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13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Demetrios Christodoulides
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as of 26-Jan-2022

Agency Code: 21XD

Proposal Number: 71160PH **Agreement Number: W911NF-17-1-0481**

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Report Date: 14-Aug-2021 Date Received: 30-Nov-2021
Final Report for Period Beginning 01-Sep-2017 and Ending 14-May-2021

Title: Supersymmetry in Optics & Photonics

Begin Performance Period: 01-Sep-2017 **End Performance Period:** 14-May-2021
Report Term: 0-Other

Submitted By: Demetrios Christodoulides Email: demetri@creol.ucf.edu
Phone: (407) 882-0074

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:**

Major Goals: The objective of this program was to utilize the degrees of freedom offered by parity-time symmetry and non-Hermiticity to develop alternative strategies in designing unique classes of photonic systems with desired attributes and functionalities. Our efforts were focused towards a number of directions. These included for example, theoretically and experimentally assessing the possibility of using exceptional points as a means to enhance the Sagnac sensitivity of ring-laser gyroscopes as well as investigating the prospect for a new family of robust, chiral mode-convertors (in either the spatial or polarization domain) based on encircling exceptional points. In addition, the possibility of using parity-time symmetry was investigated in order to promote stable lasing in topologically protected edge-modes even in the presence of fabrication defects or any other imperfections.

Accomplishments: Major Activities:
Our activities centered on non-Hermitian systems displaying multiple exceptional points (EPs) for sensing enhancement, supersymmetric characteristics, unidirectionality, and topological response.

b. Specific Objectives:
One of the main goals of this effort was to develop a theoretical framework capable of describing arrangements with multiple exceptional points in different topologies. In addition, design strategies were introduced to implement pertinent laser systems that exploit PT symmetry and supersymmetry.

c. Significant Results/Key Outcomes:
During this effort, we investigated several themes, all revolving around the physics of non-Hermitian devices and their associated degeneracies, better known as exceptional points. These topics include:
(i) evolution of non-Hermitian systems in scenarios where multiple exceptional points are involved;
(ii) robust single mode operation in arrays of lasers by combining notions of supersymmetry and non-Hermiticity;
(iii) demonstration of a unidirectional PT-symmetric microring laser operating by breaking chiral symmetry;
(iv) demonstration of a ring laser gyroscope with an EP-enhanced Sagnac sensitivity;
(v) mapping the dynamical evolution of an anchor site in multi-dimensional networks onto a 1D lattice;
(vi) gain-induced topological lattices via tailored long-range interactions;
(vii) demonstration of a room temperature electrically pumped topological insulator laser.

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Patent title: Rotation sensor, rotation sensing method, and applications, Inventors: Mercedeh Khajavikhan, Demetrios Christodoulides, Hossein Hodaei, Mohammad Soltani
Patent number: 10415970

PARTICIPANTS:

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Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Other Professional
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Person Months Worked: 13.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Gisela Lopez Galmiche
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Midya Parto
Person Months Worked: 9.00 **Funding Support:**
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Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Qi Zhong
Person Months Worked: 4.00 **Funding Support:**
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Volume: 359 Issue: 6381 First Page #:
Date Submitted: 10/10/18 12:00AM Date Published: 3/1/18 3:00PM
Publication Location:
Article Title: Topological insulator laser: Experiments
Authors: Miguel A. Bandres, Steffen Wittek, Gal Harari, Midya Parto, Jinhan Ren, Mordechai Segev, Demetrios N
Keywords: topological insulator
Abstract: Physical systems exhibiting topological invariants are naturally endowed with robustness against perturbations, as manifested in topological insulators—materials exhibiting robust electron transport, immune from scattering by defects and disorder. Recent years have witnessed intense efforts toward exploiting these phenomena in photonics. Here, we demonstrate a nonmagnetic topological insulator laser system exhibiting topologically protected transport in the cavity. The topological properties give rise to single mode lasing, robustness against defects, and significantly higher slope efficiencies compared to the topologically trivial counterparts. We further exploit the properties of active topological platforms by assembling the system from S-chiral microresonators, enforcing predetermined unidirectional lasing without magnetic fields. This work paves the way toward active topological devices with unique properties and functionalities.
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Publication Location:
Article Title: Topological insulator laser: Theory
Authors: Gal Harari, Miguel A. Bandres, Yaakov Lumer, Mikael C. Rechtsman, Y. D. Chong, Mercedeh Khajavikh
Keywords: Topological Insulator
Abstract: Topological insulators are phases of matter characterized by topological edge states that propagate in a unidirectional manner that is robust to imperfections and disorders. These attributes make topological insultator systems ideal candidates for enabling applications in quantum computation and spintronics. Here, we propose a fundamentally new concept that exploits topological effects in a unique way: the topological insulator laser. These are lasers whose lasing mode exhibits topologically-protected transport without magnetic fields. The underlying topological properties lead to a highly efficient laser, robust to defects and disorder, with single mode lasing even at very high gain values. The topological insulator laser alters current understanding of the interplay between disorder and lasing, and at the same time opens exciting possibilities in topological physics, such as topologically-protected transport in systems with gain.
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Volume: 120 Issue: 11 First Page #:
Date Submitted: 10/10/18 12:00AM Date Published: 3/1/18 10:00AM
Publication Location:
Article Title: Edge-Mode Lasing in 1D Topological Active Arrays
Authors: Midya Parto, Steffen Wittek, Hossein Hodaei, Gal Harari, Miguel A. Bandres, Jinhan Ren, Mikael C. Rec
Keywords: Edge mode laser, topological active arrays
Abstract: We report the first observation of lasing topological edge states in a 1D Su-Schrieffer-Heeger active array of microring resonators. We show that the judicious use of non-Hermiticity can promote single edge-mode lasing in such arrays. Our experimental and theoretical results demonstrate that, in the presence of chiraltime symmetry, this non-Hermitian topological structure can experience phase transitions that are dictated by a complex geometric phase. Our work may pave the way towards understanding the fundamental aspects associated with the interplay among non-Hermiticity, nonlinearity, and topology in active systems.
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Volume: 9 Issue: 1 First Page #:
Date Submitted: 10/10/18 12:00AM Date Published: 3/1/18 12:00AM
Publication Location:
Article Title: Topological hybrid silicon microlasers
Authors: Han Zhao, Pei Miao, Mohammad H. Teimourpour, Simon Malzard, Ramy El-Ganainy, Henning Schome
Keywords: Silicon
Abstract: Topological physics provides a robust framework for strategically controlling wave confinement and propagation dynamics. However, current implementations have been restricted to the limited design parameter space defined by passive topological structures. Active systems provide a more general framework where different fundamental symmetry paradigms, such as those arising from non-Hermiticity and nonlinear interaction, can generate a new landscape for topological physics and its applications. Here, we bridge this gap and present an experimental investigation of an active topological photonic system, demonstrating a topological hybrid silicon microlaser array respecting the charge-conjugation symmetry. The created new symmetry features favour the lasing of a protected zero mode, where robust single-mode laser action in the desired state prevails even with intentionally introduced perturbations.
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Volume: 1 Issue: 5 First Page #: 297
Date Submitted: 10/10/18 12:00AM Date Published: 5/1/18 12:00AM
Publication Location:
Article Title: Generalized parity–time symmetry condition for enhanced sensor telemetry
Authors: Pai-Yen Chen, Maryam Sakhdari, Mehdi Hajizadegan, Qingsong Cui, Mark Ming-Cheng Cheng, Ramy E
Keywords: Parity-time Summetry
Abstract: Wireless sensors based on micromachined tunable resonators are important in a variety of applications, ranging from medical diagnosis to industrial and environmental monitoring. The sensitivity of these devices is, however, often limited by their low quality (Q) factor. Here, we introduce the concept of isospectral party–time–reciprocal scaling (PTX) symmetry and show that it can be used to build a new family of radiofrequency wireless microsensors exhibiting ultrasensitive responses and ultrahigh resolution, which are well beyond the limitations of conventional passive sensors. We show theoretically, and demonstrate experimentally using microelectromechanical-based wireless pressure sensors, that PTX-symmetric electronic systems share the same eigenfrequencies as their parity–time (PT)-symmetric counterparts, but crucially have different circuit profiles and eigenmodes.
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Volume: 97 Issue: 2 First Page #:
Date Submitted: 10/10/18 12:00AM Date Published: 2/1/18 12:00AM
Publication Location:
Article Title: Power-law scaling of extreme dynamics near higher-order exceptional points
Authors: Q. Zhong, D. N. Christodoulides, M. Khajavikhan, K. G. Makris, R. El-Ganainy
Keywords: extreme dynamics
Abstract: We investigate the extreme dynamics of non-Hermitian systems near higher-order exceptional points in photonic networks constructed using the bosonic algebra method.We show that strong power oscillations for certain initial conditions can occur as a result of the peculiar eigenspace geometry and its dimensionality collapse near these singularities. By using complementary numerical and analytical approaches, we show that, in the parity-time (PT) phase near exceptional points, the logarithm of the maximum optical power amplification scales linearly with the order of the exceptional point. We focus in our discussion on photonic systems, but we note that our results apply to other physical systems as well.
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Date Submitted: 10/10/18 12:00AM Date Published: 1/1/18 12:00AM
Publication Location:
Article Title: Non-Hermitian physics and PT symmetry
Authors: Ramy El-Ganainy, Konstantinos G. Makris, Mercedeh Khajavikhan, Ziad H. Musslimani, Stefan Rotter, D
Keywords: Non-Hermitian, PT symmetry
Abstract: In recent years, notions drawn from non-Hermitian physics and parity-time)PT) symmetry have attracted considerable attention. In particular, the realization that the interplay between gain and loss can lead to entirely new and unexpected features has initiated an intense research effort to explore non-Hermitian systems both theoretically and experimentally. Here we review recent progress in this emerging field, and provide an outlook to future directions and developments.
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Publication Identifier Type: Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/17/19 12:00AM Date Published:
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Article Title: Winding around Non-Hermitian Singularities
Authors: Q. Zhong, M. Khajavikhan, D.N. Christodoulides, and R. El-Ganainy
Keywords: non-hermitian
Abstract: Non-Hermitian singularities are ubiquitous in non-conservative open systems. Owing to their peculiar topology, they can remotely induce observable e♂ects when encircled by closed trajectories in the parameter space. To date, a general formalism for describing this process beyond simple cases is still lacking. Here we develop a general approach for treating this problem by utilizing the power of permutation operators and representation theory. This in turn allows us to reveal a surprising result that has so far escaped attention: loops that enclose the same singularities in the parameter space starting from the same point and traveling in the same direction, do not necessarily share the same end outcome. Interestingly, we ♀nd that this equivalence can be formally established only by invoking the topological notion of homotopy. Our ♀ndings are general with far reaching implications in various ♀elds ranging from photonics and atomic physics to microwaves and acoustics.
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Volume: 363 Issue: 6427 First Page #: 623
Date Submitted: 10/17/19 12:00AM Date Published: 2/1/19 10:00AM
Publication Location:
Article Title: Supersymmetric laser arrays
Authors: Mohammad P. Hokmabadi, Nicholas S. Nye, Ramy El-Ganainy, Demetrios N. Christodoulides, Mercede
Keywords: Supersymmetric lasers
Abstract: Scaling up the radiance of coupled laser arrays has been a long-standing challenge in photonics. In this study, we demonstrate that notions from supersymmetry—a theoretical framework developed in high-energy physics—can be strategically used in optics to address this problem. In this regard, a supersymmetric laser array is realized that is capable of emitting exclusively in its fundamental transverse mode in a stable manner. Our results not only pave the way toward devising new schemes for scaling up radiance in integrated lasers, but also, on a more fundamental level, could shed light on the intriguing synergy between non-Hermiticity and supersymmetry.
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Publication Identifier Type: DOI Publication Identifier: 10.1364/OE.26.027153
Volume: 26 Issue: 21 First Page #: 27153
Date Submitted: 10/17/19 12:00AM Date Published: 10/1/18 4:00AM
Publication Location:
Article Title: Unidirectional light emission in PT-symmetric microring lasers
Authors: Jinhan Ren, Yuzhou G. N. Liu, Midya Parto, William E. Hayenga, Mohammad P. Hokmabadi, Demetrios
Keywords: laser resonators, microcavity devices, semiconductor lasers
Abstract: The synergetic use of gain and loss in parity-time symmetric coupled resonators has been shown to lead to single-mode lasing operation. However, at the corresponding resonance frequency, an ideal ring resonator tends to support two degenerate eigenmodes, traveling along the cavity in opposite directions. Here, we show a unidirectional single-moded parity-time symmetric laser by incorporating active S-bend structures with opposite chirality in the respective ring resonators. Such chiral elements break the rotation symmetry of the ring cavities by providing an asymmetric coupling between the clockwise (CW) and the counterclockwise (CCW) traveling modes, hence creating a new type of exceptional point. This property, consequently, leads to the suppression of one of the counter-propagating modes. In this paper, we first measure the extinction ratio between the CW and CCW modes in a single ring resonator in the presence of an S-bend waveguide.
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Date Submitted: 10/17/19 12:00AM Date Published: 8/1/19 4:00AM
Publication Location:
Article Title: Direct Generation of Tunable Orbital Angular Momentum Beams in Microring Lasers with Broadband Exceptional Points
Authors: William E. Hayenga, Midya Parto, Jinhan Ren, Fan O. Wu, Mohammad P. Hokmabadi, Christian Wolff, I
Keywords: microresonator, orbital angular momentum, microring laser, non-Hermitian, chirality, exceptional point
Abstract: Non-Hermitian exceptional points (EPs) represent a special type of degeneracy where not only the eigenvalues coalesce, but also the eigenstates tend to collapse on each other. Recent studies have shown that, in the presence of an EP, light?matter interactions are profoundly modified, leading to a host of unexpected optical phenomena ranging from enhanced sensitivity to chiral light transport. Here we introduce a family of unidirectional resonators based on a novel type of broadband exceptional points. In active settings, the resulting unidirectionality exhibits resilience to perturbations, thus, providing a robust and tunable approach for directly generating beams with distinct orbital angular momenta (OAM). This work could open up new possibilities for manipulating OAM degrees of freedom in applications pertaining to telecommunications and quantum information sciences, while at the same time may expand the notions of non-Hermiticity in the orbital angular momentum space.
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Publication Location:
Article Title: Sensing with Exceptional Surfaces in Order to Combine Sensitivity with Robustness
Authors: Q. Zhong, J. Ren, M. Khajavikhan, D.?N. Christodoulides, ?.?K. Özdemir, R. El-Ganainy
Keywords: lasers
Abstract: Exceptional points (EPs) are singularities that arise in non-Hermitian physics. Current research efforts focus only on systems supporting isolated EPs characterized by increased sensitivity to external perturbations, which makes them potential candidates for building next generation optical sensors. On the downside, this feature is also the Achilles heel of these devices: they are very sensitive to fabrication errors and experimental uncertainties. To overcome this problem, we introduce a new design concept for implementing photonic EPs that combine the robustness required for practical use together with their hallmark sensitivity. Particularly, our proposed structure exhibits a hypersurface of Jordan EPs embedded in a larger space, and having the following peculiar features: (1) A large class of undesired perturbations shift the operating point along the exceptional surface (ES), thus, leaving the system at another EP which explains the robustness; (2) Perturbations due to back reflec
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Volume: 5 Issue: 10 First Page #: 1342
Date Submitted: 10/17/19 12:00AM Date Published: 10/1/18 4:00AM
Publication Location:
Article Title: Fluctuations and noise-limited sensing near the exceptional point of parity-time-symmetric resonator systems
Authors: N. Asger Mortensen, P. A. D. Gonçalves, Mercedeh Khajavikhan, Demetrios N. Christodoulides, Christo
Keywords: lasers
Abstract: Exceptional points of parity-time (PT) symmetric systems hold an intriguing potential for highly sensitive sensors. Here, we theoretically explore the role of mesoscopic fluctuations and noise on the spectral and temporal properties of systems of PT -symmetric-coupled gain–loss resonators operating near the exceptional point, where eigenvalues and eigenvectors coalesce. We show that experimentally inevitable detuning in the frequencies of the uncoupled resonators leads to an unavoidable modification of the conditions for reaching the exceptional point, while, as this point is approached in ensembles of resonator pairs, statistical averaging significantly smears the spectral features. We discuss how these fluctuations affect the sensitivity of sensors based on coupled PT -symmetric resonators. Finally, we show that temporal fluctuations in the detuning and gain of these sensors lead to at least a quadratic growth of the optical power in time, implying that maintaining operation at the
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Publication Location:
Article Title: The dawn of non-Hermitian optics
Authors: Ramy El-Ganainy, Mercedeh Khajavikhan, Demetrios N. Christodoulides, Sahin K. Ozdemir
Keywords: non-hermitian opics
Abstract: Recent years have seen a tremendous progress in the theory and experimental implementations of non-Hermitian photonics, including all-lossy optical systems as well as parity-time symmetric systems consisting of both optical loss and gain. This progress has led to a host of new intriguing results in the physics of light–matter interactions with promising potential applications in optical sciences and engineering. In this comment, we present a brief perspective on the developments in this field and discuss possible future research directions that can benefit from the notion of non-Hermitian engineering.
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Volume: 5 Issue: 1 First Page #:
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Publication Location:
Article Title: Observation of twist-induced geometric phases and inhibition of optical tunneling via Aharonov-Bohm effects
Authors: Midya Parto, Helena Lopez-Aviles, Jose E. Antonio-Lopez, Mercedeh Khajavikhan, Rodrigo Amezcua-C
Keywords: optics
Abstract: Geometric phases appear ubiquitously inmany and diverse areas of the physical sciences, ranging fromclassical and molecular dynamics to quantum mechanics and solid-state physics. In the realm of optics, similar phenomena are known to emerge in the form of a Pancharatnam-Berry phase whenever the polarization state traces a closed contour on the Poincaré sphere. While this class of geometric phases has been extensively investigated in both freespace and guided wave systems, the observation of similar effects in photon tunneling arrangements has so far remained largely unexplored. Here, we experimentally demonstrate that the tunneling or coupling process in a twistedmulticore fiber systemcan display a chiral geometric phase accumulation, analogous to the Aharonov-Bohm effect. In our experiments, the tunneling geometric phase is manifested through the interference of the corresponding supermodes.
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Publication Location:
Article Title: Crossing exceptional points without phase transition
Authors: Qi Zhong, Ramy El-Ganainy
Keywords: optics
Abstract: We show that the theoretical framework linking exceptional points (EPs) to phase transitions in paritytime (PT) symmetric Hamiltonians is incomplete. Particularly, we demonstrate that the application of the squaring operator to a Jx PT lattice dramatically alter the topology of its Riemann surface, eventually resulting in a system that can cross an EP without undergoing a symmetry breaking. We elucidate on these rather surprising results by invoking the notion of phase diagrams in higher dimensional parameter space. Within this perspective, the canonical PT symmetry breaking paradigm arises only along certainprojections of the Riemann surface in the parameter space.
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Volume: 13 Issue: 2 First Page #: 1800202
Date Submitted: 10/17/19 12:00AM Date Published: 2/1/19 5:00AM
Publication Location:
Article Title: Experimental Realization of Multiple Topological Edge States in a 1D Photonic Lattice
Authors: Zhifeng Zhang, Mohammad Hosain Teimourpour, Jake Arkinstall, Mingsen Pan, Pei Miao, Henning Sch
Keywords: photonic lattice
Abstract: Topological photonic systems offer light transport that is robust against defects and disorder, promising a new generation of chip-scale photonic devices and facilitating energy-efficient on-chip information routing and processing. However, present quasi one-dimensional designs, such as the Su-Schrieffer-Heeger (SSH) and Rice-Mele (RM) models, support only a limited number of nontrivial phases due to restrictions on dispersion band engineering. Here, we experimentally demonstrate a flexible topological photonic lattice on a silicon photonic platform that realizes multiple topologically nontrivial dispersion bands. By suitably setting the couplings between the one-dimensional waveguides, different lattices can exhibit the transition between multiple different topological phases and allow the independent realization of the corresponding edge states.
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Publication Location:
Article Title: Non-Hermitian ringlaser gyroscopes with enhanced Sagnac sensitivity
Authors: Mohammad P. Hokmabadi, Alexander Schumer, Demetrios N. Christodoulides, Mercedeh Khajavikhan
Keywords: Nonlinear optics, optical sensors, photonic devices
Abstract: The synthesis of ultrathin photonic structures in order to effectively redirect and mold optical wave fronts into arbitrary shapes is of crucial importance in modern beam steering, imaging, and sensing technologies. To this end, planar subwavelength systems such as optical metasurfaces have been intensely investigated in recent years. Such arrangements rely on abrupt, yet controllable, phase shifts imparted on the incident beam, by means of judiciously designed anisotropic nanoantennas. Here, we propose and demonstrate an altogether different methodology in order to manipulate the flow of light, by adopting a diatomic parity-time (PT)-symmetric Bravais-lattice topology, the unit cell of which involves only a transparent and a lossy optical component. In this respect, a honeycomblike configuration is employed, the principal symmetries of which are progressively broken through specific geometric transformations.
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Article Title: Electrically Pumped Microring Parity-Time-Symmetric Lasers
Authors: William E. Hayenga, Hipolito Garcia-Gracia, Enrique Sanchez Cristobal, Midya Parto, Hossein Hodaei, F
Keywords: Optical Waveguides, Ring lasers, semiconductor lasers
Abstract: Microscale and nanoscale electrically pumpedlasers are expected to play an indispensable role in future photonic integrated circuits. Small footprint, low threshold, high efficiency, and large side-mode suppression ratio (SMSR) are among the most important characteristics that such on-chip emitters should exhibit—allowing for large-scale integrability, low energy consumption, and stable output power. Microring resonators are one of the main contenders for the realization of such compact light sources. However, the use of microring laser cavities has been so far hindered by their tendencyto operate in multiple modes. Quite recently, several studies have shown that notions from parity-time (PT)-symmetry and non-Hermitian physics can be utilized to effectively enforce single-mode operation in semiconductor microring laser arrangements.
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Article Title: Enhanced modulation characteristics in broken symmetric coupled microring lasers
Authors: Chi Xu, William E. Hayenga, Hossein Hodaei, Demetrios N. Christodoulides, Mercedeh Khajavikhan, Pa
Keywords: lasers
Abstract: Microscale and nanoscale electrically pumpedlasers are expected to play an indispensable role in future photonic integrated circuits. Small footprint, low threshold, high efficiency, and large side-mode suppression ratio (SMSR) are among the most important characteristics that such on-chip emitters should exhibit—allowing for large-scale integrability, low energy consumption, and stable output power. Microring resonators are one of the main contenders for the realization of such compact light sources. However, the use of microring laser cavities has been so far hindered by their tendencyto operate in multiple modes. Quite recently, several studies have shown that notions from parity-time (PT)-symmetry and non-Hermitian physics can be utilized to effectively enforce single-mode operation in semiconductor microring laser arrangements.
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Article Title: Thermodynamic conditions governing the optical temperature and chemical potential in nonlinear highly multimoded photonic systems
Authors: Midya Parto, Fan O. Wu, Pawel S. Jung, Konstantinos Makris, Demetrios N. Christodoulides
Keywords: lasers
Abstract: We show that, in general, any complex weakly nonlinear highly multimode system can reach thermodynamic equilibrium, characterized by a unique temperature and chemical potential. The conditions leading to either positive or negative temperatures are explicitly obtained in terms of the linear spectrum of the system, the input power, and the corresponding Hamiltonian invariant. Pertinent examples illustrating these results are provided in various scenarios.
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Article Title: Statistical mechanics of weakly nonlinear optical multimode gases
Authors: Konstantinos G. Makris, Fan. O. Wu, Pawel S. Jung, Demetrios N. Christodoulides
Keywords: lasers
Abstract: By utilizing notions from statistical mechanics,we develop a general and self-consistent theoretical framework capable of describing any weakly nonlinear optical multimode system involving conserved quantities. We derive the fundamental relations that govern the grand canonical ensemble through maximization of the Gibbs entropy at equilibrium. In this classical picture of statistical photo-mechanics, we obtain analytical expressions for the probability distribution, the grand partition function, and the relevant thermodynamic potentials.Our results universally apply to any other weakly nonlinear multimode bosonic system.
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Article Title: Flexible PT-Symmetric Optical Metasurfaces
Authors: N. S. Nye, A. E. Halawany, C. Markos, M. Khajavikhan, D. N. Christodoulides
Keywords: lasers
Abstract: The synthesis of ultrathin photonic structures in order to effectively redirect and mold optical wave fronts into arbitrary shapes is of crucial importance in modern beam steering, imaging, and sensing technologies. To this end, planar subwavelength systems such as optical metasurfaces have been intensely investigated in recent years. Such arrangements rely on abrupt, yet controllable, phase shifts imparted on the incident beam, by means of judiciously designed anisotropic nanoantennas. Here, we propose and demonstrate an altogether different methodology in order to manipulate the flow of light, by adopting a diatomic parity-time (PT)-symmetric Bravais-lattice topology, the unit cell of which involves only a transparent and a lossy optical component. In this respect, a honeycomblike configuration is employed, the principal symmetries of which are progressively broken through specific geometric transformations.
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Date Submitted: 9/1/20 12:00AM Date Published: 12/1/19 5:00AM
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Article Title: 2D Solitons in PT-Symmetric Photonics Lattices
Authors: Andre L.?M. Muniz, Martin Wimmer, Arstan Bisianov, Ulf Peschel, Roberto Morandotti, Pawel S. Ju
Keywords: lasers
Abstract: The synthesis of ultrathin photonic structures in order to effectively redirect and mold optical wave fronts into arbitrary shapes is of crucial importance in modern beam steering, imaging, and sensing technologies. To this end, planar subwavelength systems such as optical metasurfaces have been intensely investigated in recent years. Such arrangements rely on abrupt, yet controllable, phase shifts imparted on the incident beam, by means of judiciously designed anisotropic nanoantennas. Here, we propose and demonstrate an altogether different methodology in order to manipulate the flow of light, by adopting a diatomic parity-time (PT)-symmetric Bravais-lattice topology, the unit cell of which involves only a transparent and a lossy optical component. In this respect, a honeycomblike configuration is employed, the principal symmetries of which are progressively broken through specific geometric transformations.
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Article Title: Symmetry-controlled edge states in the type-II phase of Dirac photonic lattices
Authors: Georgios G. Pyrialakos, Nora Schmitt, Nicholas S. Nye, Matthias Heinrich, Nikolaos V. Kantartzis, Alexa
Keywords: lasers
Abstract: The synthesis of ultrathin photonic structures in order to effectively redirect and mold optical wave fronts into arbitrary shapes is of crucial importance in modern beam steering, imaging, and sensing technologies. To this end, planar subwavelength systems such as optical metasurfaces have been intensely investigated in recent years. Such arrangements rely on abrupt, yet controllable, phase shifts imparted on the incident beam, by means of judiciously designed anisotropic nanoantennas. Here, we propose and demonstrate an altogether different methodology in order to manipulate the flow of light, by adopting a diatomic parity-time (PT)-symmetric Bravais-lattice topology, the unit cell of which involves only a transparent and a lossy optical component. In this respect, a honeycomblike configuration is employed, the principal symmetries of which are progressively broken through specific geometric transformations.
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Article Title: Realizing spin Hamiltonians in nanoscale active photonic lattices
Authors: Midya Parto, William Hayenga, Alireza Marandi, Demetrios N. Christodoulides, Mercedeh Khajavikhan
Keywords: lasers
Abstract: The synthesis of ultrathin photonic structures in order to effectively redirect and mold optical wave fronts into arbitrary shapes is of crucial importance in modern beam steering, imaging, and sensing technologies. To this end, planar subwavelength systems such as optical metasurfaces have been intensely investigated in recent years. Such arrangements rely on abrupt, yet controllable, phase shifts imparted on the incident beam, by means of judiciously designed anisotropic nanoantennas. Here, we propose and demonstrate an altogether different methodology in order to manipulate the flow of light, by adopting a diatomic parity-time (PT)-symmetric Bravais-lattice topology, the unit cell of which involves only a transparent and a lossy optical component. In this respect, a honeycomblike configuration is employed, the principal symmetries of which are progressively broken through specific geometric transformations.
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Publication Location:
Article Title: Thermodynamic theory of highly multimoded nonlinear optical systems
Authors: Fan O. Wu, Absar U. Hassan, Demetrios N. Christodoulides
Keywords: lasers
Abstract: The synthesis of ultrathin photonic structures in order to effectively redirect and mold optical wave fronts into arbitrary shapes is of crucial importance in modern beam steering, imaging, and sensing technologies. To this end, planar subwavelength systems such as optical metasurfaces have been intensely investigated in recent years. Such arrangements rely on abrupt, yet controllable, phase shifts imparted on the incident beam, by means of judiciously designed anisotropic nanoantennas. Here, we propose and demonstrate an altogether different methodology in order to manipulate the flow of light, by adopting a diatomic parity-time (PT)-symmetric Bravais-lattice topology, the unit cell of which involves only a transparent and a lossy optical component. In this respect, a honeycomblike configuration is employed, the principal symmetries of which are progressively broken through specific geometric transformations.
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Volume: 14 Issue: 2 First Page #: 76
Date Submitted: 9/1/20 12:00AM Date Published: 12/1/19 5:00AM
Publication Location:
Article Title: Synthesizing multi-dimensional excitation dynamics and localization transition in one-dimensional lattices
Authors: Lukas J. Maczewsky, Kai Wang, Alexander A. Dovgiy, Andrey E. Miroshnichenko, Alexander Moroz, Ma
Keywords: lasers
Abstract: The synthesis of ultrathin photonic structures in order to effectively redirect and mold optical wave fronts into arbitrary shapes is of crucial importance in modern beam steering, imaging, and sensing technologies. To this end, planar subwavelength systems such as optical metasurfaces have been intensely investigated in recent years. Such arrangements rely on abrupt, yet controllable, phase shifts imparted on the incident beam, by means of judiciously designed anisotropic nanoantennas. Here, we propose and demonstrate an altogether different methodology in order to manipulate the flow of light, by adopting a diatomic parity-time (PT)-symmetric Bravais-lattice topology, the unit cell of which involves only a transparent and a lossy optical component. In this respect, a honeycomblike configuration is employed, the principal symmetries of which are progressively broken through specific geometric transformations.
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Paper Title: Bimodall Directional Laser
Authors: Lei Ding, alexander Schumer, Jason Leshin, Yousef Alahmadi, Absar Ul-Hassan, G. Lopez Galmiche, P
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Authors: G. Lopez-Galmiche, H.E. Lopez Aviles, A.U. Hassan, A. Schumer, T. Kottos, P. L. LiKamWa, M. Khajav
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Authors: Jae-Hyuck Choi, William Hayenga, Midya Parto, Yuzhou Liu, Babak Bahari, Demetrios Christodoulides,
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Authors: M. Parto, W. Hayenga, A. Marandi, D. N. Christodoulides, M. Khajavikhan
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Authors: Mohammad P. Hokmabadi, Alexander Schumer, Demetrios Christodoulides, Mercedeh Khajavikhan
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Authors: Yuzhou G. N. Liu, Pawel Jung, Midya Parto, William E. Hayenga, Demetrios Christodoulides, Mercedeh
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Partners

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I certify that the information in the report is complete and accurate:
Signature: Demetrios Christodoulides
Signature Date: 11/30/21 10:24AM

Technical Report

1. Non-Hermitian systems with multiple exceptional points

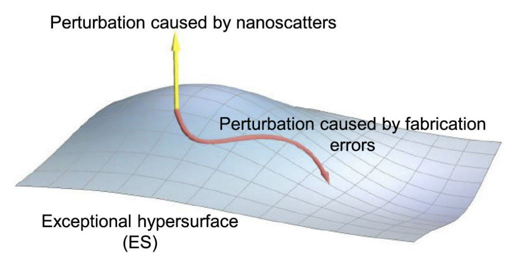

Fig. 1 A non-Hermitian photonic structure can combine robustness together with sensitivity if it exhibits a hypersurface of exceptional points with the following properties: (1) Undesired perturbations due to fabrication imperfections and experimental uncertainties shift the spectrum across the surface, leaving the system at an EP. (2) Perturbations accounting for the quantities to be measured force the spectrum out of the surface, i.e., away from EPs.

Exceptional points (EPs) are non-Hermitian degeneracies. Systems supporting EPs are extremely sensitive to external perturbations, which makes them appealing for building the next generation of optical sensors. So far, research efforts have focused only on systems supporting isolated EPs, which are also vulnerable to a large class of fabrication errors and experimental uncertainties. In our study [Physical Review Letters **122** , 153902 (2019)], we addressed this problem by introducing an exceptional hypersurface (ES) embedded in a high-dimensional parameter space which can combine the robustness required for practical use together with their intrinsic sensitivity characteristics. In particular, we indicated that robustness can be achieved if the system's response is tailored in such a way that a large class of fabrication errors and experimental uncertainties shift the operating point along the ES. Meanwhile, enhanced sensitivity can be achieved since any perturbation due to detection forces the spectrum away from the ES, thus causing a large splitting of the resonant frequency. Figure 1 illustrates this concept schematically. Our results are confirmed by numerical simulations and a five-fold enhancement was achieved in a demonstration of nanoparticle sensing.

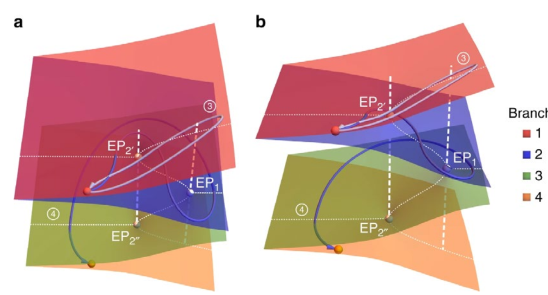

Fig. 2 Two different perspectives for a four-sheet Riemann surface and homotopy between encircling loops. The two loops 3 and 4 (blue lines) encircles EP1 (white point) in the parameter space and they are not equivalent tested by homotopy, resulting in different stroboscopic and dynamic features. On the Riemann surface, this property becomes even more evident by noting that the two loops span different sheets.

In a different study, we proposed a general formalism for treating the eigenstate exchange along arbitrary loops enclosing multiple EPs [Nature Communications **9**, 4808 (2018)]. In our analysis, we decomposed the final action of any loop into more elementary exchange processes across the relevant branch cuts with the tools from group theory and group representations. Using this formalism, we uncovered some interesting properties of multiple EP encirclement which was unknown before. Particularly, we found that trajectories that enclose the same EPs starting from the same initial point in the parameter space and following the same direction, do not necessary lead to an identical eigenstate exchange. Instead, such equivalence between the loops (resulting in the same eigenstate exchange) is guaranteed only by invoking the topological notion of homotopy (Fig. 2).

2. Supersymmetric Laser Arrays

Integrated arrays of semiconductor lasers can provide a viable avenue in scaling up the radiance (power per unit area per unit solid angle). Unfortunately, such arrays tend to support multiple spatial modes (supermodes), which in turn degrades the quality of the emitted beam. To solve this problem, we introduced the concept of supersymmetry (SUSY) and reported the realization of a supersymmetric laser array [Science **363**, 623-626 (2019)]. Specifically, the main array experiencing the gain was paired with a lossy array, called a superpartner. The introduction of the superpartner can suppress all undesired higher-order modes while simultaneously enhance the gain seen by the fundamental mode of the primary lattice laser. In implementing such lasers, we made use of the SUSY formalism first proposed by Witten so as to guarantee isospectrality between the primary laser systems and its lossy superpartner. The SUSY laser arrays were fabricated on an InP wafer with InGaAsP quantum wells as the gain material. The performance of the SUSY laser was assessed by means of a custom-made optical setup, in which the arrays were optically pumped by a fiber laser at a wavelength of 1064 nm. In our experiments, we performed a series of measurements in order to verify the anticipated SUSY response, the far-field radiation pattern from these SUSY laser systems along with their diffraction profiles. Our experimental results, shown in Fig. 3, indicate a pronounced difference in the way a SUSY laser operates as compared to a conventional laser array. As opposed to the latter, whose far field exhibits a multilobe profile with a diffraction angle of ~19° (Fig. 3D), the far field of the SUSY array displays a single bright spot, having instead a much smaller divergence angle of ~5.8° (Fig. 3F). This low-divergence behavior is a characteristic attribute of a laser array operating only in its in-phase lowest-order mode. Our results indicate that the existence of an unbroken SUSY phase in conjunction with a judicious pumping of the laser array can promote the in-phase supermode, thus producing a high-radiance emission. This mechanism of phase-locking was found to be resilient against first-order deviations in fabrication and provides a global approach that can be systematically applied to a wide range of coupled active lattices. Our results may have practical implications for designing high-brightness single-mode laser arrays from ultraviolet to midinfrared sources while introducing a platform to study, at a fundamental level, the interplay between non-Hermiticity and supersymmetry.

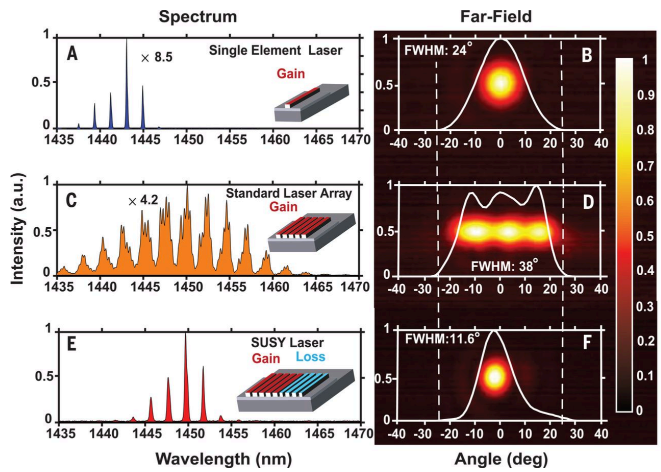

Fig. 3 Spectral and far-field characteristics of the SUSY laser array. Emission spectrum of (A) a single laser cavity, (C) a standard five-element laser array, and (E) a corresponding SUSY laser arrangement. Each longitudinal resonant frequency in the spectrum of the standard array splits into five lines corresponding to the five transverse supermodes. In contrast, the spectrum of the SUSY array is free from such undesired resonances, indicating that all higher-order modes are suppressed. (B, D, and F) Far-field diffraction patterns from the corresponding lasers. The measured diffraction angle associated with the SUSY laser is smaller than that of the standard laser array and a single waveguide laser.

3. Unidirectional PT-symmetric microring laser

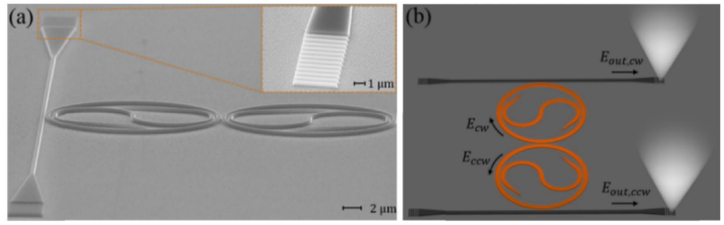

Fig. 4 Unidirectional PT-symmetric lasers. (a) SEM image of coupled microresonators incorporated with an S-bend inside the cavities. (b) Schematic of unidirectional light emission in a PT-symmetric microring system.

In previous works, it has been shown that PT-symmetric coupled resonators can lead to single-mode lasing operation. The standard coupled PT-symmetric laser, similar to a single ring, supports CW and CCW modes in both rings. This bi-directionality may have some adverse effects, such as the formation of undesirable supermodes of CW and CCW components caused by the roughness of the sidewall of microring resonators. This effect is highly detrimental since it limits the minimum detectable rotation rate in ring laser gyroscopes, as well as the detection sensitivity of non-Hermitian microcavity sensing systems.

In a work supported by this effort [Optics Express **26**, 27153 (2018)], we overcome such complications by incorporating an active S-bend element in each of the microrings in the PT-symmetric arrangement, and demonstrated a single-mode microring laser that emits unidirectional light in a robust fashion. In the proposed lasing arrangement, we incorporated active S-bend structures with opposite chirality in two coupled ring resonators (Fig. 4). Such chiral elements break the rotation symmetry of the ring cavities by providing an asymmetric coupling between the CW and the CCW traveling modes. This configuration creates a new type of an exceptional point, a so called chiral exceptional point, leading to the suppression of one of the counterpropagating modes. In our experiments, we first measured the extinction ratio between the CW and CCW modes in a single ring resonator in the presence of an S-bend waveguide. Our results showed that the intensity of one component (CCW) is much higher than the other one (CW). We then experimentally investigated the unidirectional emission in PT-symmetric systems below and above the exceptional point. Moreover, to show the versatility of our scheme, we demonstrated unidirectional light emission in systems having two S-bend ring resonators coupled through a link structure.

4. Ring laser gyroscopes with enhanced Sagnac sensitivity based on exceptional points

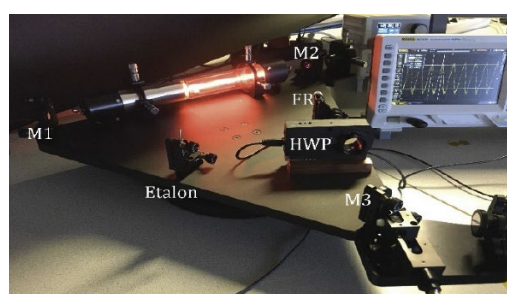

Fig. 5 Actual He-Ne ring laser gyroscope (RLG) system used in our experiments. This cavity was retrofitted with a half-wave plate (HWP), Faraday rotator (FR) and an etalon.

In another experimental study [Nature **576**, 70-74 (2019)], in collaboration with Dr. Khajavikhan's group at CREOL, we demonstrated a ring laser gyroscope (RLG) based on an exceptional point (Fig. 5) in order to boost the Sagnac scale factor. This resulted into an enhancement in sensitivity. In our experiments, we used a custom-made, He–Ne RLG (purchased from Luhs) retrofitted with a terbium gallium garnet (TGG) Faraday element and a half-wave plate (HWP) with. An etalon in the cavity promoted lasing in a specific longitudinal mode while providing some level of coupling between the CW and CCW modes. In the presence of the Faraday element, the CW mode is expected to experience lower losses than its CCW counterpart does, after passing through the Brewster windows (BWs) of the He–Ne tube. Hence, a differential loss between these two counterrotating modes and the mode-coupling process induced by a weakly scattering object can work together to establish an EP in this cavity. In general, the relativistic Sagnac shift in an RLG manifests itself as a beat frequency at a photodetector given that the CW and CCW modes lase at different frequencies. In a standard RLG arrangement, this beat frequency is always proportional to the rotation rate Ω this device is experiencing. However, the situation is very different in an RLG that is placed at or close to a second-order EP like the one used in our experiments. In this case, the beat frequency is now proportional to the square root of Ω, i.e. beat frequency $\propto \sqrt{\Omega}$. Therefore, if the rotational rate Ω is very small, the Sagnac signal can be boosted by orders of magnitude because of this square-root response. In our experiments the Sagnac resonance splitting was enhanced by up to a factor of 20, as shown in Fig. 6.

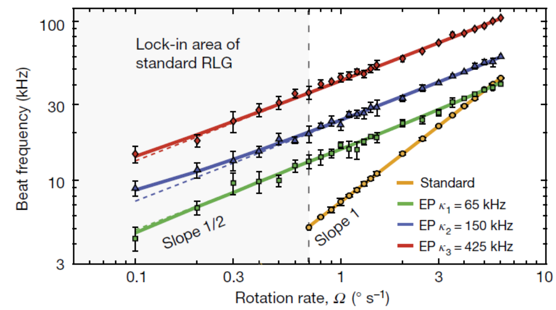

Fig. 6 Enhanced Sagnac sensitivity in a He-Ne RLG system due to the presence of an exceptional point. Beat frequency versus rotation rate Ω for a standard RLG and a non-Hermitian RLG at three different coupling strengths. The slop 1 and 1/2 stands for the linear and square-root response, respectively.

5. Synthesizing multi-dimensional excitation dynamics and localization transition in one-dimensional lattices

Complex networks with multiple connections serve as a universal model for a variety of dynamical systems. Also, the network dimensionality is supposed to be able to strongly affect the excitation dynamics, such as in the case of Anderson localization. However, the maximum number of dimensions in actual network settings is limited to three. To overcome this problem, the concept of synthetic dimensions was proposed, in which the additional dimensions can be artificially introduced. However, this inevitably comes at the steep cost of exponentially increasing complexity when attempting to access higher effective dimensions.

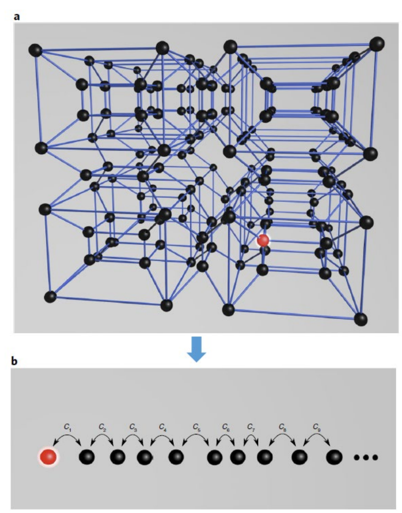

Fig. 7 Mapping a four-dimensional network (a) to a 1D lattice (b). The excitation dynamics of the first site in 1D lattice (red sphere) is the same as for the corresponding red anchor site in the four-dimensional network in (a).

In a recent study [Nature Photonics **14**, 76-81 (2020)], we introduced a new paradigm for the selective realization of a wide range of useful physical effects associated with high-dimensional networks and their non-trivial excitation dynamics. Theoretically, we showed that arbitrary Hermitian multi-dimensional lattices can be mapped to a one-dimensional (1D) lattice with judiciously tailored nearest-neighbour couplings and detunings (Fig. 7), such that the dynamics at a chosen anchor site is faithfully reproduced. This mapping was achieved by Lanczos transformation techniques, which not only preserve the optical eigenvalue spectrum as other transformations do, like supersymmetry (SUSY), but also exactly synthesize the actual local density of states. Because the method presented here does not require dynamic modulations, the static 1D equivalent lattices it yields are compatible with a broad range of existing technological platforms, including, but not limited to, the planar laser-written photonic structures that we employ in our proof-of-concept experiments.

In our experiments, we employed femtosecond laser-written photonic lattices as a test bed for the experimental characterization of our equivalent structures. We fabricated a 2D square lattice composed of six waveguides (Fig. 8(a)) as well as its 1D counterpart map as shown in Fig. 8(b). The sites in 2D square lattice have equal horizontal and vertical couplings and negligible diagonal interactions without detuning, resulting in identical waveguides with non-uniform but constant couplings in the 1D counterpart. We launched light into the anchor waveguide of the 2D lattice and the first waveguide of the 1D equivalent lattice, respectively. The evolution of light intensity in waveguides along the propagation direction was tracked by observing the emitted fluorescence. As shown in Fig. 8(c) and (d), the dynamics of the anchor site in the 2D lattice are captured by the first site of the equivalent 1D lattice very well.

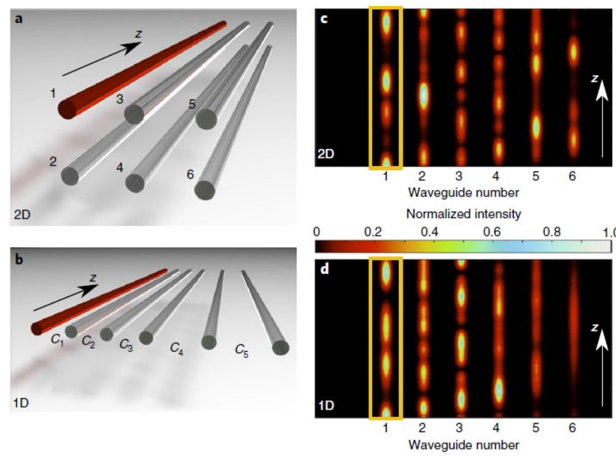

Fig. 8 Experimental verification of synthesizing the excitation dynamics of a 2D structure (a) in a 1D lattice (b). The dynamics of the anchor site in the 2D lattice (c) are captured by the first site of the equivalent 1D lattice (d) very well. The 2D structure has been inscribed at a tilt angle of 20° to allow each lattice site to be viewed without obstruction or overlay.

6. Gain-induced topological response via tailored long-range interactions

The interplay between long- and short-range interactions between the constituent elements play a pivotal role in many physical systems. In this regard, asymmetric interactions have been proposed theoretically and have predicted a host of intriguing topological phenomena, such as quantum anomalous Hall and non-Hermitian skin effects. In a recent study [Nature Physics **17**, 704-709 (2021)], we showed that such tailored asymmetric interactions can be implemented in photonic integrated platforms by exploiting non-Hermitian concepts, enabling a class of topological behaviors induced by optical gain. Specifically, we implemented the Haldane model, an archetypical lattice supporting a topological phase because of non-symmetric long-range interactions. Despite a series of theoretical breakthroughs, the original Haldane lattice has never been synthesized in solid-state in the lab. In this work, we realized long-range exchange interactions between resonant elements in a photonic arrangement. The hopping long-range

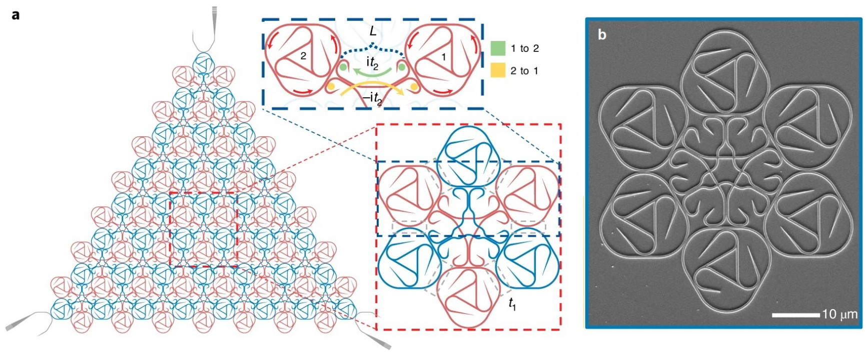

Fig. 9 The photonic topological Haldane lattice. (a) A schematic of an optical topological Haldane lattice with zigzag edges. The bottom inset depicts the Haldane honeycomb unit cell. Two sets of resonators with different perimeters are placed in close proximity to provide a NN coupling. The upper inset shows the required linkage for implementing the complex antisymmetric hopping between NNN resonators. (b) A microscope image of the fabricated single Haldane honeycomb unit cell.

interactions are tailored by the optical gain and non-Hermiticity, and the whole lattice is operated in its topological Chern regime.

The Haldane structure features a honeycomb lattice, composed of two species (Fig. 9). In our photonic structures, the two species are constructed using two sets of ring-type cavities/resonators. These two species of resonators have slightly different perimeters, thus supporting eigenfrequencies that are somewhat detuned. Besides the nearest-neighbour (NN) interactions among detuned neighbouring elements, an asymmetric exchanged between the next-nearest neighbour (NNN) elements is achieved through a fan-shaped construct and a combination of directional couplers and waveguides. The fan-shaped structure incorporated into each active resonator generates an exceptional point, and guarantees that the ring remains single-moded and enforces a unidirectional flow of light due to the interplay of gain, spontaneous emission and gain-induced nonlinearity. This unique property, a direct consequence of non-Hermiticity, is of central importance in realizing the Haldane lattice as it enables the antisymmetric coupling.

As a demonstration, the Haldane lattice containing 166 microresonators (or 66 unit cells) was fabricated on a wafer with InGaAsP multiple quantum wells (Fig. 10(a)). The lattice is terminated with zigzag edges. In addition, the light exiting the lattice at the corners of the structure was monitored through three gratings at these points. To observe the topological property of this Haldane lattice, i.e. a unidirectional flow of light around the perimeter, a metallic mask is used to selectively pump the periphery and only two of the three edges are pumped. The direction of light transport around the edges of the array is determined by comparing the

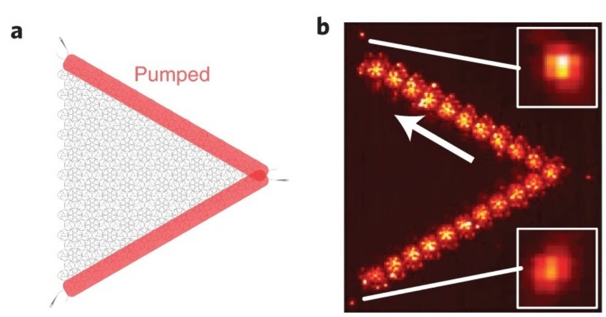

Fig. 10 Topological Haldane lattice experimental results. (a) Optical beam patterns used to pump two of the three edges of the Haldane lattice. (b) Intensity profile of the radiation emitted by this topological lattice. The output intensities at the grating couplers are compared, indicating a counterclockwise transport in the topological phase. The white arrows show the direction of the flow of light.

intensity of light exiting the grating couplers, as shown the white arrows in Fig. 10(b). As a comparison, we fabricated a non-topological lattice by placing the link farther apart from the resonators, thus reducing the strength of NNN hopping, and no light preferential direction was shown.

7. Room temperature electrically pumped topological insulator lasers

In condensed matter physics, topological insulators (TIs) represent to a new class of materials with an insulating bulk and symmetry-protected surface conducting states. Recently, the concept of topological protection has been extended from solid-state physics to photonics. In this respect, topological insulator lasers (TILs) are two-dimensional arrays of emitters that oscillate with the help of topological edge modes. So far, most of the demonstrated two-dimensional topological insulator lasers were optically pumped. Recently, an electrically pumped THz quantum cascade topological insulator laser was demonstrated, but it can only work at a cryogenic temperature of 9 K.

In a recent work [Nature Communications **12**, 3434 (2021)], we demonstrated the first room temperature, electrically pumped topological insulator laser that operates at telecom wavelengths. Our TIL array is composed of a 10×10 network of microring resonators coupled via a set of anti-resonant link objects, which imitates the quantum spin Hall effect for photons. To emulate a synthetic gauge field, the position of the links is judiciously vertically shifted from one row to another. Moreover, the topological lasing was achieved by applying gain only to the peripheral elements through the incorporation of metal electrodes (Fig. 11(a)). The collected electroluminescence emission profile from the topological insulator laser, as shown in Fig. 11(b), appears to be extended across all the gain elements at the periphery of the lattice. The emission spectrum of the device (Fig. 11(c)) indicates the single frequency emission. Our work is expected to pave the way towards the realization of a new class of electrically pumped coherent and phase-locked laser arrays that operate at a single frequency and an extended spatial mode.

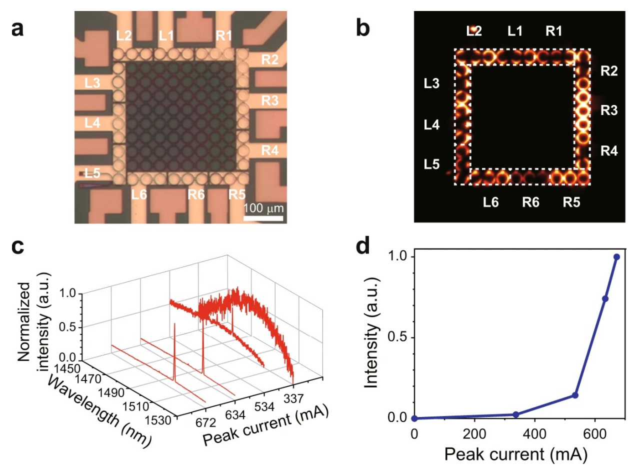

Fig. 11 Electrically pumped topological insulator. (a) The microscope image of the fabricated topological insulator laser array (top view). In order to selectively excite the topological edge mode, electrodes are designed only at the perimeter of the array. R and L labels indicate that the position of the metal pad connected to the electrode is on the right and left, respectively. (b) Intensity profile image of topological insulator laser array when all peripheral sites are pumped at the same level. (c) Spectral evolution of the laser emission as a function of the peak pump current. (d) Measured light-current curve of the laser.