Symmetry protected and accidental bound states in the continuum in photonic-crystal structures, studied by the resonant-state expansion

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The resonant state expansion (RSE) is a novel rigorous method for calculating resonant states (RSs) of a photonic system [1]. These are the eigensolutions of Maxwell's wave equation (MWE) with outgoing boundary conditions. Using a complete set of the RSs of a simpler system as a basis, the RSE makes a mapping of the MWE onto a linear eigenvalues problem, determining the full set of the RSs of a complex system.

In addition to higher numerical efficiency [2,3] compared to other computational methods, the RSE provides an intuitive physical picture of resonant phenomena, capable of explaining features observed in optical spectra. So far, the RSE has been applied to finite open optical systems of different geometry and dimensionality, as well as to homogeneous and inhomogeneous planar waveguides [3]. Very recently, the RSE was generalized to magnetic, chiral and bi-anisotropic optical systems [4], enabling its further application to metamaterials. The RSE has also been used in first perturbation order for photonic crystal (PC) structures to describe sensing of the refractive index by a periodic array of plasmonic nano-antennas [5].

Very recently, we have developed a photonic-crystal RSE (PC-RSE) [6], a new rigorous approach to accurately calculate the RSs of planar PC systems, using a homogeneous slab as a basis system and treating the PC structure as a periodic modulation on top of the slab, see the inset in Fig.1. The periodicity of PC structures mixes all possible Bragg harmonics. Therefore, the basis RSs have to be taken with different in-plane wave numbers. As a result, the Green's function of MWE acquires branch cuts in the complex frequency plane, which must be taken into account in the PC-RSE along with the RSs. This presents the major complication of the PC-RSE which we have dealt with by splitting the cuts into a series of discrete, artificial cut states added for completeness to the basis of RSs, similar to what has been done in [3]. Using, for illustration, a dielectric slab periodically modulated in one direction, we demonstrate the accuracy and efficiency of the PC-RSE for finding the RSs of photonic crystals.

We use the advantages of the PC-RSE, namely its high efficiency and accuracy, as well as the analytical form of the eigenmode expansion, to study the origin of the optical modes of a PC system and their evolution with structural and material parameters, such as the period d, the thickness $2b$ of the periodic layer, and the permittivity contrast β, see Fig.1 and illustrations provided in [6]. This allows us to reveal the role of different basis states of the homogenous dielectric slab in the formation of the eigenmodes of the PC slab. We show in particular that the guided modes have the dominant contribution to the symmetry protected bound states in the continuum (BICs) and to high-quality (high-Q) quasi-guided modes (QGMs). We also study the contribution of different basis states to other types of modes, such as Fabry-Perot, leaky and cut modes.

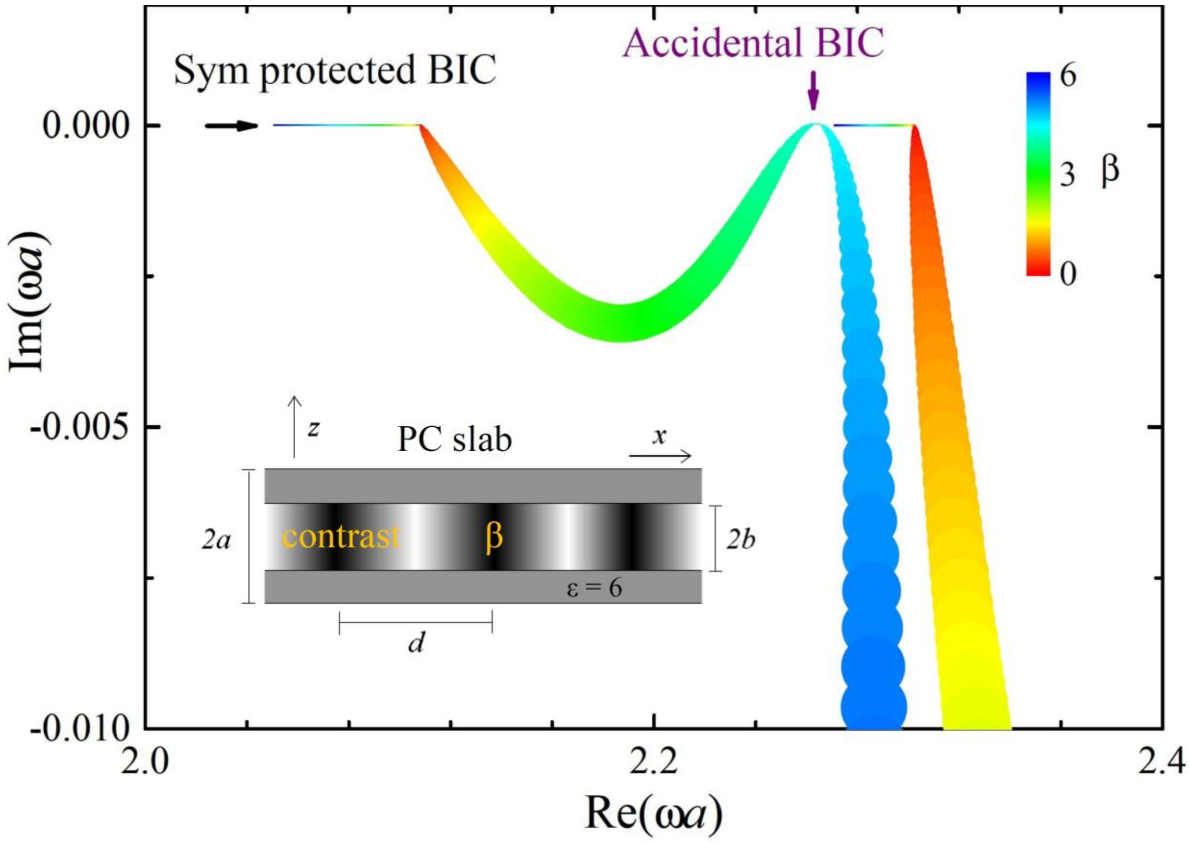

Figure 1: Evolution of the RSs of a PC slab (sketched in the inset) with the contrast β (color coded) of the periodic modulation of the permittivity of a homogenous dielectric slab with permittivity ε=6. The center of the circle shows the position of the RS frequency, while its area is proportional to the 0^{th} Bragg channel contribution to the wave function. A doubly degenerate fundamental guided mode splits into a BIC-QGM pair. The BIC in this pair is protected by symmetry, having for any β a strictly vanishing contribution of the 0^{th} Bragg channel. The evolution of the QGM is going through an accidental BIC.

We focus in this work on both symmetry protected and accidental BICs. Figure 1 demonstrates both types of BICs, tracing the evolution of the fundamental guided mode of a homogeneous slab with increase of the periodic modulation contrast β. Being doubly degenerate by symmetry at β=0 (no modulation), the guided mode splits for nonzero β into a symmetry-protected BIC and a quasi-guided mode (QGM), the latter having a high but finite Q-factor. These two modes are further separated as β increases. However, as can be seen in Fig. 1, for a certain value of β, the QGM transforms into an accidental BIC with an infinite Q factor. This transformation is accompanied by a morphological change of the wave function, which is further investigated and discussed in this work.

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