every case, the point with $\omega'(k) = 0$ corresponds to an EPD, where several Bloch eigenmodes (propagating and/or evanescent) collapse on each other, giving rise to non-Bloch (algebraically diverging) Floquet eigenmodes.

The EPD nature of these stationary points only manifests itself at the boundaries or other defects of the periodic structure.

Our focus is with the Stationary Inflection Point (SIP) associated with the frozen mode regime.

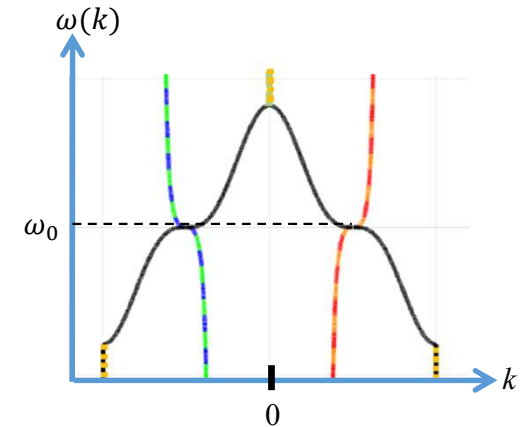
Frozen mode regime associated with SIP in bounded periodic structures

A SIP is an Exceptional Point of Degeneracy (EPD) where three Bloch eigenmodes (one propagating and two evanescent) collapse on each other, forming a set of three Floquet eigenmodes:

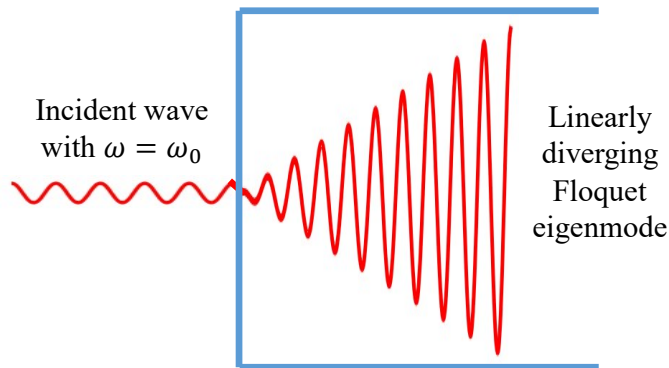
$$\Psi_0(z), \quad \Psi_1(z) \propto z, \quad \Psi_2(z) \propto z^2.$$

Here $\Psi_0(z)$ is a propagating Bloch mode with zero group velocity $v_g = \omega'(k) = 0$, while $\Psi_1(z) \propto z$ and $\Psi_2(z) \propto z^2$ are algebraic, spatially diverging Floquet modes.

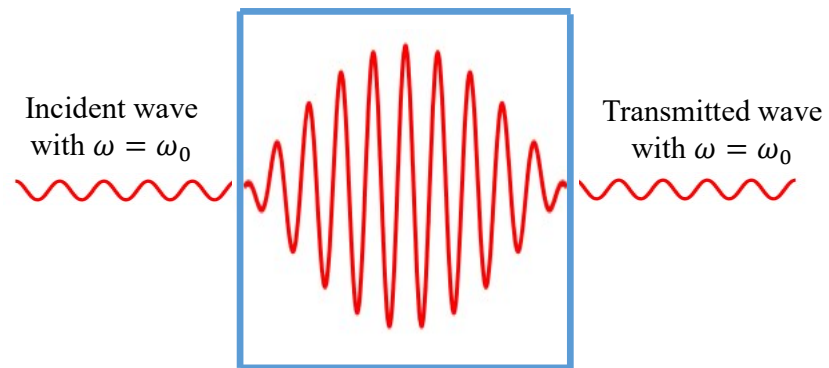
(Figotin & Vitebskiy 2011; Li, Vitebskiy, Kottos 2017)



Frozen mode regime in a semi-infinite waveguide

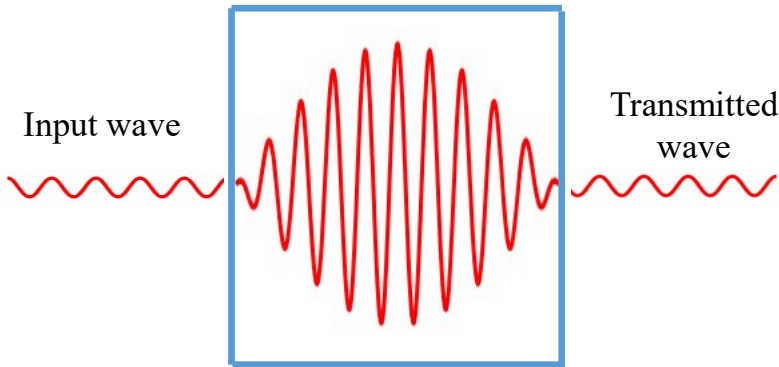


Frozen mode regime in a finite waveguide



Why are we interested in the frozen mode regime?

Frozen mode regime vs Cavity resonance



In either case, the field distribution inside the periodic structure looks similar, and the effective quality factor $Q \propto N^3$. Yet, there are several fundamental differences between the frozen mode regime and a cavity resonance.

Unlike a common cavity resonance, the frozen mode regime requires a certain degree of complexity of the periodic structure, which must support at least three Bloch eigenmodes (one propagating and two evanescent) with the same symmetry to support the SIP-related EPD.

Practical advantages of the frozen mode regime over common cavity resonances

1. The high Q-factor of the frozen mode regime can be achieved without compromising on its bandwidth. By contrast, the bandwidth of a cavity resonance reduces sharply with the rise of its Q-factor.
2. The frozen mode regime is much more resilient to losses, structural imperfections, changing boundary conditions, other disturbances, compared to common cavity resonances in the same system.
3. It provides a single-mode operation regardless of the size and shape of the photonic structure, whereas a high-Q resonant cavity supports multiple resonant modes with closely located frequencies.

The above features make the frozen mode regime particularly attractive for the enhancement of various light-matter interactions, including all time-cumulative and nonlinear interactions.

Effects of Weak Nonlinearity on Wave Propagation in Periodic Waveguides Supporting an Exceptional Point Degeneracy in Bloch Dispersion Relation

1) Nonlinear Wavepacket Dynamics in Proximity of a Stationary Inflection Point.

S. Landers, A. Kurnosov, I. Vitebskiy, and T. Kottos. Phys. Rev. B 109, 024312 (2024)

2) Unidirectional amplification in the frozen mode regime enabled by a nonlinear defect.

S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Optics Lett. 49, 4967 (2024)

3) Robust Nonlinear Isolators Based on Frozen Mode Exceptional Point Degeneracies.

S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Phys. Rev. Res. 7, 013110 (2025)

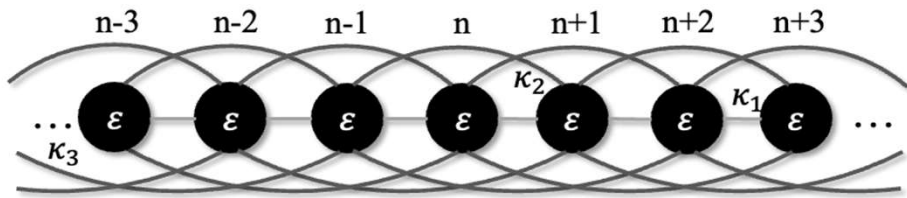
These publications consider different effects of weak nonlinearity on the frozen mode regime associated with SIP-related Exceptional Point Degeneracy in Bloch Dispersion Relation.

Nonlinear wavepacket dynamics in proximity of a stationary inflection point

S. Landers, A. Kurnosov, I. Vitebskiy, and T. Kottos. Phys. Rev. B 109, 024312 (2024)

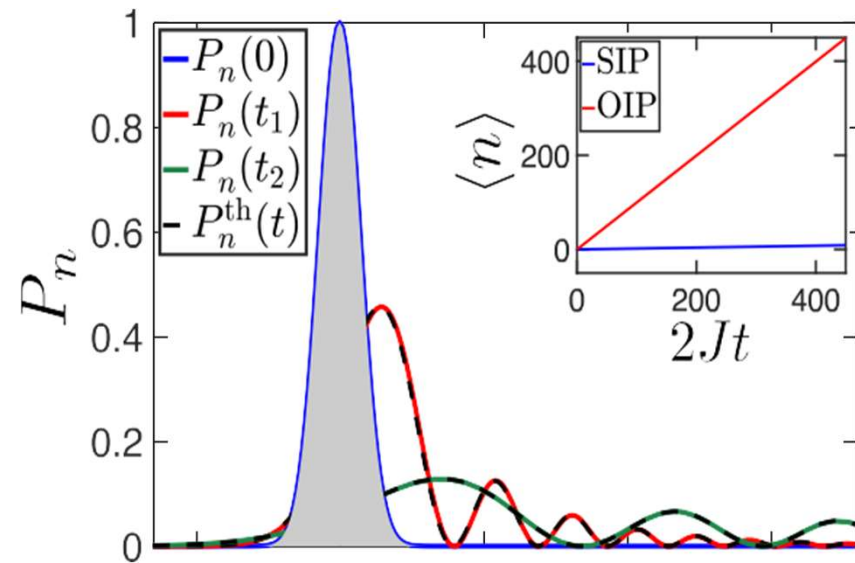
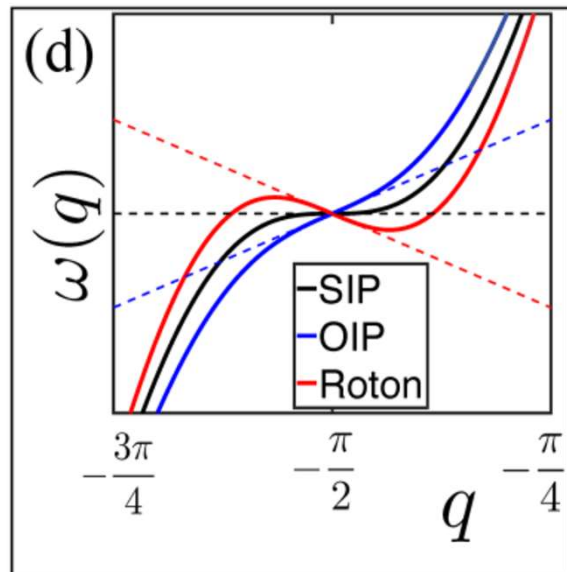
Linear dynamics of the wavepacket centered at a SIP

S. Landers, A. Kurnosov, I. Vitebskiy, and T. Kottos. Phys. Rev. B 109, 024312 (2024)

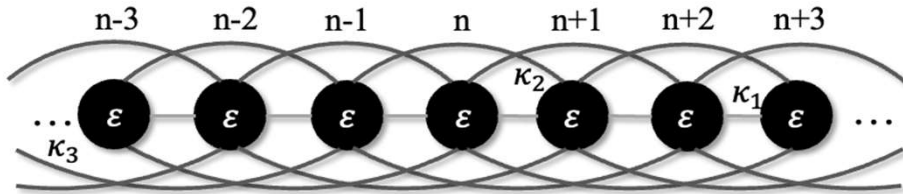


Temporal Coupled Mode Theory

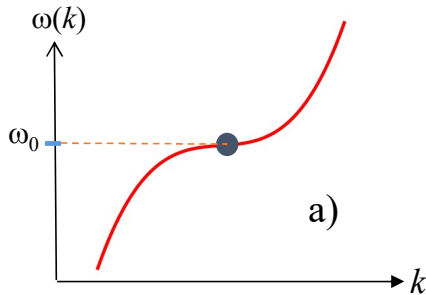
$$i \frac{d\psi_n}{dt} = -J(\psi_{n+1} + \psi_{n-1}) - J_3(\psi_{n+3} + \psi_{n-3})$$



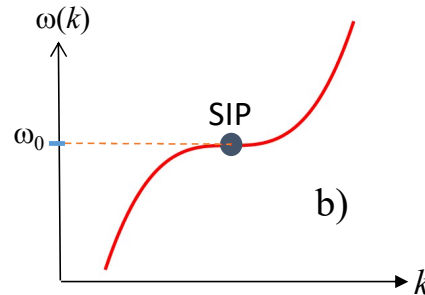
Nonlinear dynamics of the wavepacket centered at a SIP



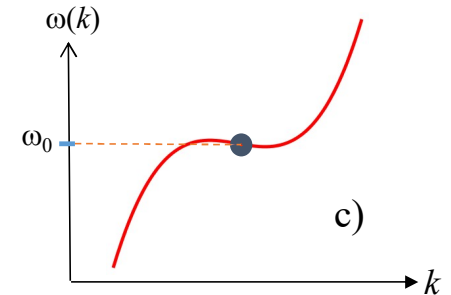
$$i \frac{d\psi_n}{dt} = -J(\psi_{n+1} + \psi_{n-1}) - J_3(\psi_{n+3} + \psi_{n-3}) - \chi \psi_n |\psi_n|^2$$



At $\omega = \omega_0$: $\omega''(k) = 0$, $\omega(k) > 0$



At $\omega = \omega_0$: $\omega''(k) = 0$, $\omega(k) = 0$



At $\omega = \omega_0$: $\omega''(k) = 0$, $\omega(k) < 0$

The nonlinearity can either accelerate the speed of ballistic pulse propagation, it can slow it down or even reverse the direction of pulse propagation.

We use the model based on a chain of coupled resonators, where the nonlinearity is attributed either to each individual resonator, or to the coupling between the neighboring resonators.

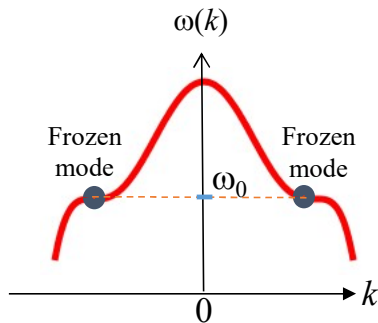
The detailed analysis can be found in (Landers, et al, Phys. Rev. B 109, 024312 (2024))

Nonlinear Isolators Based on Frozen Mode Regime

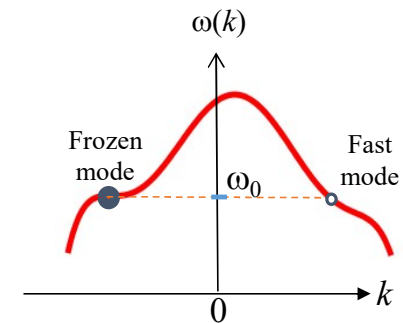
*S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos.
Phys. Rev. Res. 7, 013110 (2025)*

Linear Frozen Mode in Nonreciprocal and/or Asymmetric Periodic Waveguides

Two examples of Bloch dispersion relations with SIP at $\omega = \omega_0$

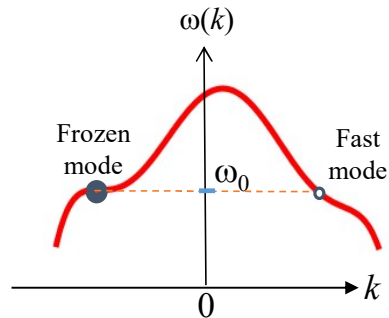


Reciprocal **and/or** spatially symmetric structure: $\omega(k) = \omega(-k)$

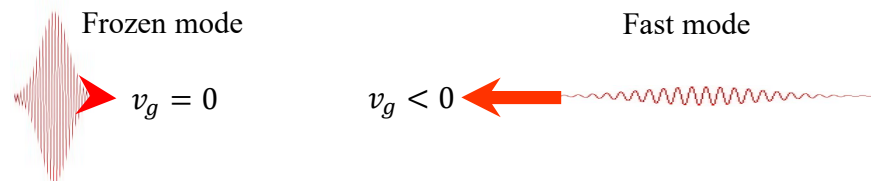


Nonreciprocal **and** spatially asymmetric structure: $\omega(k) \neq \omega(-k)$

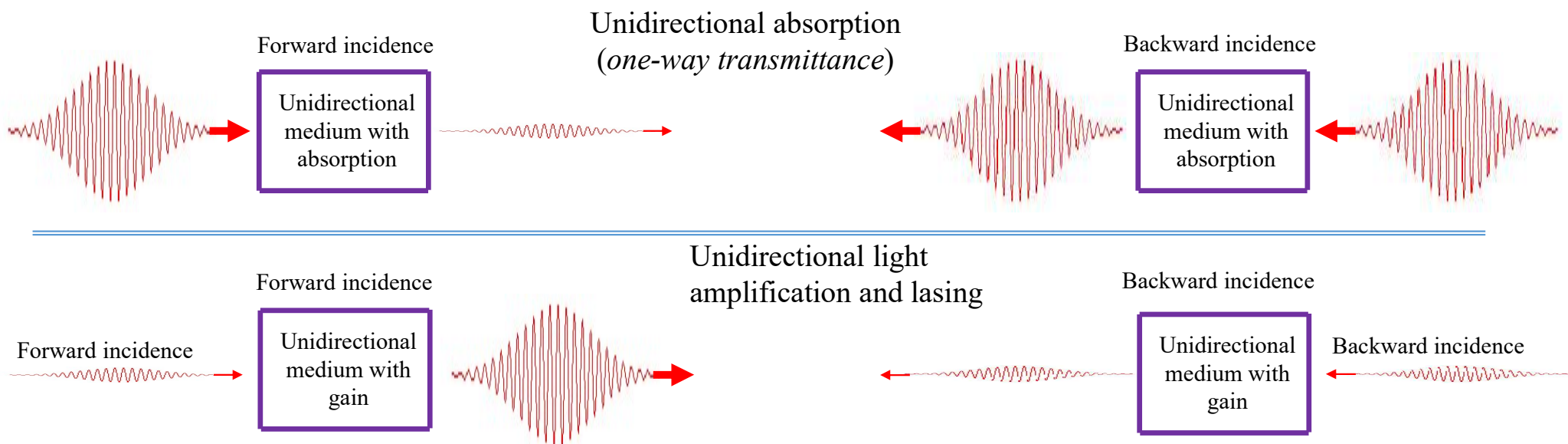
Linear Unidirectional Absorption / Amplification at the Frozen Mode Regime



Bloch dispersion relation in a nonreciprocal chiral (spatially asymmetric) waveguide



Frozen mode regime and electromagnetic unidirectionality associated with a SIP

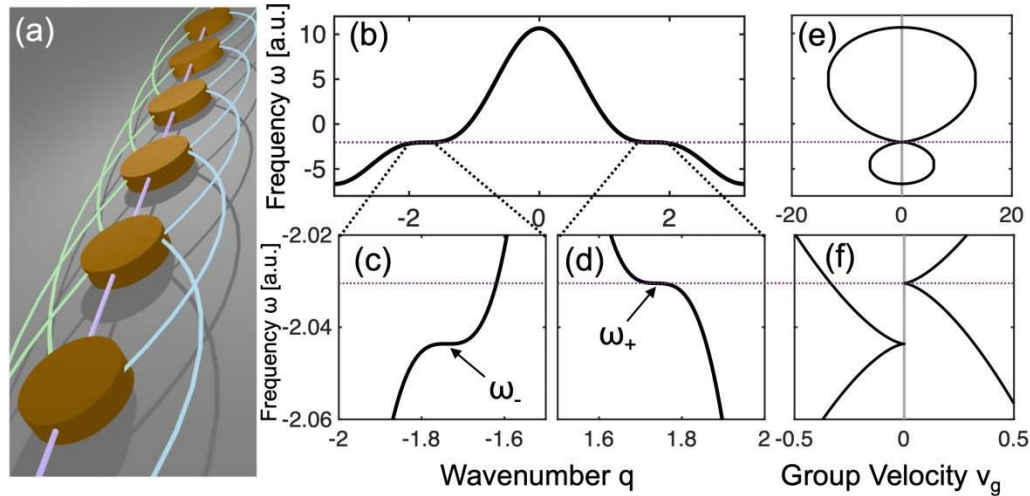
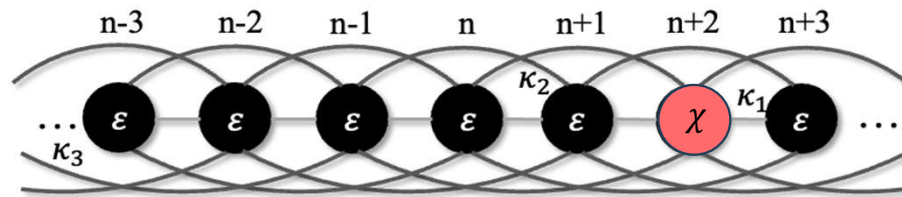


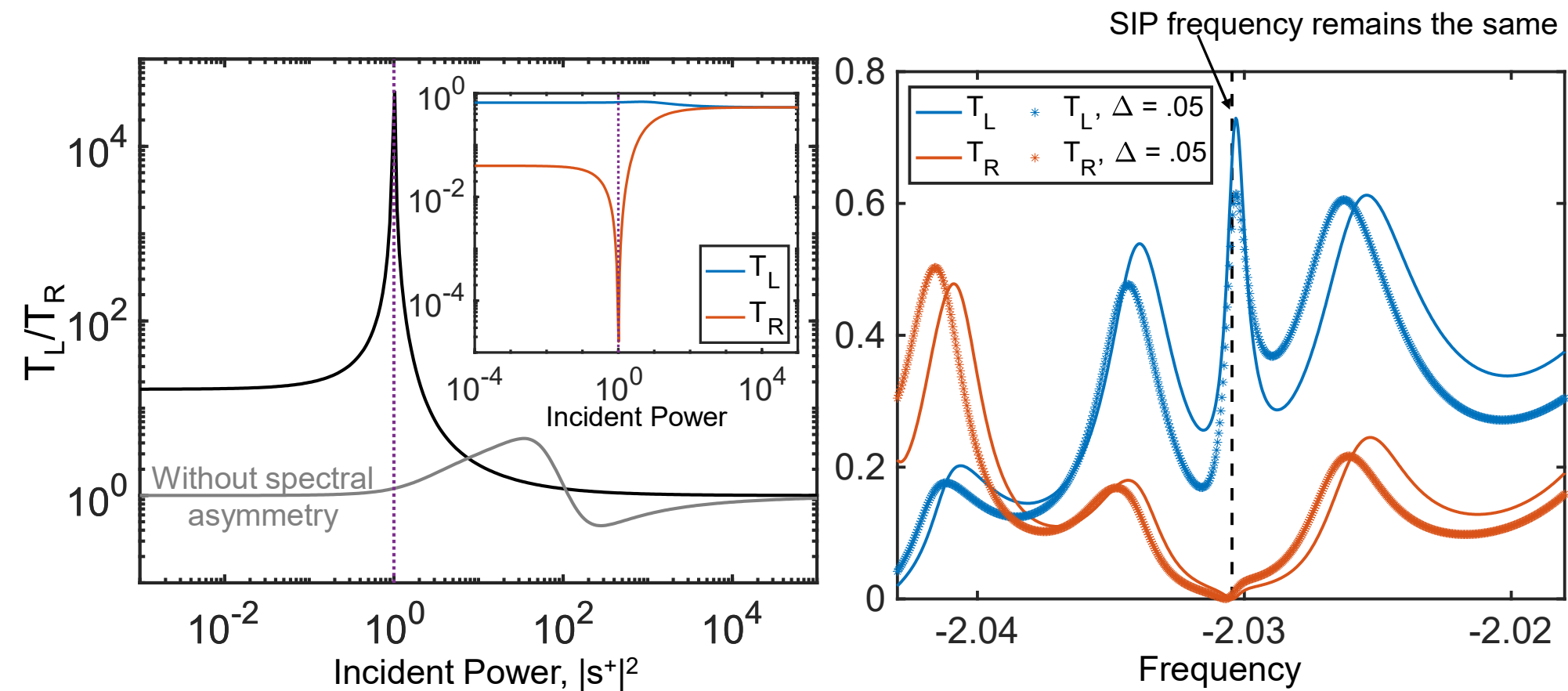
Unidirectional absorption and unidirectional amplification can be achieved in spatially asymmetric structures with either nonreciprocity or nonlinearity.

We show that both unidirectional absorption and unidirectional amplification can be dramatically enhanced if we use both mechanisms simultaneously.

Nonlinear Isolators Based on Frozen Mode Regime

S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Phys. Rev. Res. 7, 013110 (2025)

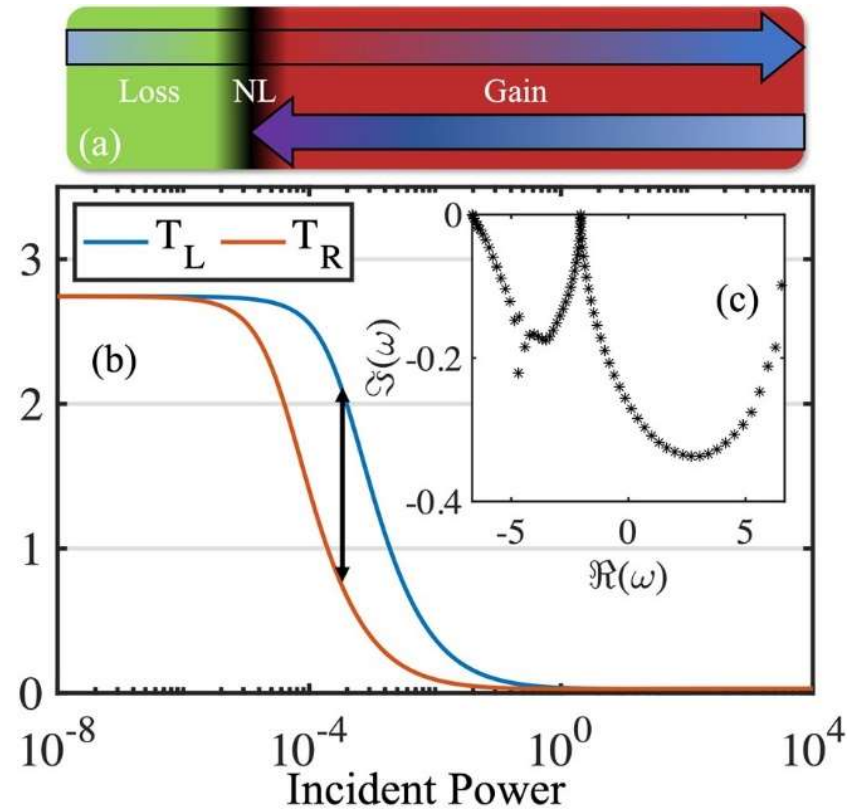
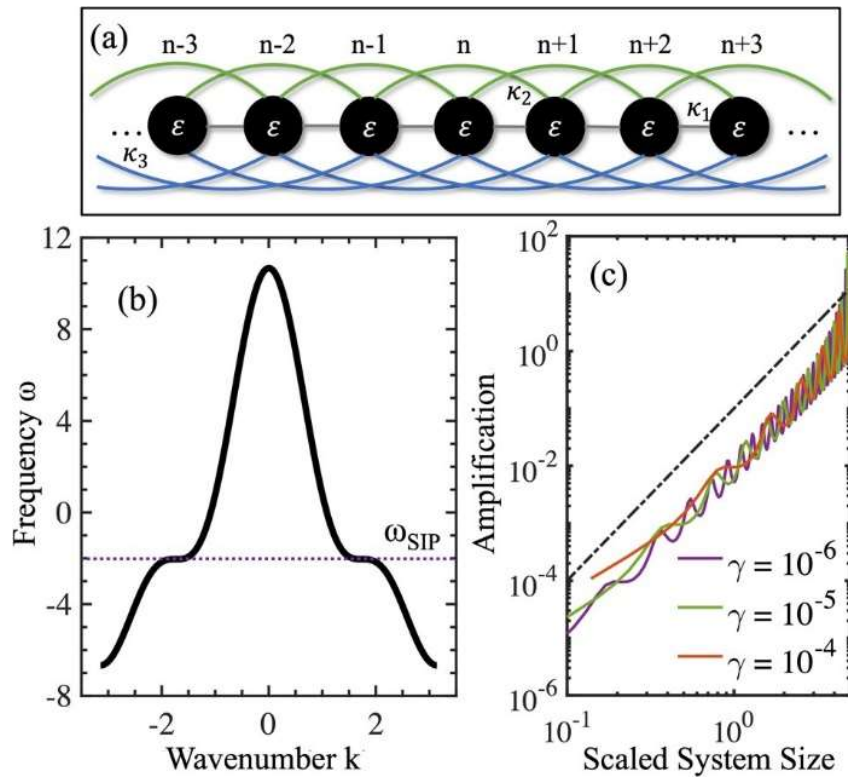




The details can be found in S. Landers, et al, Phys. Rev. Res. (2025)

Unidirectional amplification enabled by a nonlinear defect.

S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Optics Lett. 49, 4967 (2024)



Our publications on the subject :

- E. Makri, H. Ramezani, I. Vitebskiy, and T. Kottos. *Concept of a reflective power limiter based on nonlinear localized modes*. Phys. Rev. A89, 031802 (2014).
- E. Makri, I. Vitebskiy, T. Kottos. *Reflective optical limiter based on resonant transmission*. Phys. Rev. A91, 043838 (2015).
- E. Makri, K. Smith, A. Chabanov, I. Vitebskiy, T. Kottos. *Hypersensitive Transport in Photonic Crystals with Accidental Spatial Degeneracies*. Scientific Reports 6, 22169 (2016)
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- R. Thomas, I. Vitebskiy, T. Kottos. *Resonant cavities with phase-changing materials*. Optics Letters 42, 4784 (2017)
- R. Kononchuk, A. Chabanov, M. Hilario, B. Jawdat, B. Hoff, V. Vasilyev, N. Limberopoulos, I. Vitebskiy. *Reflective Photonic Limiter for the W-band*. Metamaterials, Marseille (2017)
- R. Thomas, F. M. Ellis, I. Vitebskiy, T. Kottos. *Self-Regulated Transport in Photonic Crystals with Phase-Changing Defects*. Phys. Rev. A97, 013804 (2018).
- A. Sarangan, J. Duran, V. Vasilyev, N. Limberopoulos, I. Vitebskiy, I. Anisimov. *A Broadband Reflective Optical Limiter Based on GST Phase Change Material*. IEEE Phot 10, 2200409 (2018)
- R. Thomas, E. Makri, T. Kottos, B. Shapiro, I. Vitebskiy. *Unidirectional photonic circuit with a phase-change Fano resonator*. Phys. Rev. A98, 053806 (2018)
- R. Thomas, F. Ellis, I. Vitebskiy, T. Kottos. *Self-regulated transport in photonic crystals with phase-changing defects*. Phys. Rev. A97, 013804 (2018)
- N. Antonellis, R. Thomas, M.A. Kats, I. Vitebskiy, and T. Kottos. *Nonreciprocity in Photonic Structures with Phase-Change Components*. Phys. Rev. Appl. 11, 024046 (2019)
- R. Thomas, A. A. Chabanov, I. Vitebskiy, T. Kottos. *Light-induced optical switching in asymmetric metal-dielectric microcavity with phase-change material*. Europhys. Lett. 126, 64003 (2019).
- S. Suwunnarat, R. Kononchuk, A. Chabanov, N. I. Limberopoulos, I. Vitebskiy, and T. Kottos. *Enhanced Nonlinear Instabilities in Photonic Circuits with Exceptional Point Degeneracies*. Photonics Research 6, 737 (2020)
- A. Sarangan, G. Ariyawansa, I. Vitebskiy, I. Anisimov. *Optical switching performance of thermally oxidized vanadium dioxide with an integrated thin film heater*. Optical Materials Express, Vol. 11, No. 7, p. 2348 (2021)
- W. Tuxbury, L. J. Fernandez-Alcazar, I. Vitebskiy, T. Kottos. *Scaling theory of absorption in the frozen mode regime*. Optics Letters, Vol. 46, No. 13, 3053 (2021)
- A. Parareda, I. Vitebskiy, J. Scheuer, F. Capolino. *Frozen mode in asymmetric serpentine optical waveguide*. Submitted to: Advance Photonic Research (2021)
- Carl Pfeiffer, Igor Anisimov, Ilya Vitebskiy, Andrey Chabanov. "Magnetization Free Faraday rotators based on composite structures". (Patent application, 2021)
- R. Kononchuk, S. Suwunnarat, M. Hilario, A. Baros, B. Hoff, V. Vasilyev, I. Vitebskiy, T. Kottos, A. Chabanov. *A reflective mm-wave photonic limiter*. Science Advances 8, 1827 (2022).

Our publications on the subject (continuation):

- M. Nada, T. Mealy, S. Islam, I. Vitebskiy, R. Gibson, R. Bedford, O. Boyraz, F. Capolino. *Design of a Modified Coupled Resonators Optical Waveguide Supporting a Frozen Mode*. Journal of Lightwave Technology, 3266311 (2023)
- M. Lust, I. Vitebskiy, I. Anisimov, N. Ghalichechian. "Thermo-Optic VO₂-Based Silicon Waveguide Mid-Infrared Router with Asymmetric Activation Thresholds and Large Bistability" Optics Express, v. 31, 23260 (2023)
- F. Riboli, R. Kononchuk, F. Tommasi, A. Boschetti, S. Suwunnarat, I. Anisimov, I. Vitebskiy, D. Wiersma, S. Cavalieri, T. Kottos, A. Chabanov. *Optical limiter based on PT-symmetry breaking of reflectionless modes*. Optica, 10, 1302 (2023)
- S. Landers, A. Kurnosov, I. Vitebskiy, and T. Kottos. *Nonlinear Wavepacket Dynamics in Proximity to a Stationary Inflection Point*. Phys. Rev. B 109, 024312 (2024)
- S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. *Unidirectional amplification in the frozen mode regime enabled by a nonlinear defect*. Optics Lett. 49, 4967 (2024)
- L. Salvini, F. Riboli, R. Kononchuk, F. Tommasi, A. Boschetti, S. Suwunnarat, I. Anisimov, I. Vitebskiy, D. Wiersma, S. Cavalieri, T. Kottos, A. Chabanov. *Optical limiter based on PT-symmetry breaking of reflectionless modes*. Proceedings of SPIE, Volume 13140, Advances in Materials and Innovations in Device Applications XVIII; 1314003 (2024)
- N. Furman, A. Herrero-Parareda, I. Vitebskiy, R. Gibson, B. Thompson, R. Bedford, F. Capolino. *Impact of Fabrication Disorder on Lasing near a Stationary Inflection Point*. To appear in Phys. Rev. A (2025)
- S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. *Robust Nonlinear Isolators Based on Frozen Mode Exceptional Point Degeneracies*. To appear in Phys. Rev. Res. (2025)

Awarded US Patent

Vitebskiy, N. Limberopoulos, A. Chabanov, I. Anisimov, C. Pfeifer. *Layered Sheet Polarizers and Isolators Having Non-Dichroic Layers*. US patent number 12,092,848. Issued on 09/27/2024

Pending US patent

A. Chabanov (UTSA), C. Pfeiffer (AFRL), I. Anisimov (AFRL), and I. Vitebskiy (AFRL). "Magnetization-Free Faraday Rotators"

Thank You