Wright-Patterson AFB, January 2025

Wave propagation in 1D and 2D periodic arrays with spectral singularities

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This report outlines the main achievements of the first year of the three-year Lab Task 24RYCOR008

Key Collaborators

AFRL/RY: 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)

The project includes four distinct topics

1. Frozen mode approach to light amplification, lasing, and control of pulse propagation
2. Photonic structures with nonlinear and phase changing components for optical and MW limiting, switching, and nonlinear isolation
3. Control of light propagation using spectral singularities in planar photonic arrays supporting glide-plane symmetry
4. Nonreciprocal metamaterials with zero net magnetization providing Faraday rotation in the absence of bias magnetic field

1. Frozen mode regime in nonreciprocal, nonlinear, and active media

Latest publications on the subject

- 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)

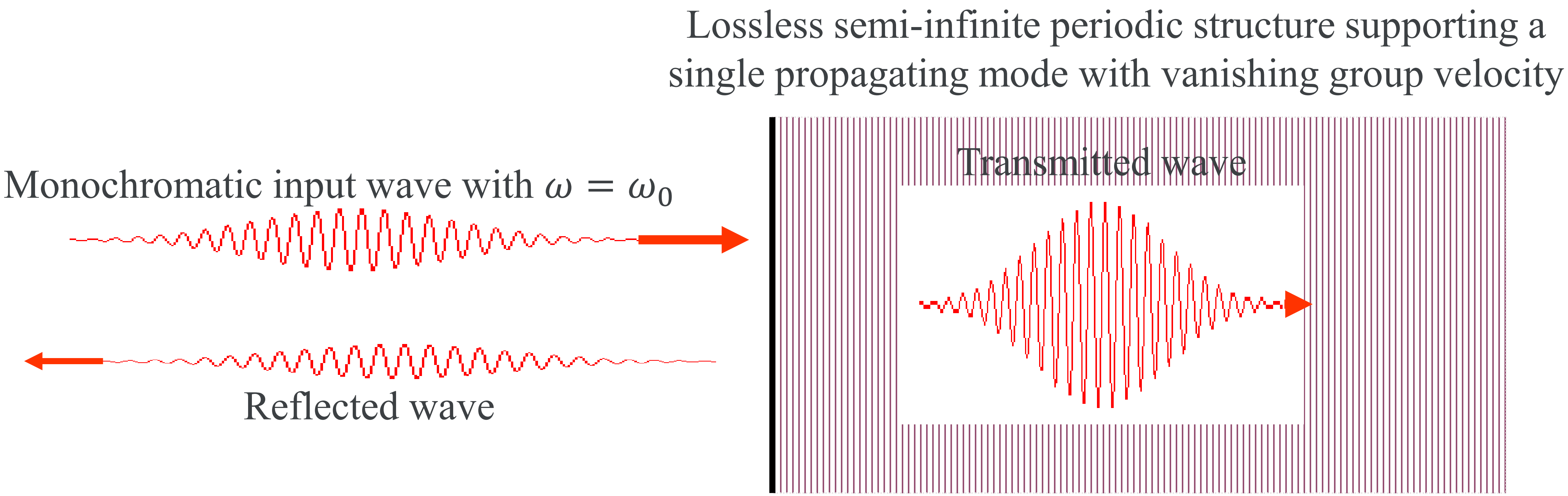
- Unidirectional amplification in the frozen mode regime enabled by a nonlinear defect.
  S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Optics Lett. 49, 4967 (2024)

- Robust Nonlinear Isolators Based on Frozen Mode Exceptional Point Degeneracies.
  S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. To appear in Phys. Rev. Res. (2025)

- Impact of Fabrication Disorder on Lasing near a Stationary Inflection Point
  N. Furman, A. Herrero-Parareda, I. Vitebskiy, R. Gibson, B. Thompson, R. Bedford, F. Capolino.. Submitted to Phys. Rev. A (2025)

A brief reminder of what the frozen regime is

Scattering problem for a semi-infinite periodic structure supporting a single propagating mode the group velocity of which vanishes at $\omega = \omega_0$



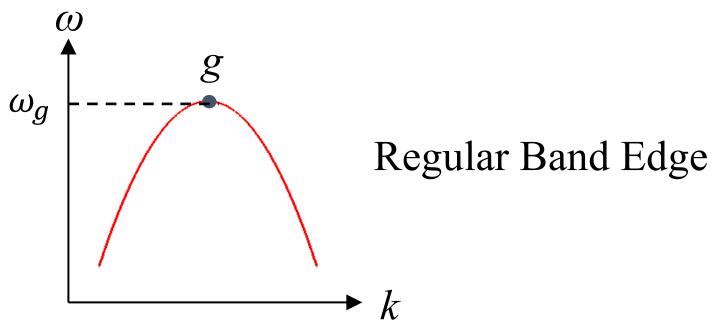
The question: Given that the energy flux of a single propagating mode is $\boldsymbol{S} = \boldsymbol{W} \times \boldsymbol{v}_g$, will the input wave with $\omega = \omega_0$ be converted into the slow (frozen) mode inside the periodic medium, or will it be totally reflected?

The answer essentially depends on the type of the stationary point $\omega_0 = \omega(k_0)$ of the Bloch dispersion relation.

Scattering problem for a semi-infinite periodic array supporting a single propagating mode with zero group velocity at a certain frequency. There are three qualitatively different possibilities:

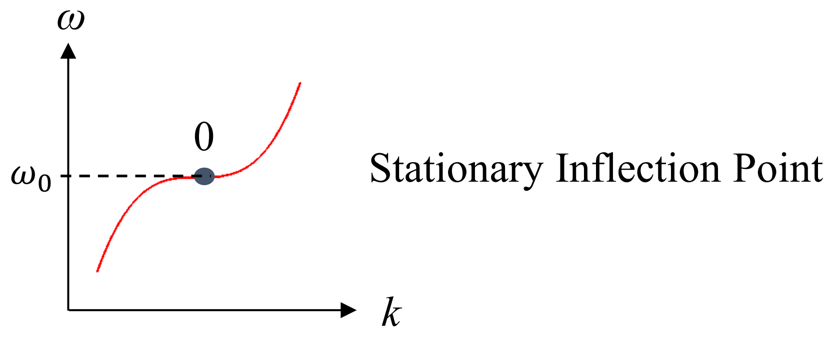
Regular Band Edge (RBE)

At $\omega = \omega_g$, the input wave is reflected back to space (***total reflection***)



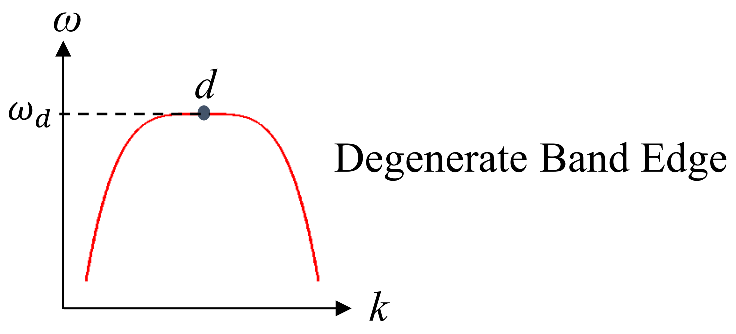
Stationary Inflection Point (SIP)

At $\omega = \omega_0$, the input wave is converted into the diverging frozen mode. The energy flux of the frozen mode can be close to that of the incident wave, implying ***little or no reflection***.
(*Figotin & Vitebskiy, 2011*).



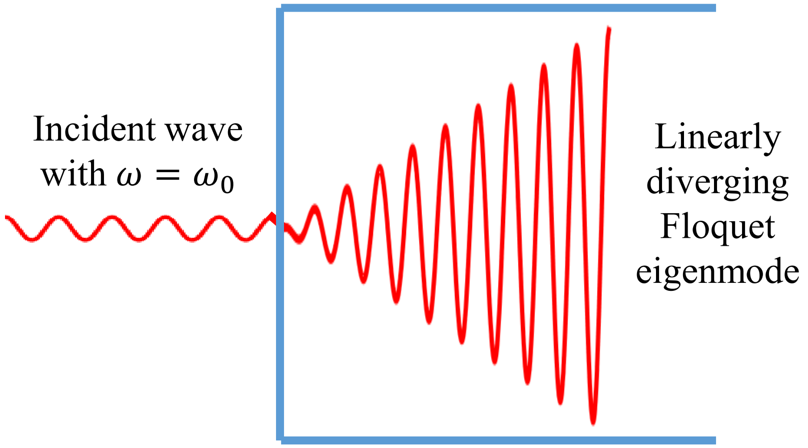
Degenerate Band Edge (DBE)

At $\omega = \omega_d$, the input wave is reflected back to space (similar to the case of a regular band edge), but not before producing a diverging frozen mode inside the structure (similar to the case of a stationary inflection point). The energy flux of the frozen mode inside the periodic structure is zero in this case, implying ***total reflection***.
(*Figotin & Vitebskiy, 2011*).

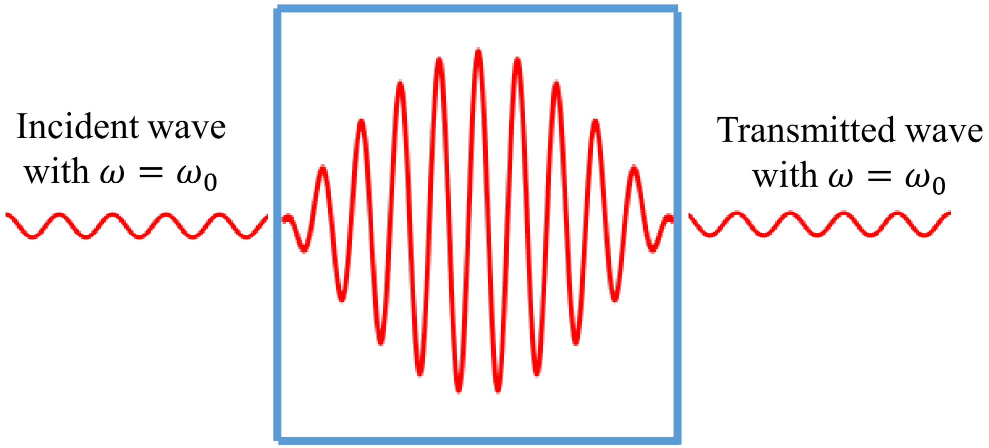


The frozen mode is not just a Bloch wave with zero group velocity.

Frozen mode regime in a semi-infinite waveguide



Frozen mode regime in a finite waveguide

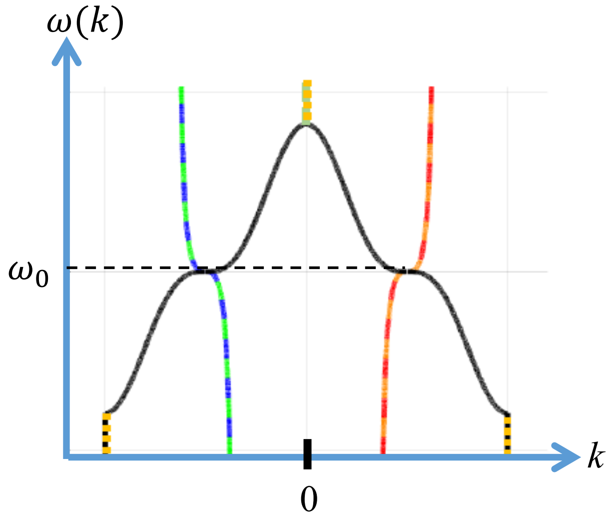


A SIP is an Exceptional Point of Degeneracy (EPD) where three Bloch eigenmodes (one propagating and two evanescent) collapse on each other, forming a set of three Floquet eigenmodes:

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

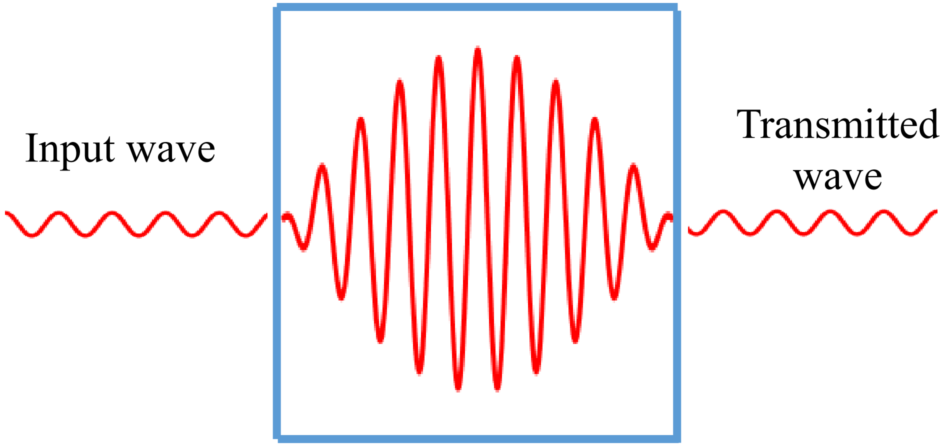
Here $\Psi_0(z)$ is a propagating Bloch mode with zero group velocity $v_g = \omega'(k) = 0$, while $\Psi_1(z) \propto z$ and $\Psi_2(z) \propto z^2$ are algebraic, spatially diverging Floquet modes.

(*Figigotin & Vitebskiy 2011; Li, Vitebskiy, Kottos 2017*)



(*Nada, et al*)

Frozen mode regime vs. Fabri-Perrot resonance in a finite periodic structure



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.

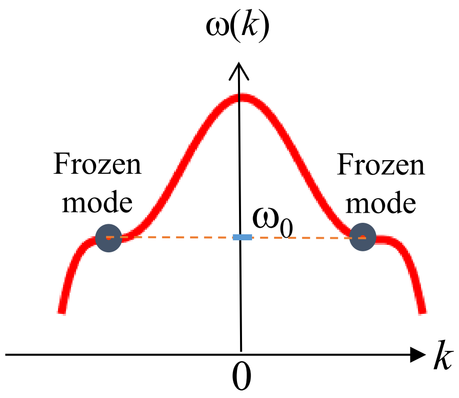
Unlike a common cavity resonance, the frozen mode regime requires a certain degree of complexity of the periodic structure. It must support at least three Bloch eigenmodes (one propagating and two evanescent) with the same symmetry to support the EPD.

On the other hand, the frozen mode regime has some big advantages:

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 regular resonant cavity with large dimensions supports multiple resonant modes with closely located frequencies.

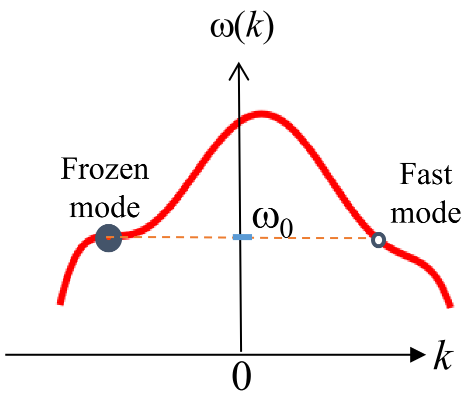
The above features make the frozen mode regime particularly attractive for the enhancement of various light-matter interactions, including all time-cumulative and nonlinear interactions.

Frozen mode in spatially asymmetric and/or nonreciprocal structures



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

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



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

Effects of nonlinearity on the frozen mode regime

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)

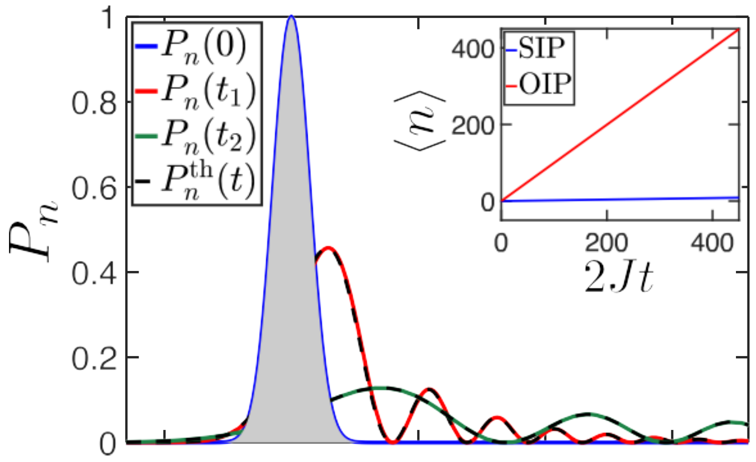
2) Unidirectional amplification in the frozen mode regime enabled by a nonlinear defect.
S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. Optics Lett. 49, 4967 (2024)

3) Robust Nonlinear Isolators Based on Frozen Mode Exceptional Point Degeneracies.
S. Landers, W. Tuxbury, I. Vitebskiy, T. Kottos. To appear in Phys. Rev. Res. (2025)

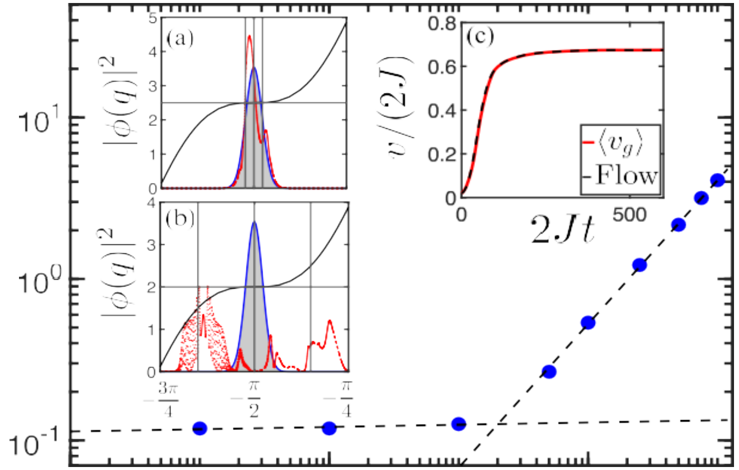
The above publications describe three qualitatively different effects of weak nonlinearity on the frozen mode regime. Each of them has different potential applications.

Nonlinear Wavepacket Dynamics in Proximity of a Stationary Inflection Point

Landers, et al, Phys. Rev. B 109, 024312 (2024)



Time evolution of a linear pulse centered at a SIP. No ballistic propagation



A stationary value of flow as a function of nonlinearity (blue dots). The transition between the SIP and the ballistic regimes occurs when the pulse in q space "spills out" of the initial Gaussian peak between $\chi = 0.1$and $\chi = 0.5$.

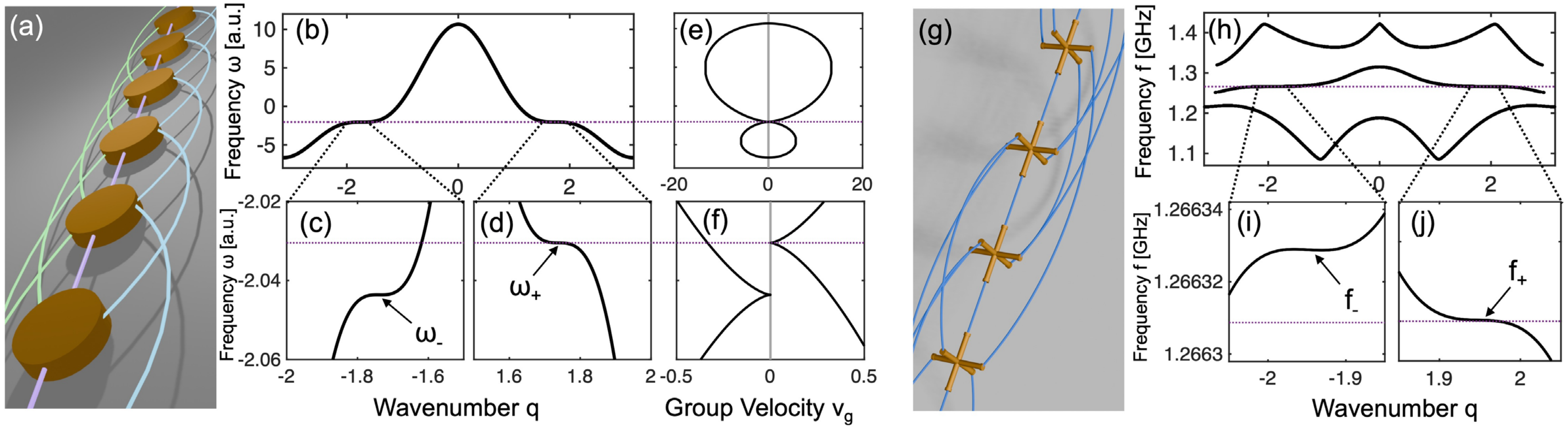
The nonlinearity can result in ballistic propagation of SIP-centered pulses, with the speed and even the direction of propagation essentially dependent on the pulse amplitude. This unique feature emerging from the interplay between an SIP and nonlinearity.

Possible applications include a power router and a non-resonant Q switch, which prevents radiation from leaking from a system unless the pulse amplitude exceeds a threshold value.

In either cases, a combination of the enhanced amplitude of the frozen mode and the enhanced response to nonlinearities in the vicinity of an SIP provides great flexibility in achieving desirable threshold values.

Robust Nonlinear Isolators Based on Frozen Mode Exceptional Point Degeneracies

S. Landers, et al. To appear in Phys. Rev. Res. (2025)



A combination of nonreciprocity and spatial asymmetry result in asymmetric Bloch dispersion relation: $\omega(k) \neq \omega(-k)$.

We proposed a design protocol to achieve a robust isolation based on the frozen mode regime in the presence of a nonlinear defect and a weak nonreciprocity. The underlying mechanism relies on the sharp variation of the group velocity in proximity to the SIP frequency, so that even ***a weak spectral asymmetry will result in a dramatic directional dependence of the nonlinear interaction***. This is particularly desirable at optical wavelengths where both nonreciprocal and nonlinear effects are usually week.

The proposed protocol maintains the usual practical advantages of the frozen-mode-based approach, such as the bandwidth advantage and robustness with respect to structural imperfections.

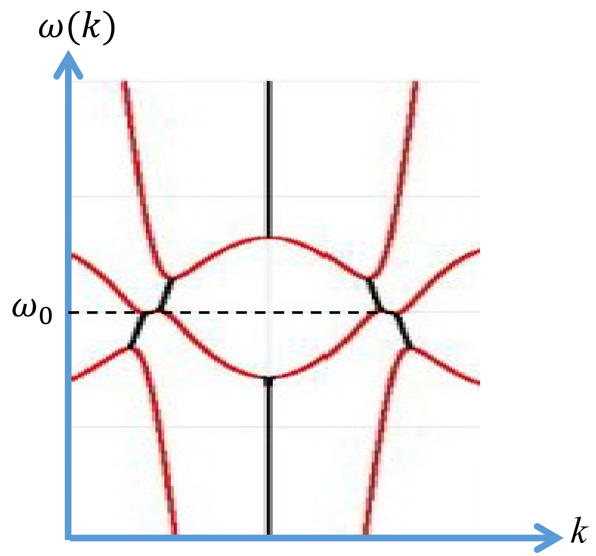
Same ideas can be extended to unidirectional amplifiers, Q-switches, cavity-free lasers, and power limiters.

Practical aspects of realization of the frozen mode regime at optical wavelengths

At MW frequencies, the frozen mode regime has been realized on different platforms and successfully implemented in practical devices.

At optical wavelengths, the frozen mode regime has been realized too, but there are some issues remaining. Specifically, in the case of coupled optical waveguides with 1D periodicity, the practical challenges include

- To avoid radiative losses, we have to work with high-order photonic bands. As a consequence, there are a number of photonic band edges in close proximity of the frozen mode frequency (see the example).
- Strong interference of equally powerful Fabry-Perrot resonances with closely located resonant frequencies.



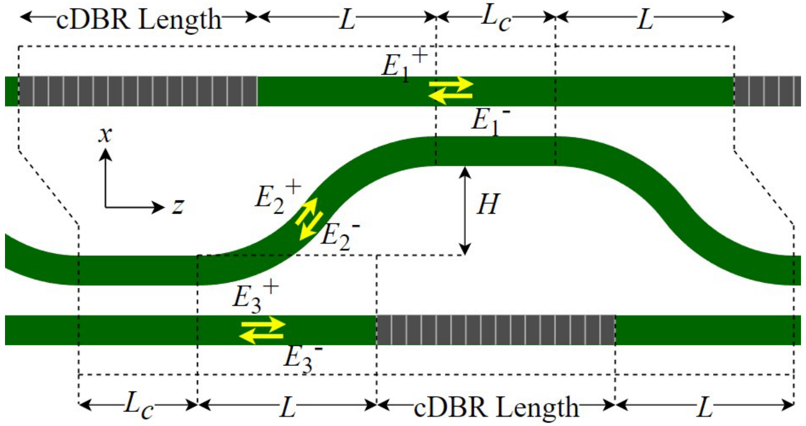
Example of Bloch dispersion relation of a periodic optical waveguide. The frozen mode frequency is in close proximity of several photonic band edges. (*Nada, et al, 2024*)

There are several ways to address one or both of the above problems, for instance:

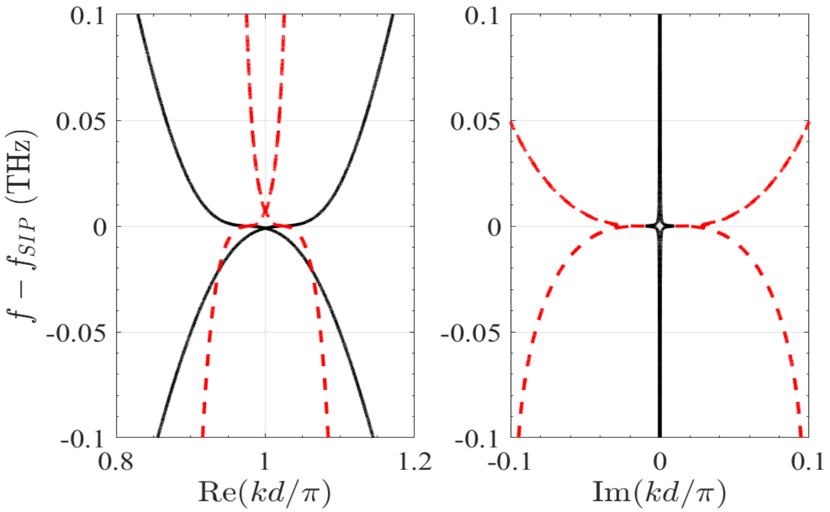
- Switching to 2D arrays can alleviate both problems and provide additional benefits.
- Making reflectionless boundary conditions for at least one of the two interfaces can eliminate Fabry-Perrot resonances
- Introducing magneto-optical and/or nonlinear component in a combination with structural chirality can also eliminate the backward propagating wave, along with Fabry-Perrot resonances.

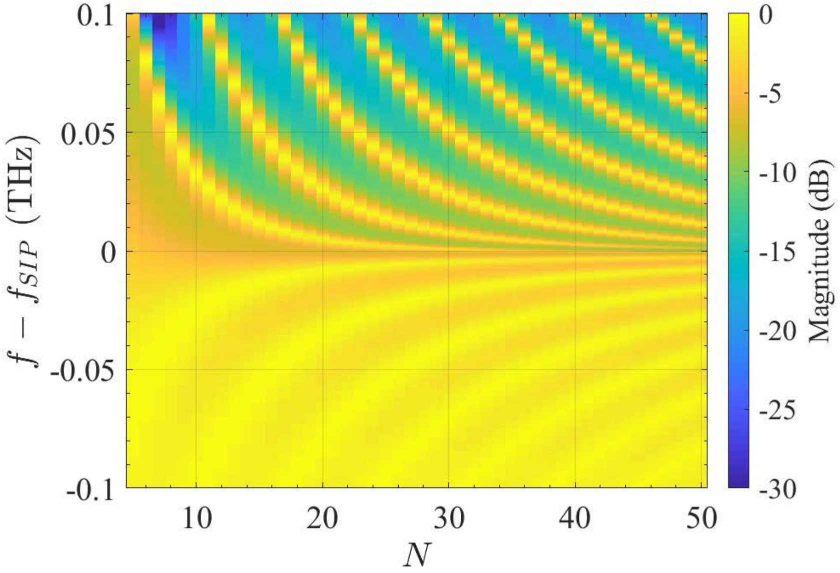
Impact of Fabrication Disorder on Lasing near a Stationary Inflection Point

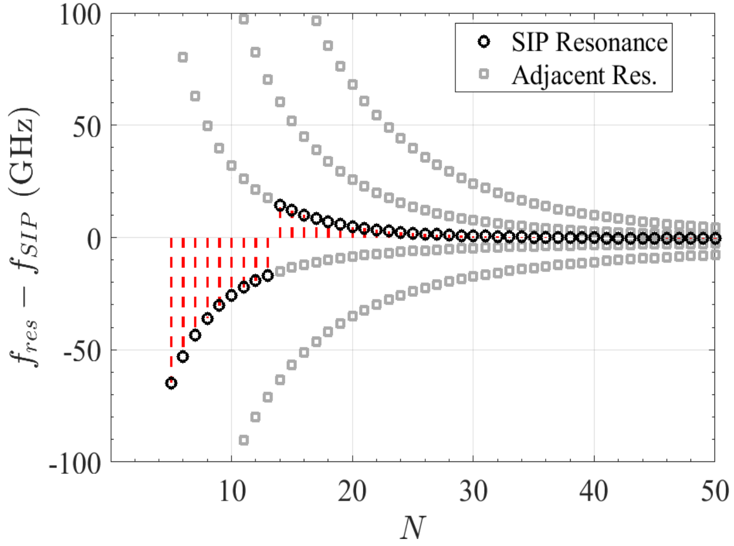
N. Furman, A. Herrero-Parareda, I. Vitebskiy, R. Gibson, B. Thompson, R. Bedford, F. Capolino. Submitted to Phys. Rev. A (2025)



Unit cell of the waveguide with glide-plane symmetry







Finite length transfer function resonances. The SIP resonance is defined as the closest to the SIP frequency (a black circles), with other adjacent resonances displayed as grey squares. The red dashed line represents the distance from the resonance to the SIP frequency and the lines become shorter as N increases.

OTHER PROJECTS

2. Nonreciprocal metamaterials with zero net magnetization

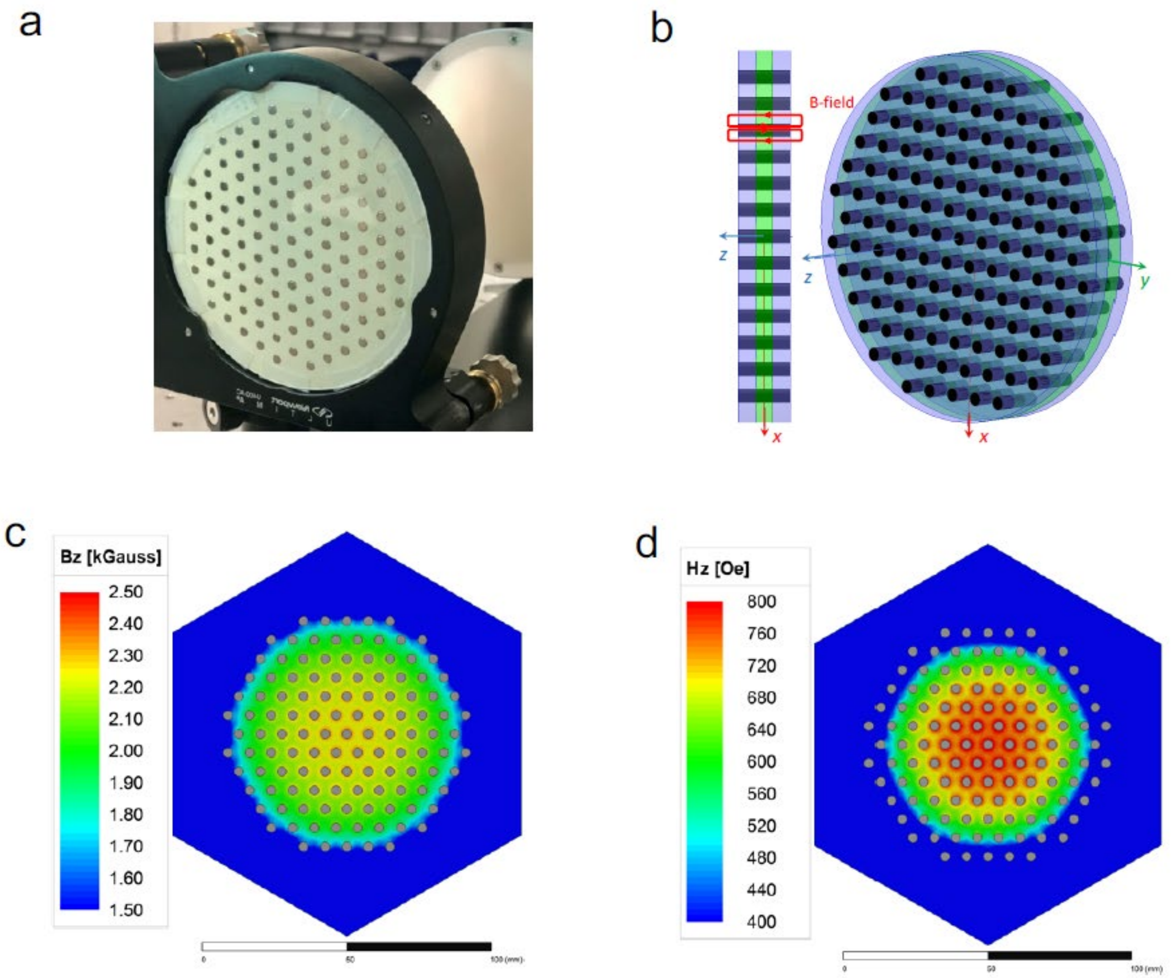
Joint project with Carl Pfeiffer (AFRL/RY) and Andrey Chabanov (U. of Texas)

The key component of most nonreciprocal devices, such as microwave and optical isolators, circulators, and nonreciprocal phase shifters is a magneto-optical material placed in an external magnetic field. This traditional approach involves the use of bulky magnets, which can be a major problem, especially in small devices. Alternatively, one can use permanently magnetized materials, such as ferrites or ferromagnets with high coercivity. Such materials display nonreciprocal electromagnetic properties even in the absence of external bias magnetic field. The magnetized materials, though, create their own demagnetization field.

One common problem with both externally biased and self-biased approach is related to the existence of a relatively strong magnetic field inside and outside the magneto-optical component. There are some important applications/devices which cannot tolerate even a tiny magnetic field, but they still require nonreciprocal components for optical isolation or other nonreciprocal functionalities. In addition, the demagnetization field inside the magnetized material is shape-dependent and can be non-uniform, unless the shape of the magnetized component is strictly ellipsoidal. The field non-uniformity inside magneto-optical material can compromise the performance of the nonreciprocal device.

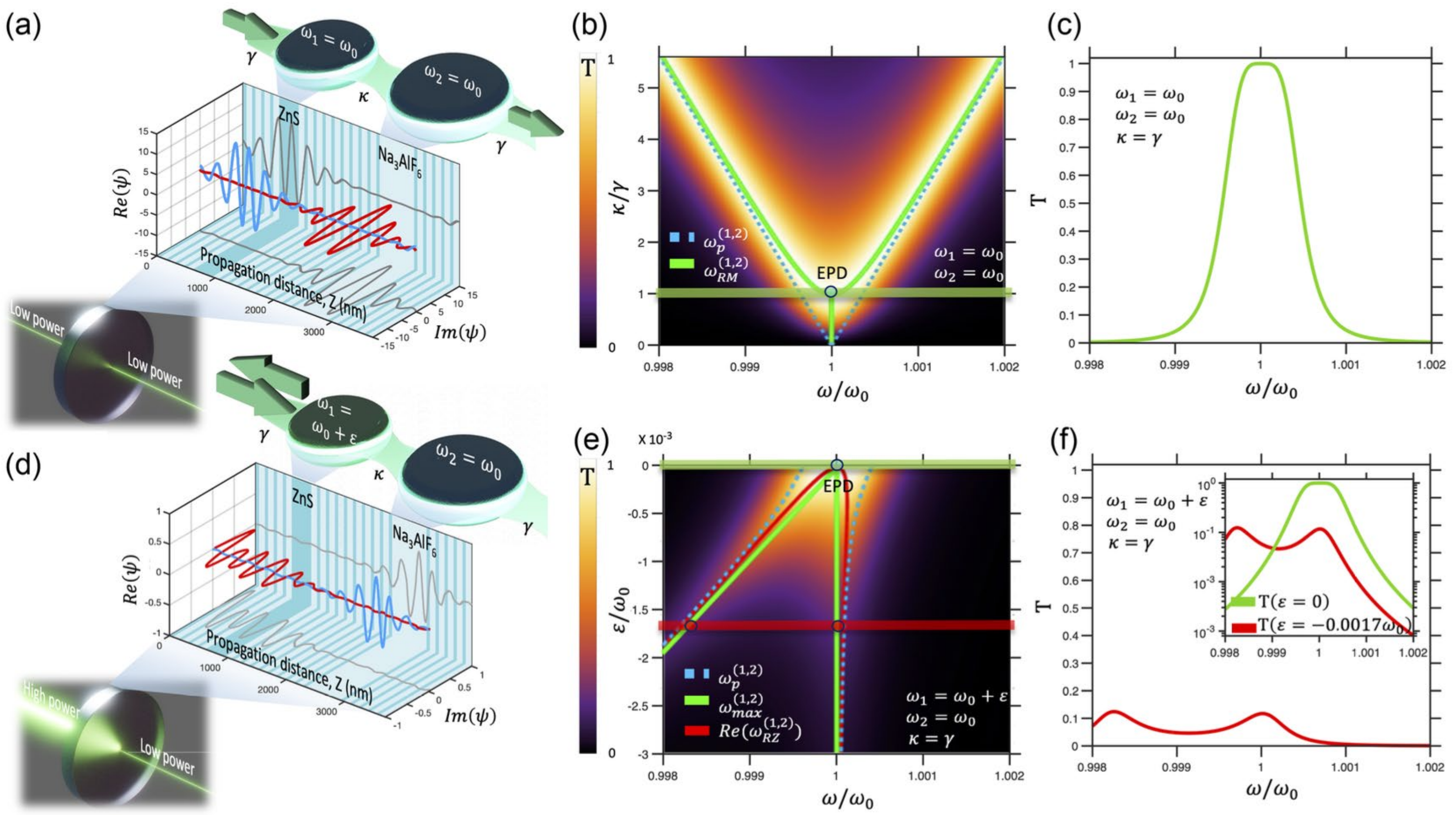
We design nonreciprocal composite structures, with zero net magnetization, providing strong Faraday rotation and/or nonreciprocal phase shift even without bias magnetic field. As opposed to the rare-earth-based compensated ferrites, the proposed composite structures can maintain zero net magnetization and constant Faraday rotation within a wide temperature range.

X-band realization of a nonreciprocal metamaterial, having zero net magnetization and producing strong (45°) Faraday rotation without bias magnetic field. This is an array of neodymium magnets (dark blue) incorporated in the YIG disc (green) and sandwiched between two impedance-matching layers (violet). The device performance is broadband temperature independent (*Patent pending*, *Manuscript in preparation, Carl Pfeiffer, A. Chabanov, et al, 2025*)



Optical limiter based on PT-symmetry breaking of reflectionless modes

L. Salvini, F. Riboli, R. Kononchuk, F. Tommasi, A. Boschetti, S. Suwunnarat, I. Anisimov, I. Vitebskiy, D.Wiersma, S. Cavalieri, T. Kottos, A. Chabanov. Proceedings of SPIE, Volume 1314003 (2024)



a) Artistic view (bottom), schematic (middle), and coupled-mode-theory (CMT) equivalent system (top) of the three-mirror resonator composed of cryolite (Na3AlF6) and zinc sulfide (ZnS) layers.

b,c,e,f) transmittance vs frequency

Compared to existing limiter designs, our optical limiter offers a customizable limiting threshold, high damage threshold, nanosecond activation time, and broadband laser protection. Additionally, we have shown a method to achieve an even broader transmission spectral bandwidth by implementing this concept in a four-cavity resonator with greater coupling strength using similar materials.

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).

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E. Makri, K. Smith, A. Chabanov, I. Vitebskiy, T. Kottos. *Hypersensitive Transport in Photonic Crystals with Accidental Spatial Degeneracies*. Scientific Reports **6**, 22169 (2016)

J. Vella, J. Goldsmith, A. Browning, N. Limberopoulos, I. Vitebskiy, E. Makri, T. Kottos. *Experimental realization of a reflective optical limiter*. Phys. Rev. Appl. **5**, 064010 (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)

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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)

Submitted Papers

- 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*. Submitted to 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