Quality factor enhancement in photonic crystal slabs by manipulation of the ring of exceptional points

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***Abstract*—Presently, we investigate the influence of the extent of a ring of exceptional points on the Q-factor of three-dimensional photonic crystal slabs. By changing the thickness of the slab, the extent of the ring of exceptional points is varied, allowing us to recover the Dirac cones in open, non-Hermitian systems. In this case, three bound states in the continuum are exhibited close to the Γ-point. For an optimized thickness of the slab, the associated Q-factors are found to grow rapidly with the size of the slab. The present results may lead to novel, small area and high Q-factor photonic crystal surface-emitting lasers.**

Keywords—exceptional point, Dirac point, small area high Q-factor PhC lasers,

I. Introduction

Photonic crystals (PhCs) can exhibit accidental Dirac cones of linear dispersion [1]. Considered PhCs are periodic arrangements of circularly shaped air-holes following square lattice, where a is a lattice constant. These configurations provide a well-established platform for studying topological properties of Dirac cones. It has been shown that Dirac cones are deformed in non-Hermitian system, e.g. open systems which exhibit radiation losses, resulting in creation of rings of exceptional points [2]. The real and imaginary parts of the eigenvalues coalesce at an exceptional point (EP) [3]. The real parts of the eigenfunctions create a two-dimensional flat band within the ring. This band provides a high density of states. Moreover, strong dispersion of the imaginary part close to the Γ-point allows to considerably improve the performance of large-area single mode PhC lasers [4]. Furthermore, Dirac points have been shown to be related to bound states in the continuum (BICs) [5]. BICs are solutions of wave equation that are perfectly confined despite being inside the continuum of unbounded modes. They are characterized by an infinite Q-factor.

Presently, we investigate the influence of the extent of a ring of EPs on the Q-factor of a 3D PhC slab. It is found that the extent of the ring of EPs can be reduced and Dirac cone can be recovered in open, non-Hermitian system by changing thickness of the slab. This leads to considerable reduction in the radiation losses, and thus to the enhancement of the Q-factor. The Q-factor is found to rapidly increase with size of the slab when its thickness is optimized. This is the result of all three BICs being exhibited in vicinity of the Γ-point. These results may lead to new designs of low threshold lasers.

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II. Configurations

All computations in this work were performed numerically in COMSOL Multiphysics, version 5.2a. It uses finite element method and eigenfrequency solver was used in our calculations. In our investigations, two models have been employed; they are depicted in Fig. 1.

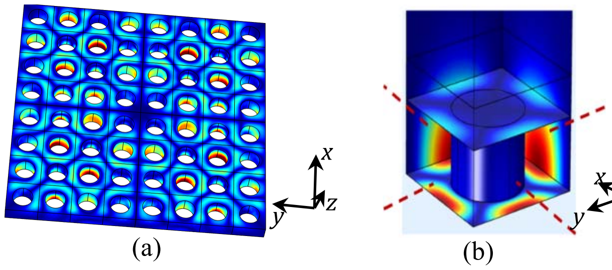

Fig. 1. (a) Unit cell of the PhC slab of finite thickness, h, with depicted amplitude of the H_z for a non-degenrate mode at the Dirac point (b) 3D model of a PhC slab of finite thickness, h, with circular air-holes embedded in air with dimensions $8a$ x $8a$. Amplitude of the H_z of the highest Q mode is depicted.

The configurations are investigated under the transverse-electric-like (TE-like) polarization; out-of-plane component of the magnetic field intensity (the H-field), H_z, and in-plane components of the electric field intensity (the E-field), E_x, E_y, are present. The models are terminated with perfect magnetic conductor boundary condition in the middle of the thickness to enforce TE-like polarization. Fig. 1(a) shows the 3D model of the PhC slab of finite thickness, h, consisting of a square lattice with dimensions $8a$ x $8a$ of circular air-holes introduced in a dielectric material, $\varepsilon_d = 10.05$. The slab is submerged in air and perfectly matched layer terminates the computational domain imitating infinite environment. The simplified model, which is considered at first, is shown in Fig. 1(b). It is a unit cell of the PhC slab of finite thickness, h. It is terminated with periodic boundary conditions in the x and y directions.

III. Results

Firstly, a 2.5D model of the PhC slab, see Fig. 1(a), is considered. This is a non-Hermitian system because of an open boundary in the z direction. We have varied the thickness of the slab and for each case the air-hole size has been adjusted to ensure the Dirac-like dispersion at the Γ-point. Particularly, we observed that for varying thickness of the slab, the extent of the ring of EPs varies periodically, see

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Figs. 2 (a) and (b). Moreover, the Dirac cone exhibited by a 2D unit cell of a PhC (Hermitian system) is recovered for a specific thickness of the slab, see Fig. 2(b). As the thickness approaches an optimal value equal to the effective wavelength in the slab, the imaginary parts of the eigenvalues become negligibly small, as shown in Fig. 2 (c) and (d). It leads to significant reduction of radiation losses and the system begins to behave approximately as a Hermitian system.

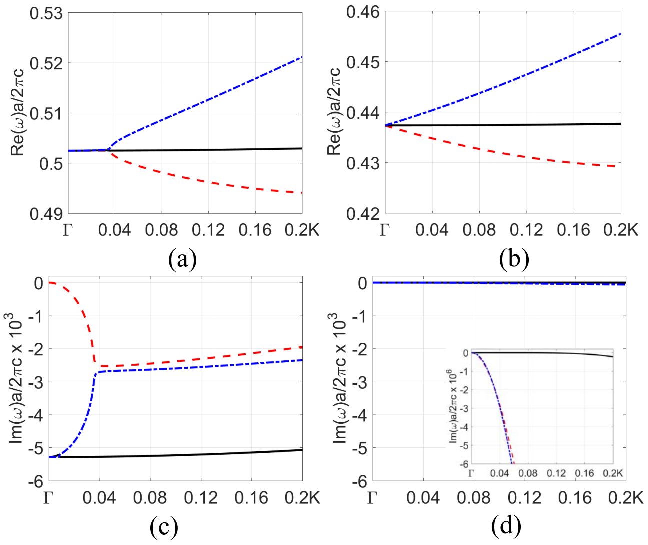

Fig. 2. Real (a), (b) and imaginary (c), (d) parts of eigenvalues plotted versus in-plane wavenumber, k, in Γ-K direction of the PhC slab with a finite thickness h = 250nm (a), (c) and h = 711.3nm (b), (d), respectively. Inset in (d), shows the data in Fig. 2 (d) multiplied by a factor of 10^3.

Fig. 2 illustrates that the imaginary (real) part of the eigenvalue is dispersive and non-degenerate inside (outside) the ring of EPs. At one of the points the imaginary and the real parts are identical. This is an EP and a ring of EPs is formed around the Γ-point because the air-hole exhibits rotational symmetry. As the imaginary parts become negligibly small, the flat band crossing the Dirac point exhibits very high out-of-plane Q-factors over a broad range of in-plane wavenumbers, k, see Fig. 3 (a) and (b), where the Q-factors are plotted in dB, $10log_{10}(Q)$. In Fig. 3(a) it is seen that only one of the bands exhibits BIC at the Γ-point. This is a symmetry-protected BIC, which is always found at the Γ-point.

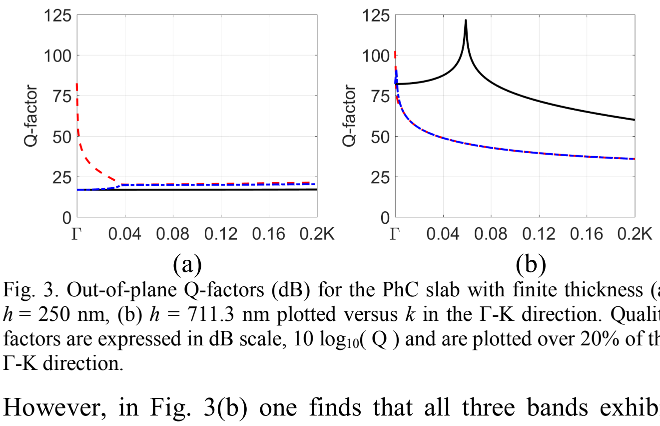

Fig. 3. Out-of-plane Q-factors (dB) for the PhC slab with finite thickness (a) h = 250 nm, (b) h = 711.3 nm plotted versus k in the Γ-K direction. Quality factors are expressed in dB scale, 10 $\log_{10}$(Q) and are plotted over 20% of the Γ-K direction.

However, in Fig. 3(b) one finds that all three bands exhibit BICs very close to the Γ-point. Furthermore, it is observed that the Q-factor is higher than 60 dB over 20% of the Γ-K direction for the flat band crossing Dirac point. This is an extraordinarily high value, especially bearing in mind that for the 250nm-thick slab, the Q-factor has reached 80dB only at the BIC. Moreover, the band is characterized by a very low group velocity as it is flat. This leads to small in-plane losses, and thus high in-plane Q-factors. These results are exploited in the design of small area, high Q-factor PhC slabs.

We next consider the 3D model of the PhC slab shown in Fig. 1(a). Table 1 presents the highest Q-factor values in the frequency range of the Dirac cones for the PhC slabs of various sizes and the two thicknesses considered above. It is found that the Q-factors rise rapidly with the size of the slab when its thickness is optimized and equals the effective wavelength. On the other hand, when the slab is 250nm-thick, hundreds of unit cells would be needed to satisfy the constructive interference condition very close to the Γ-point and exploit the symmetry-protected BIC [6].

TABLE I

THE HIGHEST Q-FACTOR IN THE FREQUENCY RANGE OF THE DIRAC CONES FOR THE PHC SLABS OF VARIOUS SIZES AND THICKNESSES.

	250nm	711.3nm
4*a* x 4*a*	60	260
6*a* x 6*a*	90	420
8*a* x 8*a*	110	1100
10*a* x 10*a*	130	1100
12*a* x 12*a*	150	2600

We have found that the extent of the ring of EPs is connected to the presence of the BICs close to the Γ-point. The extent of the ring can be reduced and Dirac cone can be recovered in open, non-Hermitian system by varying thickness of the slab. This results in reduction of radiation losses and significant enhancements of the Q-factor. It is found to rapidly increase with size of the slab when the thickness is optimized. The present results may lead to interesting small area and high Q-factor photonic crystal surface-emitting lasers.

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