Essay: Photonic Crystals as a Platform to Explore New Physics

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Photonic crystals are artificial materials characterized by a photonic band structure that governs the propagation of light waves. The photonic gap was originally introduced to inhibit spontaneous emission and facilitate photon localization. In this essay, I will highlight how, despite the established understanding of photonic crystals, they remain highly relevant today. Their design flexibility, the duality symmetry inherent in Maxwell's equations, and their functionality across a wide frequency range all allow the exploration of new areas in physics, each revealing unique phenomena. Examples include band topology and topological effects in structured light fields, as well as geometric concepts such as quantum geometry and the properties of non-Euclidean spaces. Furthermore, photonic crystals provide a valuable platform for studying non-Hermitian physics, including exceptional points and the non-Hermitian skin effect. Beyond their fundamental significance, these properties hold promise for advancing photonic technologies.

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Advancements in photonic crystals research—Photonic crystals (PhCs) are optical materials defined by a periodic arrangement of components with spatially varying relative permittivity and permeability [1] and characterized by a photonic band structure (Fig. 1). In their simplest form, one-dimensional (1D) PhCs consist of alternating layers of materials with different refractive indices, creating a photonic band gap that prevents certain wavelengths of light from propagating. This concept can extend to two-dimensional (2D) and three-dimensional (3D) structures, commonly known as 2D [Fig. 1(a)] and 3D PhCs. In this essay, I will take a broader view of PhCs and include any systems described by an electromagnetic (EM) band structure, including periodic arrays of waveguides, electronic circuit elements, and transmission cables. When used in applications, PhCs can take various forms, including slabs that exhibit both 2D and 3D characteristics, as well as PhC fibers [2].

In the early stages of PhC research, the focus was on creating an "absolute gap" in the band structure. The density of states becomes zero within an absolute gap, which suppresses spontaneous emission [3] and enables photon localization [4]. While 1D PhCs inherently possess a gap (which can be demonstrated using the Kronig-Penney model, a well-known model for understanding band structure in periodic potentials), achieving an absolute gap in higher dimensions requires special consideration [5]. Later research revealed that in the long wavelength limit, some PhCs can produce unusual effective parameters, such as negative or zero permittivity and permeability, especially in structures with subwavelength metallic resonators. This discovery propelled the development of metamaterials [6], many of which were initially based on subwavelength PhCs [7], enabling novel phenomena like cloaking and superlenses that were previously deemed impossible [8,9]. It also inspired the application of the band structure concept to other types of waves, such as acoustic and elastic waves, leading to the study of phononic crystals [10]. In recent years, photonic band structures have emerged as valuable tools for exploring both topological [11,12] [Fig. 1(c)] and non-Hermitian phenomena [13] [Fig. 1(d)], which are currently prominent areas of research. Studying topological phenomena necessitates a comprehensive examination of the entire Brillouin zone, while investigating non-Hermitian physics involves analyzing complex band structures when the momentum or the frequency becomes complex.

In this essay, I will argue how nowadays PhCs remain an exceptional platform for various investigations and will highlight potential areas for future research. While topological phenomena have been extensively studied in electronic systems and non-Hermitian physics in other contexts, PhCs offer an invaluable and controllable

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platform for exploration. Unlike electrons, which follow Fermi statistics and whose transport phenomena are primarily relevant near the Fermi level, photons enable meaningful transport across all frequency bands. Furthermore, electronic band structure calculations often rely on mean-field approximations, such as those used in standard density functional theory implementations, where many-body electron-electron interactions are treated in an averaged manner, whereas Maxwell's equations can be solved almost exactly. The existence of a light cone in photonic systems gives rise to unique phenomena that do not have direct analogs in electron systems. Experimentally, photonic systems are more accessible for fabrication and measurement, and interesting phenomena in photonic systems can occur at room temperature and under less stringent conditions than in other platforms. EM wave systems possess numerous controllable degrees of freedom, including structure, time, and material response, and allow for the incorporation of gain or loss and relatively easy implementation of time variation. This makes them well-suited for studying non-Hermitian physics. Moreover, the structural designability of PhCs allows for the use of artificial resonators, making it possible to realize changing unit cell sizes to realize artificial gauge fields. Finally, various forms and degrees of disorder can be introduced in a highly controlled manner in PhCs, making them ideal for studying localization and the effects of disorder.

A platform to study topological photonics—For the reasons above, in the past decade, PhCs have emerged as a platform for exploring and realizing topological photonics. For example, 2D magnetic PhCs, typically consisting of an array of magnetic cylinders arranged in a 2D lattice [Fig. 1(c)], facilitate the emergence of a topologically nontrivial gap resulting from time-reversal symmetry breaking, characterized by Chern numbers and chiral edge states [14]. This behavior parallels that observed in electronic quantum anomalous Hall systems. Additionally, there have been many realizations of photonic valley Hall crystals, which open a gap at photonic Dirac points due to inversion symmetry breaking. These structures are analogs to electronic valley Hall systems [15,16]. Photonic topological material phenomena can extend beyond reproducing effects observed in electronic systems. Because of their structural degrees of freedom, EM systems can exhibit a wide range of intriguing physical behavior, limited only by our imagination. For instance, magnetic PhCs can be used to realize complex phenomena in 3D, such as photonic axion insulators [17,18], which typically require the breaking of time-reversal symmetries, and are characterized by a coupling between the electric and magnetic fields through the axionlike term in the EM Lagrangian. These artificial materials, which demonstrate axionlike physics in a tabletop platform, are good for exploring advanced physics, such as connections to particle physics and condensed matter. However, whether they are practical for real-world applications, such as on-chip implementations, remains uncertain. Despite this, their exhibition of topological hinge states underscores the significant potential of PhC structures for investigating high-dimensional topological physics and their broader implications.

PhCs also exhibit unique features due to the inherent symmetries of EM waves. One notable symmetry is "duality," which refers to the invariance of Maxwell's equations under the exchange of the electric and the magnetic field. This symmetry is naturally preserved in free space. This symmetry is typically broken inside materials because the electric and magnetic resonances occur at different frequencies and exhibit varying strengths. Despite this, PhCs can be designed to have specific electric and magnetic responses to restore duality. By doing so, we can explore photonic topological phases that transcend the

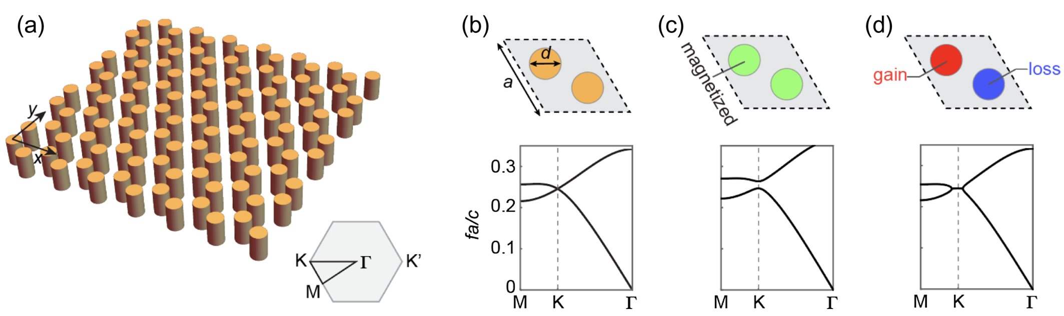

FIG. 1. (a) Schematic of a two-dimensional (2D) photonic crystal (PhC) with a honeycomb lattice of yttrium iron garnet (YIG) cylinders (lattice constant a, cylinder diameter $d = 0.44a$). The inset shows the Brillouin zone. (b) Solving Maxwell's equations with periodic boundary conditions, we get a photonic band structure. In the case of a YIG PhC with specific material parameters (relative permittivity $\varepsilon_z = 13$ and relative permeability $\mu = 1$), a Dirac point emerges at the K point in the Brillouin zone, formed by the first two bands. (c) Magnetizing the YIG cylinders (modeled with $\varepsilon_z = 13$, $\mu = \begin{pmatrix} 1 & -0.5i \\ 0.5i & 1 \end{pmatrix}$) opens a frequency band gap at the K point. The photonic band under the gap acquires a nonzero Chern number, making the gap "topologically nontrivial." (d) We can make the system non-Hermitian by introducing gain and loss (modeled with $\varepsilon_z = 13 \pm i$, $\mu = 1$), as illustrated in the inset. This leads to the opening of a momentum gap. The figure shows the real part of the eigenvalues, while the eigenvalues within the momentum gap acquire an imaginary component (not shown).

conventional classification of bosonic topological phases, which traditionally rely on time-reversal and spatial symmetries. A notable example involves the combined symmetry $\mathrm{T_x} = \mathrm{T}\,\mathrm{M_x}\,\mathrm{D}$, which integrates time-reversal symmetry (T), mirror reflection symmetry ($\mathrm{M_x}$, with respect to a plane), and EM duality (D) [19]. We note that $\mathrm{T_x^2} = -1$. This is significant, as the time-reversal symmetry operator is different for fermions and bosons. For fermions, the time-reversal symmetry operator $T^2 = -1$. In contrast, for bosons $\mathrm{T}^2 = +1$. Because of this distinction, certain topological phases and features protected by time-reversal symmetry in fermionic systems do not naturally appear in bosonic systems. As this combined symmetry exhibits fermionlike behavior, characterized by $\mathrm{T_x^2} = -1$, we should be able to use photonic systems to realize fermionic topological features such as Kramers Weyl points and Kramers nodal lines. The combined symmetry also allows 2D optical systems to host $\mathrm{Z_2}$ topological insulators and quantum spin-Hall-like effects, conventionally thought to occur in fermionic systems. In fact, some early demonstrations of photonic topological insulators have effectively employed duality symmetry [20].

EM duality does not simply replicate fermionic time-reversal symmetry. Combining EM duality and space group symmetries can realize topological features such as 3D Dirac points [21]. Photonic systems with joint symmetries of EM duality and spatial transformations can, in principle, even transcend both conventional bosonic and fermionic topological classifications. Achieving EM duality also has practical significance. For instance, duality can enable impedance matching and can lead to remarkable phenomena, such as perfect transparency or reflectionless interfaces, which are highly desirable in applications like absorbers, waveguides, and optical cloaks. That said, realizing EM duality comes with challenges. EM duality is often limited to a narrow frequency range, and extending to a broader band will require future effort. In some applications, implementing combined symmetries of EM duality and a spatial symmetry (e.g., rotation operation R) does not require strictly self-dual materials ($\varepsilon = \mu$), but rather allows for spatially symmetric distributions where $\varepsilon(\mathrm{R}r) = \alpha\mu(r)$ with α being constant. This alleviates the stringent material requirements, making implementation significantly more feasible.

Application to synthetic gauge fields, non-Abelian effects—PhCs are good platforms to realize synthetic gauge fields, which provide a way to control light propagation. In its simplest form, a smooth spatial variation of the unit cell structure in real space is equivalent to a shift in the Bloch momentum and hence behaves like a vector potential. The effective gauge field can influence the trajectory of photons and can mimic the effect of magnetic fields acting on charged particles. It can help to realize photonic topological phases such as the integer quantum Hall effect [22]. Going beyond that, exploring non-Abelian gauge field effects [23,24] is a fascinating direction to follow. In the context of wave physics, non-Abelian gauge fields can be used to realize observable phenomena such as "Zitterbewegung," which is a trembling motion of wave trajectories and also non-Abelian Aharonov-Bohm interference [23,24]. Non-Abelian gauge theory is pivotal to fundamental physics, and non-Abelian braiding statistics are believed to be useful for fault-tolerant topological quantum computation. Non-Abelian phenomena arise when the final state of a physical system depends on the sequence of operations performed, and photonic systems, with their vast degrees of freedom, offer ideal platforms to study and demonstrate such non-commutative phenomena. For example, non-Abelian lattice gauge fields within the synthetic frequency dimension have been experimentally demonstrated using polarization as the degree of freedom [25]. Current synthetic non-Abelian gauge fields achieved in PhC platforms typically act as static background fields without dynamical backaction from the optical field. Consequently, they do not necessarily satisfy the Yang-Mills equations that govern fundamental gauge fields in quantum field theory. Can we achieve genuine dynamical interactions between synthetic gauge fields and light? One possible approach involves using nonlinear optical media to create field-strength-dependent gauge potentials, which might be realizable in nonlinear PhCs. The greater challenge, however, is to achieve synthetic gauge fields that satisfy the Yang-Mills equations. This would require imposing gauge invariance and introducing additional dynamical constraints on the synthetic gauge fields.

PhCs can also be used to realize other non-Abelian effects in the context of topological photonics. Unlike traditional topological classification theory, which focuses on single gaps between valence and conduction bands, multigap topological classification theory introduces an alternative viewpoint that considers systems where all band gaps remain open simultaneously [26]. This approach is particularly applicable to classical wave systems, exemplified by optical systems, where operating frequencies are not constrained by the Fermi energy, allowing simultaneous consideration of all band gaps. For PT-symmetric systems, it is possible to classify multigap topological phases using the rotation of the eigenvector frame, which is described by the non-Abelian (generalized) quaternion groups [26]. The noncommutativity between different non-Abelian topological phases leads to diverse physical effects, including new topological phases not identified by traditional classification theory. "Photonic lattices" are ideal for experimentally realizing and exploring this type of topological description, as their band structures can be precisely engineered to exhibit frame rotation characteristics [27]. Photonic lattices include waveguide arrays (e.g., those created by laser writing), periodic arrays of electronic circuits, and transmission cables connecting lattice points in a regular pattern. While these systems are not solid-state systems in the traditional sense, they possess a well-defined EM band structure. Moreover, in many cases, their band dispersion corresponds closely to that described by the tight-binding model. Non-Abelian topological invariants (such as quaternions) differ fundamentally from their Abelian counterparts in that they are not integers. Conventional bulk-boundary correspondence typically connects integer-valued bulk invariants to the number of integer-valued boundary modes. However, establishing a bulk-boundary correspondence for non-Abelian systems, where the invariants are noninteger, requires us to move beyond these conventional frameworks. The rigorous mathematical foundation for such systems is still under development. Furthermore, if the system is non-Hermitian, the problem becomes even more complex, adding additional layers of difficulty. Much work remains to be done in this area.

Another challenge in extending to non-Hermitian systems lies in the fact that the eigenvectors are no longer orthogonal. We must consider not only the eigenvector frame rotation but also frame deformation and the complexities introduced by exceptional points. An open question is how to track the rotation of eigenvectors when they coalesce at exceptional points. Furthermore, photonic lattices can be a great playground to explore movement of degeneracies (nodal points) in momentum space in systems of more than two bands [28,29], as well as the formation of nodal-line structures in optical systems, which can be difficult to explain otherwise. Photonic platforms that implement the braiding of optical modes in periodic photonic systems naturally induce non-Abelian geometric phases, facilitating the implementation of non-Abelian holonomic quantum computation, which utilizes these geometric phases as quantum logic gates, enabling the execution of quantum computations with enhanced robustness [30–32].

Quantum geometry and extension to non-Euclidean geometries—Quantum geometry [33] provides deeper insights into band theory and its implications for the transport of waves. Despite its name, quantum geometry is entirely relevant to classical waves, especially those with a band structure. Mathematically, quantum geometry is described by a geometric tensor. The imaginary part measures how the phase of the eigenstates changes as the system moves in parameter space: this is the Berry curvature, which determines the band topology. The real part defines the quantum metric, which measures the local distance between neighboring eigenstates. The quantum metric has been gaining increasing attention because of its relevance to a wide range of phenomena [34–37]. Quantum metric sets a bound for the spatial localization of maximally localized Wannier functions and hence is useful for understanding transport. In conventional wave physics, disorder typically induces scattering, which can lead to wave localization. However, in some specific flat-band model systems, disorder in system parameters that define the model can promote transport [38–40], which is quite counterintuitive. The concept of the quantum metric may provide insight into these unusual phenomena, specifically by clarifying the conditions under which disorder can enhance transport from a band structure perspective.

Photonic systems provide a highly controllable platform capable of producing flat bands in different dimensions. It is well-known that flat bands in photonics can lead to slow light phenomena, which are highly relevant for technological applications. Additionally, they provide a convenient platform for exploring novel physics. The flatness of the band can be adjusted, the gaps between the flat band and other bands can be engineered, and the degree of disorder, whether truly random or correlated, can also be controlled. Photonic systems can enable precise experimental investigation of quantum geometry and its impact on transport properties. The study of non-Hermitian systems introduces additional complexity as eigenstates become nonorthogonal. Different definitions of the quantum metric are possible [41], and determining the most appropriate one for describing specific phenomena often requires experimental validation. PhCs are particularly well-suited for such controlled experiments. One step further, PhCs can serve as experimental platforms to understand the role of quantum metrics in systems with nonlinearity or in time-dependent systems.

PhCs are typically understood within the framework of Euclidean geometry. In contrast, "hyperbolic lattices," which have negative curvature, provide a platform for extending band theory beyond the confines of Euclidean geometry, allowing us to explore how curvature and topology influence signal and energy propagation. Their translation group is non-Abelian [42,43], meaning that the irreducible representations become higher-dimensional. Consequently, the hyperbolic band theory needed to describe these systems is different from the Euclidean band theory. The presence of negative curvature and noncommutative symmetry groups challenges traditional methods of defining topological invariants. The concept of bulk-edge correspondence becomes more complex due to the noncommutative nature of the symmetry group and the exponential growth of the boundary. Hyperbolic lattices have been successfully realized in experiments using circuit systems [44–46]. Photonic lattices may serve as a good platform for developing new mathematical frameworks to describe topological properties in nonflat geometries, as well as provide an experimental platform to test theoretical predictions in a controlled environment.

Photonic slab applications—PhC slabs are periodic in 2D but extend over a small thickness in the third dimension. They support guided resonances, which can either remain confined within the slab or couple to radiation modes in the light cone and leak out. PhC slabs are perhaps the best platforms to realize the so-called bound states in the continuum (BICs) [47]. First proposed in 1929 in the context of quantum mechanics [48], BICs are nonradiative modes that paradoxically exist within the spectrum of radiative states. They serve as a good platform for investigating the interplay between symmetry, topology, and interference effects and hold great potential for applications requiring extremely high-Q factors. PhC slabs can be used to explore their underlying mechanisms, which include symmetry protection and destructive interference. This is a very active area of ongoing research.

In electronic systems, topology typically refers to the band topology within the bulk. On the other hand, in PhC slabs, topology can also be studied in the context of far-field radiation [49]. An important consequence is the connection to topological singularities in the radiation field, such as C points and V points, which are frequently discussed in optics [50]. The zero coupling of BICs to vacuum modes creates a singularity in momentum space, where the far-field polarization forms a vortex, or V point. By tuning system parameters, PhC slabs can also generate polarization singularities such as C points where the polarization state is circular. The ability to manipulate these singularities makes PhC slabs a unique platform for studying the topological emergence and annihilation of singularities. Further research into the correspondence between far-field radiation topology, such as the winding of the radiation field polarization, and the near-field band topology could provide new insights into light-matter interactions.

PhC slabs are effective for generating and manipulating vector beams for optical information processing, imaging, holography, and optical tweezers, as well as for creating structured light fields [51,52]. The incorporation of nonlinear effects into PhC slabs further enhances their capabilities, enabling dynamic control over singularities and other phenomena such as topological charge transitions. However, addressing nonlinearity presents theoretical and numerical challenges that require significant further research. Future studies could focus on developing robust mechanisms for controlling polarization singularities, exploring nonlinear dynamics, and designing practical devices to harness these phenomena. The potential of PhC slabs is vast, but several challenges must be overcome. Taking BICs as an example, one of the primary challenges lies in the high precision required to achieve the system parameters necessary for their realization. The finite size of fabricated PhC slabs poses another limitation. While theoretical calculations often assume an infinitely extended 2D plane, real devices are constrained by fabrication limits. Studying disorder and finite-size effects is not only crucial for bridging the gap between theory and applications but may also reveal new and interesting phenomena. BICs are isolated points in k space, and it would be fascinating to observe an entire resonance band exhibiting ultrahigh fidelity. BICs can exist as a band with different symmetries embedded in a continuum of bulk states. However, it is difficult for an entire band of slab modes to remain uncoupled from the vacuum due to symmetry considerations. Nevertheless, achieving a wide resonance band with high fidelity deserves further investigation.

Beyond the concepts of BICs, PhC slabs hold promise for various applications such as generating structural colors [53], energy harvesting [54], and passive radiative cooling [55]. These efforts will undoubtedly continue. PhC slabs can be designed to respond to small changes in their surrounding environment, making them useful for chemical and biological sensing. Advances in nanofabrication enable the creation of compact waveguides, bends, and splitters on a chip, making PhC slabs a promising platform for integrated photonic circuits and a good choice for implementing on-chip photonic devices. Moreover, PhC slabs provide a versatile platform for the realization of advanced light-emitting devices such as high-power and high beam quality surface-emitting lasers [56,57], and topological singularities can potentially further enhance their capability [58].

Non-Hermitian phenomena—Because of the relative ease with which gain and loss can be introduced, PhCs and photonic lattices provide an ideal platform for studying complex band structure and experimentally realizing non-Hermitian phenomena such as "exceptional points" (EPs) [59], where two or more eigenmodes coalesce. At these degeneracies, the Hamiltonian matrix becomes defective, meaning the number of independent eigenvectors is less than the dimension of the matrix. Non-Hermitian systems exhibit interesting topological features near EPs. In Hermitian systems, topology is primarily defined by the properties of eigenvectors and their associated invariants, such as the Chern number. Non-Hermitian systems can have complex eigenvalues that can exhibit their own topological properties, such as winding numbers in the complex energy plane. EPs manifest as branch points on different Riemann surfaces of eigenvalues, and encircling these EPs in parameter space induces permutations and braiding of eigenvalue bands [60,61]. Encircling an EP requires the ability to adiabatically vary system parameters, and in optics, such adiabatic variations can be designed, and dynamical encircling of EPs can be implemented in waveguide systems.

Photonic lattices are good platforms to explore the role of symmetry in open systems due to their flexibility in defining and fabricating structures with different symmetries. Non-Hermitian systems exhibit broader symmetries and richer degeneracies than their Hermitian counterparts due to the addition of Hermitian conjugation as a symmetry operation. Under these non-Hermitian symmetries, degeneracies can form intricate geometric structures, such as cusps and nexus points, which can arise at some higher-order EPs (e.g., third-order EPs). These structures often serve as sources of topologically protected edge modes in non-Hermitian photonic systems. Some of these novel degeneracies cannot be described by traditional topological invariants and may require the development of new mathematical tools, opening the door to unexplored topological states and effects. PhCs should be useful for studying the transition between Hermitian and non-Hermitian systems, especially in the presence of degeneracies such as Dirac points in momentum space, which can be easily achieved in photonic systems. Gain, loss, and symmetry-breaking mechanisms can be precisely controlled, making them advantageous compared to other systems for studying these transitions.

One key feature of EPs is their sensitivity to perturbations. For example, the eigenvalue dispersion near an EP exhibits square-root-like slopes, which may be useful for sensing. However, in practical sensing considerations, the signal-to-noise ratio is the key factor, and whether EP-based optical sensing systems are viable requires careful consideration [62]. PhCs represent a good platform to test how EP properties can be harnessed, including the incorporation of nonlinearity or extending these ideas to the quantum regime. Additionally, the interplay between eigenvalue braiding around EPs and loss-induced nonadiabaticity can lead to fascinating phenomena, such as asymmetric mode switching during the dynamical encirclement of EPs.

Another fascinating phenomenon that PhCs can explore is the "non-Hermitian skin effect" (NHSE) [63]. In 1D non-Hermitian lattices with point gaps, the bulk energy spectra under open boundary conditions can differ dramatically from those under periodic boundary conditions. In Hermitian systems, boundary formation typically introduces only a "measure zero" number of boundary states in the bulk band gap. In contrast, certain non-Hermitian systems exhibit a significant alteration of the bulk spectrum itself, with a large fraction of bulk states localized near the boundaries (skin modes). In higher-dimensional systems, the NHSE becomes even more diverse and complex. While in 1D systems, NHSE requires nonreciprocity, higher-dimensional systems can exhibit NHSE even in reciprocal crystals [64,65]. In such cases, the emergence of skin modes becomes strongly geometry-dependent, with their appearance determined by the orientation of the open boundaries, and the boundary modes can exhibit a range of exponential decay constants. The eigenmodes of an arbitrarily big sample depend on how the edges are formed. This raises an intriguing question of whether the eigenmode spectra in non-Hermitian systems exhibit a well-defined thermodynamic limit in the traditional sense. PhCs provide an ideal platform to experimentally investigate these counterintuitive effects.

It is relatively straightforward to fabricate non-Hermitian PhCs with anisotropic microstructures and to cut them along directions misaligned with their principal optical axes. Such configurations should, in principle, reveal the geometry-dependent skin modes predicted by NHSE theory. However, the questions of why this phenomenon has not been widely observed, and whether it is because experimental probes often measure real-frequency responses while NHSE modes exist at complex frequencies, remain. As recent methodologies now allow for probing complex frequency responses [66], one wonders whether NHSE phenomena be further explored in photonic experiments. While PhCs offer a rich platform for studying non-Hermitian physics, the mathematical framework needed to describe many of these phenomena remains complex and challenging. The interplay between non-Hermiticity and topology is an exciting frontier for theoretical exploration, but its practical utility remains an open question. Topological lasers [67–69] and lasers leveraging EP physics [70,71] could serve as a promising platform for exploring this interplay and unlocking its potential applications.

Photonic time crystals—Time, like space, is a fundamental dimension. When we extend the concept of PhCs into the time domain, we open the door to effects that are not seen in spatially modulated crystals [72–74]. However, it is worth clarifying some terminology. In fundamental physics, a time crystal refers to a system with a time-independent many-body Hamiltonian that exhibits periodic oscillations over time, even in its ground state, corresponding to spontaneous symmetry breaking in the time dimension [75]. In contrast, the term "photonic time crystal" usually refers to a time-dependent system in which the constitutive parameters are periodically modulated. In photonic time crystals, the spatial periodicity characteristic of traditional PhCs is replaced by temporal periodicity. This results in a Floquet band structure, where the band dispersion shows gaps in Bloch momentum. In contrast, in spatial PhCs, band gaps occur in frequency. These systems are inherently non-Hermitian, and the edges of the momentum gaps are EPs, a hallmark feature of non-Hermitian systems. Inside the momentum gaps, the system is in a "broken phase" where the eigenvalues become complex, corresponding to modes that grow or decay exponentially in amplitude. While photonic time crystals present exciting opportunities for new physics, realizing them experimentally is challenging. Opening significant momentum gaps requires high-speed modulation with a large refractive index contrast, which is technologically difficult. Temporal modulations can amplify certain modes, but they can also introduce nonlinear instabilities, intriguing to study but difficult to implement as stable and efficient devices. I anticipate a wealth of new and exciting work in this area.

Concluding remarks—Even as a mature field, there is still much to explore within the realm of photonic band structure. For instance, metallic PhCs featuring interconnected metallic structures support quasistatic bands that exhibit unconventional dispersion properties influenced by the topological connectivity in real space. This challenges conventional effective medium theories in the long-wavelength limit and the usual group theory treatment [76].

Investigating these phenomena from the perspectives of symmetry and topology would be an interesting endeavor.

Another fascinating area of study involves exploring exceptional points in non-Hermitian systems, including photonic time crystals, at the quantum level. For example, how does the radiation rate of a quantum emitter change in the presence of a momentum gap? A thorough analysis that provides definitive answers may necessitate a complete quantum mechanical treatment [77]. Further research in this domain could advance quantum sensing technologies. The interplay between temporal modulations and quantum coherence effects also offers a promising avenue for investigation. Moreover, PhC slabs and circuits can create tailored optical environments that enhance entanglement generation, as well as the control and interaction of entangled states, which is useful for developing solutions for quantum computing and information processing.

In this context, we also note that "phononic crystals," including acoustic crystals, are being studied with a similar level of interest as photonic crystals. While some differences exist, such as the absence of spin in acoustic waves and their lack of coupling to magnetic fields, they also exhibit a well-defined band structure under periodic boundary conditions. This characteristic makes them equally valuable for investigating fundamental physics, particularly phenomena that can be analyzed through a band-theoretic framework, such as band topology and non-Hermiticity [78–81]. Moreover, phononic crystals are macroscale structures, which simplifies fabrication. This accessibility accelerates the validation of theoretical models and the development of practical applications. For example, "acoustic metamaterials," which draw inspiration from phononic crystals, are already demonstrating significant potential in areas such as noise suppression [82].

Going back to PhC research, the incorporation of artificial intelligence (AI) will likely attract significant future research effort. Traditionally, algorithms such as genetic algorithms have been employed to design structures based on specific performance metrics. AI algorithms can optimize these designs more effectively. Inverse design is now a reality, allowing researchers to specify desired optical properties and utilize AI to derive corresponding structural designs [83–85]. As AI-assisted design becomes increasingly common, we can anticipate seeing a growing number of real-world applications for PhCs and photonic lattices.

Lastly, we reiterate that one of the most compelling advantages of PhCs lies in their ease of fabrication, particularly when contrasted with more intricate systems such as condensed matter platforms. Their structural parameters and external control variables can be precisely tuned, enabling accurate measurements and direct comparisons with theoretical predictions. This inherent simplicity and versatility not only make PhCs a good platform to explore fundamental physics but also accelerate the transition to practical applications, ranging from advanced communications and high-precision sensing to next-generation computing.

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[1] J. D. Joannopoulos *et al.*, Photonic crystals: Molding the flow of light (Princeton University Press, Princeton, USA, 2011).
[2] P. Russell, Photonic crystal fibers, Science **299**, 358 (2003).
[3] E. Yablonovitch, Inhibited spontaneous emission in solid-state physics and electronics, Phys. Rev. Lett. **58**, 2059 (1987).
[4] S. John, Strong localization of photons in certain disordered dielectric superlattices, Phys. Rev. Lett. **58**, 2486 (1987).

[5] K. M. Ho, C. T. Chan, and C. M. Soukoulis, Existence of a photonic gap in periodic dielectric structures, Phys. Rev. Lett. **65**, 3152 (1990).

[6] C. Simovski and S. Tretyakov, *An Introduction to Metamaterials and Nanophotonics* (Cambridge University Press, Cambridge, 2020).

[7] D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, Metamaterials and negative refractive index, Science **305**, 788 (2004).

[8] J. B. Pendry, Negative refraction makes a perfect lens, Phys. Rev. Lett. **85**, 3966 (2000).

[9] D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, Metamaterial electromagnetic cloak at microwave frequencies, Science **314**, 977 (2006).

[10] V. Laude, *Phononic Crystals: Artificial Crystals for Sonic, Acoustic, and Elastic Waves* (De Gruyter, Berlin, 2020).

[11] L. Lu, J. D. Joannopoulos, and M. Soljačić, Topological photonics, Nat. Photonics **8**, 821 (2014).

[12] T. Ozawa *et al.*, Topological photonics, Rev. Mod. Phys. **91**, 015006 (2019).

[13] L. Feng, R. El-Ganainy, and L. Ge, Non-Hermitian photonics based on parity–time symmetry, Nat. Photonics **11**, 752 (2017).

[14] Z. Wang, Y. Chong, J. D. Joannopoulos, and M. Soljačić, Observation of unidirectional backscattering-immune topological electromagnetic states, Nature (London) **461**, 772 (2009).

[15] J. R. Schaibley, H. Yu, G. Clark, P. Rivera, J. S. Ross, K. L. Seyler, W. Yao, and X. Xu, Valleytronics in 2D materials, Nat. Rev. Mater. **1**, 16055 (2016).

[16] H. Xue, Y. Yang, and B. Zhang, Topological valley photonics: Physics and device applications, Adv. Photonics Res. **2**, 2100013 (2021).

[17] C. Devescovi, A. Morales-Pérez, Y. Hwang, M. García-Díez, I. Robredo, J. Luis Mañes, B. Bradlyn, A. García-Etxarri, and M. G. Vergniory, Axion topology in photonic crystal domain walls, Nat. Commun. **15**, 6814 (2024).

[18] G.-G. Liu *et al.*, Photonic axion insulator, Science **387**, 162 (2025).

[19] M. G. Silveirinha, PTD symmetry-protected scattering anomaly in optics, Phys. Rev. B **95**, 035153 (2017).

[20] A. B. Khanikaev, S. H. Mousavi, W.-K. Tse, M. Kargarian, A. H. MacDonald, and G. Shvets, Photonic topological insulators, Nat. Mater. **12**, 233 (2013).

[21] Q. Guo, B. Yang, L. Xia, W. Gao, H. Liu, J. Chen, Y. Xiang, and S. Zhang, Three dimensional photonic Dirac points in metamaterials, Phys. Rev. Lett. **119**, 213901 (2017).

[22] M. Aidelsburger, S. Nascimbene, and N. Goldman, Artificial gauge fields in materials and engineered systems, Quantum Simul. Simul. Quantique **19**, 394 (2018).

[23] Y. Yang, C. Peng, D. Zhu, H. Buljan, J. D. Joannopoulos, B. Zhen, and M. Soljačić, Synthesis and observation of non-Abelian gauge fields in real space, Science **365**, 1021 (2019).

[24] Y. Yang, B. Yang, G. Ma, J. Li, S. Zhang, and C. T. Chan, Non-Abelian physics in light and sound, Science **383**, eadf9621 (2024).

[25] D. Cheng, K. Wang, C. Roques-Carmes, E. Lustig, O. Y. Long, H. Wang, and S. Fan, Non-Abelian lattice gauge fields in photonic synthetic frequency dimensions, Nature (London) **637**, 52 (2025).

[26] Q. Wu, A. A. Soluyanov, and T. Bzdušek, Non-Abelian band topology in noninteracting metals, Science **365**, 1273 (2019).

[27] Q. Guo, T. Jiang, R.-Y. Zhang, L. Zhang, Z.-Q. Zhang, B. Yang, S. Zhang, and C. T. Chan, Experimental observation of non-Abelian topological charges and edge states, Nature (London) **594**, 195 (2021).

[28] S. Chen, A. Bouhon, R. J. Slager, and B. Monserrat, Non-Abelian braiding of Weyl nodes via symmetry-constrained phase transitions, Phys. Rev. B **105**, L081117 (2022).

[29] F. N. Ünal, A. Bouhon, and R.-J. Slager, Topological Euler class as a dynamical observable in optical lattices, Phys. Rev. Lett. **125**, 053601 (2020).

[30] T. Iadecola, T. Schuster, and C. Chamon, Non-Abelian braiding of light, Phys. Rev. Lett. **117**, 073901 (2016).

[31] X.-L. Zhang, F. Yu, Z.-G. Chen, Z.-N. Tian, Q.-D. Chen, H.-B. Sun, and G. Ma, Non-Abelian braiding on photonic chips, Nat. Photonics **16**, 390 (2022).

[32] V. Neef, J. Pinske, F. Klauck, L. Teuber, M. Kremer, M. Ehrhardt, M. Heinrich, S. Scheel, and A. Szameit, Three-dimensional non-Abelian quantum holonomy, Nat. Phys. **19**, 30 (2023).

[33] P. Törmä, Essay: Where can quantum geometry lead us?, Phys. Rev. Lett. **131**, 240001 (2023).

[34] P. Törmä, S. Peotta, and B. A. Bernevig, Superconductivity, superfluidity and quantum geometry in twisted multilayer systems, Nat. Rev. Phys. **4**, 528 (2022).

[35] T. Liu *et al.*, Quantum geometry in condensed matter, Natl. Sci. Rev. **12**, nwae334 (2024).

[36] T. Ozawa and B. Mera, Relations between topology and the quantum metric for Chern insulators, Phys. Rev. B **104**, 045103 (2021).

[37] Y. Onishi and L. Fu, Fundamental bound on topological gap, Phys. Rev. X **14**, 011052 (2024).

[38] S. Peotta and P. Törmä, Superfluidity in topologically nontrivial flat bands, Nat. Commun. **6**, 8944 (2015).

[39] Z. C. F. Li *et al.*, Flat band Josephson junctions with quantum metric, Phys. Rev. Research **7**, 023273 (2025).

[40] C. W. Chau *et al.*, Disorder-induced delocalization in flat-band systems with quantum geometry, arXiv:2412.19056.

[41] C. Chen Ye, W. L. Vleeshouwers, S. Heatley, V. Gritsev, and C. Morais Smith, Quantum metric of non-Hermitian Su-Schrieffer-Heeger systems, Phys. Rev. Res. **6**, 023202 (2024).

[42] J. Maciejko and S. Rayan, Hyperbolic band theory, Sci. Adv. **7**, eabe9170 (2021).

[43] M. Hu, J. Lin, and K. Ding, Unveiling non-Hermitian spectral topology in hyperbolic lattices with non-Abelian translation symmetry, arXiv:2412.05607.

[44] A. J. Kollár, M. Fitzpatrick, and A. A. Houck, Hyperbolic lattices in circuit quantum electrodynamics, Nature (London) **571**, 45 (2019).

[45] W. Zhang, H. Yuan, N. Sun, H. Sun, and X. Zhang, Observation of novel topological states in hyperbolic lattices, Nat. Commun. **13**, 2937 (2022).

[46] A. Chen *et al.*, Hyperbolic matter in electrical circuits with tunable complex phases, Nat. Commun. **14**, 622 (2023).

[47] C. W. Hsu, B. Zhen, A. Douglas Stone, J. D. Joannopoulos, and M. Soljačić, Bound states in the continuum, Nat. Rev. Mater. **1**, 16048 (2016).

[48] J. Von Neumann and E. Wigner, Über merkwurdige diskrete Eigenworte, Phys. Z. **30**, 465 (1929).

[49] B. Zhen, C. W. Hsu, L. Lu, A. Douglas Stone, and M. Soljačić, Topological nature of optical bound states in the continuum, Phys. Rev. Lett. **113**, 257401 (2014).

[50] W. Liu, W. Liu, L. Shi, and Y. Kivshar, Topological polarization singularities in metaphotonics, Nanophotonics **10**, 1469 (2021).

[51] S. Joseph, S. Pandey, S. Sarkar, and J. Joseph, Bound states in the continuum in resonant nanostructures: An overview of engineered materials for tailored applications, Nanophotonics **10**, 4175 (2021).

[52] M. Kang, T. Liu, C. T. Chan, and M. Xiao, Applications of bound states in the continuum in photonics, Nat. Rev. Phys. **5**, 659 (2023).

[53] D. Wang, Z. Liu, H. Wang, M. Li, L. Jay Guo, and C. Zhang, Structural color generation: From layered thin films to optical metasurfaces, Nanophotonics **12**, 1019 (2023).

[54] W. Liu, H. Ma, and A. Walsh, Advance in photonic crystal solar cells, Renew. Sustain. Energ. Rev. **116**, 109436 (2019).

[55] S. Fan and W. Li, Photonics and thermodynamics concepts in radiative cooling, Nat. Photonics **16**, 182 (2022).

[56] K. Hirose, Y. Liang, Y. Kurosaka, A. Watanabe, T. Sugiyama, and S. Noda, Watt-class high-power, high-beam-quality photonic-crystal lasers, Nat. Photonics **8**, 406 (2014).

[57] M. Yoshida, S. Katsuno, T. Inoue, J. Gelleta, K. Izumi, M. De Zoysa, K. Ishizaki, and S. Noda, High-brightness scalable continuous-wave single-mode photonic-crystal laser, Nature (London) **618**, 727 (2023).

[58] L. Yang, G. Li, X. Gao, and L. Lu, Topological-cavity surface-emitting laser, Nat. Photonics **16**, 279 (2022).

[59] M.-A. Miri and A. Alù, Exceptional points in optics and photonics, Science **363**, eaar7709 (2019).

[60] E. J. Bergholtz, J. C. Budich, and F. K. Kunst, Exceptional topology of non-Hermitian systems, Rev. Mod. Phys. **93**, 015005 (2021).

[61] K. Ding, C. Fang, and G. Ma, Non-Hermitian topology and exceptional-point geometries, Nat. Rev. Phys. **4**, 745 (2022).

[62] J. Wiersig, Review of exceptional point-based sensors, Photonics Res. **8**, 1457 (2020).

[63] R. Lin, T. Tai, L. Li, and C. H. Lee, Topological non-Hermitian skin effect, Front. Phys. **18**, 53605 (2023).

[64] K. Zhang, Z. Yang, and C. Fang, Universal non-Hermitian skin effect in two and higher dimensions, Nat. Commun. **13**, 2496 (2022).

[65] W. Wang, M. Hu, X. Wang, G. Ma, and K. Ding, Experimental realization of geometry-dependent skin effect in a reciprocal two-dimensional lattice, Phys. Rev. Lett. **131**, 207201 (2023).

[66] F. Guan, X. Guo, K. Zeng, S. Zhang, Z. Nie, S. Ma, Q. Dai, J. Pendry, X. Zhang, and S. Zhang, Overcoming losses in superlenses with synthetic waves of complex frequency, Science **381**, 766 (2023).

[67] M. A. Bandres, S. Wittek, G. Harari, M. Parto, J. Ren, M. Segev, D. N. Christodoulides, and M. Khajavikhan, Topological insulator laser: Experiments, Science **359**, eaar4005 (2018).

[68] Y. Zeng *et al.*, Electrically pumped topological laser with valley edge modes, Nature (London) **578**, 246 (2020).

[69] A. Dikopoltsev *et al.*, Topological insulator vertical-cavity laser array, Science **373**, 1514 (2021).

[70] K. Takata, K. Nozaki, E. Kuramochi, S. Matsuo, K. Takeda, T. Fujii, S. Kita, A. Shinya, and M. Notomi, Observing exceptional point degeneracy of radiation with electrically pumped photonic crystal coupled-nanocavity lasers, Optica **8**, 184 (2021).

[71] B. Zhu, Q. Wang, D. Leykam, H. Xue, Q. J. Wang, and Y. D. Chong, Anomalous single-mode lasing induced by nonlinearity and the non-Hermitian skin effect, Phys. Rev. Lett. **129**, 013903 (2022).

[72] M. M. Asgari, P. Garg, X. Wang, M. S. Mirmoosa, C. Rockstuhl, and V. Asadchy, Theory and applications of photonic time crystals: A tutorial, Adv. Opt. Photonics **16**, 958 (2024).

[73] Emanuele Galiffi *et al.*, Photonics of time-varying media, Adv. Opt. Photonics **4**, 014002 (2022).

[74] E. Lustig, O. Segal, S. Saha, C. Fruhling, V. M. Shalaev, A. Boltasseva, and M. Segev, Photonic time-crystals: Fundamental concepts, Opt. Express **31**, 9165 (2023).

[75] F. Wilczek, Quantum time crystals, Phys. Rev. Lett. **109**, 160401 (2012).

[76] H. Watanabe and L. Lu, Space group theory of photonic bands, Phys. Rev. Lett. **121**, 263903 (2018).

[77] J. Bae *et al.*, Cavity quantum electrodynamics of photonic temporal crystals, arXiv:2501.03106.

[78] H. Xue, Y. Yang, and B. Zhang, Topological acoustics, Nat. Rev. Mater. **7**, 974 (2022).

[79] X. Zhang, F. Zangeneh-Nejad, Z.-G. Chen, M.-H. Lu, and J. Christensen, A second wave of topological phenomena in photonics and acoustics, Nature (London) **618**, 687 (2023).

[80] J. Lu, W. Deng, X. Huang, M. Ke, and Z. Liu, Non-Hermitian topological phononic metamaterials, Adv. Mater. 2307998 (2023).

[81] L. Huang *et al.*, Acoustic resonances in non-Hermitian open systems, Nat. Rev. Phys. **6**, 11 (2024).

[82] M. Yang and P. Sheng, Acoustic metamaterial absorbers: The path to commercialization, Appl. Phys. Lett. **122**, 260504 (2023).

[83] W. Ma, Z. Liu, Z. A. Kudyshev, A. Boltasseva, W. Cai, and Y. Liu, Deep learning for the design of photonic structures, Nat. Photonics **15**, 77 (2021).

[84] P. R. Wiecha, A. Arbouet, C. Girard, and O. L. Muskens, Deep learning in nano-photonics: Inverse design and beyond, Photonics Res. **9**, B182 (2021).

[85] W. Ji *et al.*, Recent advances in metasurface design and quantum optics applications with machine learning, physics-informed neural networks, and topology optimization methods, Light **12**, 169 (2023).