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Some Perspectives on Non-Hermitian Metamaterials and Metasurfaces

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Abstract

Originally inspired by quantum-physics concepts such as parity-time symmetry, non-Hermitian metastructures characterized by spatially modulated distributions of loss and gain are eliciting a growing attention in optics and photonics. Within this framework, contrary to conventional wisdom, losses are not considered as second-order, detrimental effects to be minimized or compensated for, and their interplay with gain is instead instrumental for engineering unconventional light-matter interaction effects. Here, we compactly review some recent developments and perspectives in this fascinating research area.

1 Introduction

In electromagnetics engineering, losses are naturally considered an unavoidable, detrimental effect to be mitigated. Accordingly, material constituents exhibiting gain (e.g., semiconductors, dyes, quantum dots) are typically utilized to compensate for their presence. However, the emergence of new concepts and ideas originated in quantum physics, such as the parity-time (PT) symmetry [1], has recently changed this traditional perspective, suggesting fundamentally different interaction mechanisms. These concepts have resonated in many disciplines, generating a steadily increasing interest in the physics of non-Hermitian systems [2].

In view of the well-known formal analogies, non-Hermitian concepts can be translated to electromagnetic scenarios by means of spatial modulation of loss and gain [3], which is becoming technologically viable at various frequencies, ranging from microwaves to optics. Besides the inherent academic interest from the fundamental-physics side, thinking of losses in a "positive" acceptation brings about new dimensionalities and perspectives in the engineering of metamaterials and metasurfaces, by broadening the constitutive-parameter design space to the entire complex plane.

In what follows, we review some recent results and emerging ideas in this research area, originating from a series of ongoing collaborations with other research groups. Specifically, we focus on non-Hermitian doping of epsilon-near zero media, extreme-parameter non-Hermitian metamaterials, and "line-waves" in PT-symmetric metasurfaces.

2 Summary of Recent Results and Emerging Ideas

2.1 Non-Hermitian Doping of Epsilon-Near Zero Media

Recently, the concept of "doping" has been translated from solid-state-physics to two-dimensional photonic scenarios in connection with epsilon-near-zero (ENZ) host media, showing that it is possible to obtain a broadly tunable effective magnetic response (ranging from perfectly magnetic conductor to epsilon-and-mu-near-zero), by introducing a single, non-magnetic doping particle at an arbitrary position [4]. In an ongoing collaboration with Prof. Nader Engheta (University of Pennsylvania, USA), we have put forward a possible extension of the photonic-doping concept to non-Hermitian scenarios characterized by suitably tailored distributions of gain and loss either in the doping particles or the host medium [5, 6]. In these scenarios, the resulting effective permeability can be tailored over broad regions of the complex plane. This enables a variety of exotic electromagnetic responses and novel waveguiding mechanisms, which can be in principle reconfigured by varying the optical gain (e.g., via optical pumping). For instance, it is possible to attain sensible signal amplification in conjunction with near-zero reflection or transmission, and to enhance/control the waveguiding at a gain-loss interface [7, 8], while operating in the presence of small gain-loss levels.

2.2 Extreme-Parameter Non-Hermitian Metamaterials

Within the framework of a related collaboration, we have been exploring the properties of multilayered metamaterials composed of constituent layers alternating loss and gain. Via simple homogenization models based on conventional mixing formulae (e.g., Maxwell-Garnett), loss and gain may perfectly compensate, giving rise to *real-valued* effective parameters, which, in the epsilon-near-zero limit, may reach *extreme* (very large or small) values [9]. This yields extremely anisotropic responses that can enable the propagation of high-wavenumber modes of particular interest for sub-wavelength imaging. We highlight that this mechanism differs fundamentally from that observed in hyperbolic metamaterials, and is induced by the opposite-signed imaginary (rather than real) parts of the permittivities. We have also explored nonlocal (i.e., spatial dispersion) effects, which are not accounted for in conventional homogenization approaches, but may significantly affect the electromagnetic response in this type of structures [10]. Moreover, we have also addressed possible practical implementations in terms of realistic gain materials [11], and are currently exploring potential applications to nano-lasers and high-resolution imaging.

2.3 Line-Waves in Parity-Time-Symmetric Metasurfaces

It was recently shown, theoretically [12] and experimentally [13], that planar surface-impedance discontinuities with opposite-signed reactances can support one-dimensional waves that are bound both in-plane and out-of-plane around the discontinuity. These "line-waves" are of great interest for a variety of applications ranging from integrated photonics to sensing and switching. In collaboration with Prof. Andrea Alù's Group (ASRC-CUNY, USA), we are exploring the non-Hermitian extension of this concept [14]. By extending to a PT-symmetric scenario the analytic theory developed in [15], we have identified the conditions in the complex-impedance plane for such a phenomenon to occur. These non-Hermitian line waves may be interpreted as the one-dimension analog of the surface waves supported at gain-loss interfaces [7, 8]. We are currently exploring possible applications to reconfigurable waveguides and lasing, as well as practical implementations based on photoexcited graphene [16].

3 Conclusions

We have reviewed some recent results and new ideas in the emerging field of non-Hermitian metamaterials and metasurfaces. Expected outcomes from these studies may define new pathways in the exploitation of the delicate loss-gain interplay to leverage new functionalities in electromagnetic metastructures. In particular, novel guiding and radiating structures exhibiting abrupt state transitions may be conceived, and new unusual propagation effects may be engineered, with potential applications to lasing, nanophotonics, sensing and high-resolution imaging.

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