PHOTONICS INSIGHTS

A journey through bound states in the continuum in periodic optical structures

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Bound states in the continuum (BIC) were first identified by von Neumann and Wigner[1] almost a century ago. At that time, they pointed out an intriguing phenomenon: a state could be bound by a special oscillating potential distribution, even when the state's energy is higher than the maximum of the potential. According to the principles taught in elementary quantum mechanics, the energy of such a state should lie within the continuum spectrum; thus it is referred to a bound state in the continuum. In the past two decades, thanks to advancements in fabrication technology, this counterintuitive phenomenon has been intensively investigated and extended to various kinds of classical wave systems[2–4]. According to the non-existence theorem[5], a system sustaining a BIC must be periodic in at least one direction unless materials with extreme parameters (i.e., $\varepsilon, \mu = 0$ or ∞) are chosen[6,7]. Periodicity along with the flexibility, tunability, and rich application prospects of optical systems make periodic optical structures an excellent platform for exploring BICs.

The recently published review article[8] by Wang *et al.* presents a systematic categorization and summary of the mechanisms, physical effects, and applications of BICs in periodic optical structures. Additionally, the review identifies several promising future research directions. The review is logically organized, guiding readers from the fundamental physical mechanisms of BICs to their effects and practical applications. The authors meticulously connect each section, ensuring smooth transitions and maintaining a coherent narrative throughout the review. Overall, this review can serve as a navigational beacon for researchers in this field and provide significant inspiration at the same time.

A merit of this review is its in-depth understanding of the physical mechanisms of BICs. The same physical phenomenon can be interpreted from alternative directions. Rather than adopting a single perspective, this review provides a multifaceted view of the origins of BICs in periodic optical systems. The discussion begins by explaining the physical mechanisms of BICs using an effective non-Hermitian Hamiltonian to address radiation loss in an open system within the Friedrich-Wintgen (FW) framework. This review shows that three types of BICs—original FW BIC, symmetry-protected BIC, and accidental BIC—in periodic optical systems can all be captured by the general FW mechanism[9]. In addition to the FW mechanism, this review also compares the benefits and drawbacks of exploring BICs using either plane-wave or Bloch-wave bases[10,11], highlighting the unique advantages of rigorous derivation or effective computation from these two perspectives. The advantages of choosing a proper basis are further enriched by discussing the multipolar perspective[12,13], which explains the radiation properties of BICs through local source interference and multipole expansion.

A substantial proportion of recent studies in this field rely on the topological characteristics of BICs. This review provides a comprehensive definition of the topological numbers typically used to characterize BICs. Subsequently, the review highlights the topological characteristics of BICs[14], offering insights into the unique contribution of topology to the formation mechanisms of BICs. An essential parameter in defining the topology of BICs is the number of radiation channels. The review also includes an analysis of multiple radiation channels[11,15] beyond the diffraction limit, illustrating how these channels influence the creation and stability of BICs. Such a multidimensional analysis allows readers to appreciate the intricate and diverse nature of BICs.

After elucidating the physical mechanisms of BICs, the review naturally progresses to the intriguing effects enabled by BICs. The topological characteristics of BICs enable their robust evolution in optical systems exhibiting certain symmetries. By tuning structural parameters or system symmetry, many evolutionary behaviors of BICs (or C points that can be created by breaking the BICs) under the topological charge conservation law[14] are reviewed, such as merging BICs, splitting BICs, higher-order topological charges, and unidirectional guided resonance (UGR). As a complete review, this work also discusses the situation of quasi-BICs[16] that emerge when a system slightly deviates from the BIC conditions. Various types of quasi-BICs are fully elucidated, including those achieved by engineering structural symmetries, quasi-BICs in photonic quasicrystals and moiré photonic structures, miniaturized BICs in finite-sized photonic crystal slabs, and chiral quasi-BICs. The rich physical effects of optical field confinement and ultranarrow linewidth control are discussed subsequently.

The topological characteristics of BICs provide new degrees of freedom for light manipulation. The nontrivial winding phases surrounding BICs facilitate vortex light generation,

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optical spin-orbit interactions, coherent polarization conversion, and topological optical force distribution. The high-Q characteristics of BICs have also been adopted to enhance light–matter interaction, achieving strong coupling between optical modes and excitons, promoting polariton formation, and enabling polariton Bose-Einstein condensate[17].

With the intriguing effects of BICs being identified, the review continues with BIC-related applications. In this section, the practical applications and benefits of BIC properties are explored. The utilization of BICs achieves optical cavities with very large Q factors (infinite for ideal BICs with no intrinsic loss), significantly reducing the lasing thresholds. Photonic crystal surface-emitting lasers (PCSELs)[18], as an important type of laser, are an ideal platform to exhibit the unique advantages of BICs in periodic optical systems. Key events that contribute to high-performance PCSELs are listed in the review. The topological properties of BICs also enable beam pattern modulation, facilitating vortex and chiral beam lasers. Additionally, the ultranarrow linewidth of BICs makes them highly sensitive to environmental perturbations, enabling sensing with high precision for refractive index and chirality changes[19]. These sensing schemes are promising for environmental monitoring and medical diagnostics.

In the conclusion section, the review provides a comprehensive summary of the entire text. Additionally, this section introduces and classifies optical measurement systems such as band measurement and Q factor measurement. The inclusion of experimental setups is a notable and unique feature of this review, especially as it provides theoretical researchers with valuable insights into how BICs in periodic optical systems are characterized. Furthermore, this review offers a visionary and forward-looking outlook on the future of BIC research, discussing potential physical mechanisms, effects, and potential applications in periodic optical systems.

Overall, the review by Wang *et al*. provides a comprehensive and accessible understanding of BICs, with a detailed classification and clear description of existing works on periodic structures. In particular, the discussion of physical mechanisms from multiple perspectives is commendable and highly inspiring for readers. The discussion on the effects and applications is complete and accurate. It offers unique views on future innovations and research directions. The review also provides an extensive list of references, showcasing its comprehensive nature and thoroughness. The references are meticulously organized and clearly cited, allowing readers to easily trace back the original sources for further reading. This thorough citation practice not only adds credibility to the review but also serves as a valuable resource for researchers looking to explore specific aspects of BICs in more detail.

In summary, this review is a valuable contribution to the field, providing detailed insights into the physical mechanisms, effects, and applications of BICs in periodic optical structures. Its comprehensive scope, in-depth analysis, and visionary outlook make it an ideal resource for researchers and scholars interested in or intending to engage in related research.

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