PHOTONICS Research

Introduction to non-Hermitian photonics in complex media: PT-symmetry and beyond

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This special issue is dedicated to the emerging field of non-Hermitian photonics of complex media, with emphasis on PT-symmetric optical structures. In particular, the papers highlight the variety of applications being considered and the ways in which non-Hermitian optics can improve their performance.

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The beginning of the 21st century in photonics could reasonably be characterized as marking a seismic shift in the goals and methodology of optical research. Whereas previous centuries were focused on figuring out the limitations of what light can be made to do, the new century is marked by discovering how to circumvent all those limitations through the design of novel materials. The metamaterials revolution that began in the year 2000 can be viewed as the turning point, in which it became recognized that it was not only possible to design materials which can possess almost any optical properties imaginable, such as a negative refractive index, but that new phenomena and applications were made possible by such materials, such as superlenses [1–4].

The manipulation of gain and loss in a balanced way, including but not limited to parity-time (PT) symmetry, is a relative newcomer to this revolution in optical design. PT symmetry was first introduced in quantum mechanics by Bender and Boettcher [5], and in that context it already unraveled preconceived constraints on its field. Because quantum observables, such as energy, are required to have real eigenvalues to correspond to "real" quantities, it had long been assumed that the operators associated with those observables must be Hermitian [6–8]. In the case of the time-independent Schrödinger equation, this in turn implied that the quantum potential must be real-valued. This simultaneously satisfied another fundamental condition on solutions to the Schrödinger equation: that probability must be conserved. But Bender and Boettcher showed that a potential with a spatially symmetric real part and an antisymmetric imaginary part—symmetric under inversion of parity and time—could also have real eigenvalues and conservation of probability (do you mean quasi-probability?) under certain conditions. Strikingly, they also showed that the PT symmetry, and its appealing characteristics, can be spontaneously broken by changing a parameter of the potential beyond a critical threshold. This represents an effective phase transition in the system's eigenvalue spectrum that immediately suggests application in switchable devices. Closely related to the concept of PT-symmetry is also the notion of exceptional points, where eigenvalues and eigenvectors coalesce for some critical values of the parameters [9–12]. The two different phase regimes of unbroken symmetry with real spectrum and broken symmetry with complex spectrum are separated in the parameter space by an exceptional point.

It took about a decade for the concept of PT symmetry to make its way into optics theoretically [13–15] and experimentally [16,17]. In this case, the real and imaginary parts of the potential are replaced by the real and imaginary parts of the refractive index. PT symmetry in optics, then, represents a material system with a spatially symmetric real part of the refractive index and a spatially anti-symmetric imaginary part of the refractive index [13–15]. This latter condition automatically implies that there is a balanced distribution of loss (positive imaginary part) and gain (negative imaginary part) in the system [16,17]. It was soon demonstrated that PT symmetric waveguides exhibit a phase transition based on the value of the gain amplitude, and that the response of PT symmetric systems can show behavior that may be loosely referred to as "nonreciprocal", or more accurately asymmetric, such as a system being perfectly transmitting from one direction of illumination and strongly scattering, yet perfectly transmitting, from the opposite direction.

Since that early work, parity-time symmetry, as well as more general configurations of balanced gain and loss, has led to a plethora of experimental implementations with various promising applications [18–34].

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It should be noted that the early studies of PT symmetry were restricted to monochromatic excitations, much like the earliest metamaterial studies that did the same. In general, it has been shown that optical structures with dispersion can be truly PT symmetric only for discrete frequencies; however, this does not mean that the generalized gain-loss distributions at other frequencies are not of interest. In the first paper of this feature issue, the effect of dispersion is taken into account in one-dimensional non-Hermitian optical heterostructures, and exceptional points and phase transitions of the system are identified. It is noted that a structure that is on average lossy may nevertheless amplify an incident wave at the appropriate frequency.

The reduction of dispersion is the goal in one of the invited papers of this special issue. Three approaches are given for producing a flat band in an optical lattice, and such flat bands can play an important role in light localization.

Gain media have obviously played a crucial role in the development of lasers, and it is almost natural to wonder how more general gain–loss configurations will change their operation; two papers contributed to this issue show that very different laser systems stand to benefit. In one of these, a surface-emitting circular Bragg laser is designed with a radial non-Hermitian structure. By working with a chirped radial structure instead of layers of equal radial thickness, the authors produce more versatile modal discrimination and control over azimuthal output modes. In the other paper on PT symmetry and lasers, the authors demonstrate the ability to switch from a bistable PT symmetric lasing state to a single mode broken symmetry state through the use of a cross-coupling element, without a need to change the gain or loss properties directly.

Non-Hermitian systems also show promise for improving ultrasensitive sensors, as is demonstrated in the second invited article that investigates the use of a pair of whispering gallery resonators, a PT-symmetric dimer, as a nanoparticle sensor. By driving their sensor right at the phase transition point of PT-symmetry, the author demonstrates a significant increase in sensitivity as well as a narrower linewidth due to the presence of gain. This study shows the feasibility of PT-symmetric whispering gallery resonators as practical nanoparticle or biomolecule sensors.

PT-symmetric dimers arranged in a circular “necklace” configuration are investigated in another article in this issue, and the symmetry properties of the resulting ring are studied in detail. Among the noteworthy results of this research is the observation that the symmetry properties of the system can be changed by adjusting the phase properties of the input field. The authors suggest that such necklaces could find use as output port replicators.

Non-Hermitian systems can also find use in quantum optical applications, as the final paper in this special issue shows. The generation of photon pairs via spontaneous parameteric down-conversion is investigated in a pair of coupled waveguides with different amounts of loss, with the asymmetric loss replacing the traditional gain-loss configuration. The control of loss in one of the waveguides provides a new degree of control over the state of output entangled photons in the system.

Though it arguably started as a physical curiosity, the field of non-Hermitian photonics has advanced to the stage where its principles can be incorporated into an impressively diverse number of optical systems and applications, and they are showing novel effects and improvements of performance overall. These articles serve to highlight the recent advances that have already been made and hint at possibilities to come.

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