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Bound state in the continuum in 1D chain of dielectric disks: theory and experiment

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Abstract. In this work we experimentally observe a symmetry protected optical bound state in the continuum (BIC) with zero angular momentum in 1D array of ceramic disks at GHz frequencies. We analyze the dependence of Q factor of BIC on the number of the disks and the level of the material losses. We confirmed theoretical prediction about quadratic growth of the Q factor with the number of the disks and its following saturation due to material losses.

1. Introduction

It is well known that the spectrum of a dielectric waveguide consists of the guided and leaky modes. Usually, the leaky modes are unwanted since they result in considerable losses and, therefore, hinder the operation of optical devices. However, the radiation losses can be totally canceled. In this case, we have a bound state embedded in the radiation continuum. The simplest way to cancel the radiation losses and get *bound state in the continuum* in a slab or cylindrical waveguide is to periodically modulate their permittivity along the direction of the translation symmetry. The periodicity discretises the number of open (diffraction) channels and makes them finite at each frequency. By choice of the proper design of the unit cell it is possible to make all amplitudes of (diffraction channels) outgoing waves equal to zero. This mechanism is analyzed in details in [1, 2, 3].

First, the concept of BIC was proposed in quantum mechanics in 1929 by E. Wigner and J. von Neuman [4]. In optics, it has been actively studied over the last 10 years. The significant results were achieved for this short period. It was shown that BICs are very prospective for many applications from lasing [5, 6], and filtering [7, 8] and biosensing [9, 10]. The latest achievements in physics of BIC are reviewed in [11].

To date, BICs in 1D periodic arrays were considered only theoretically in spite of these system are very prospective for generation of light with orbital angular momentum. In this work, we demonstrate first experimental observation and provide detailed analysis of BICs in 1D axially symmetric finite array of dielectric scatterers.

2. Sample and Setup

As an experimental sample we use an array of disks fabricated from BaO-TiO₂ microwave ceramic with the permittivity of $\varepsilon=40$ at GHz frequencies. The radius and the height of the disks are $D=10.2$ mm and $h=10.1$ mm, respectively. The period of the array is $L=15.1$ mm.



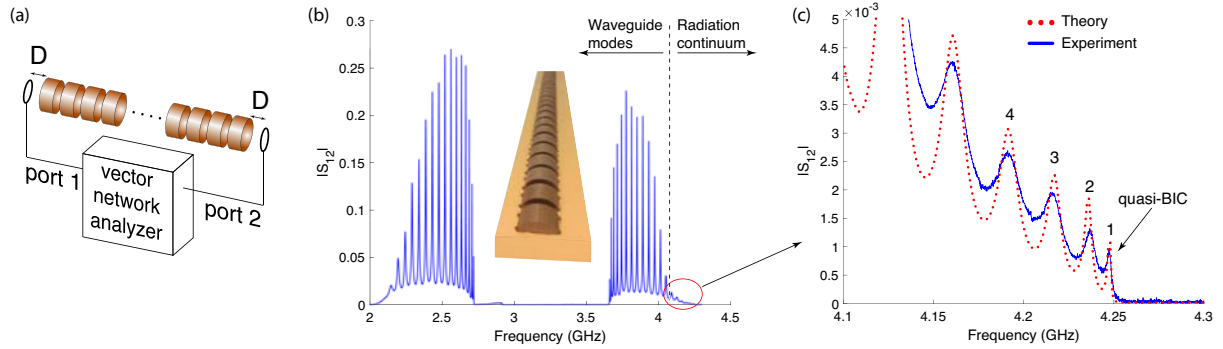


Figure 1. (a) Experimental setup for measurements of transmission spectra through the 1D array of dielectric disks. (b) Spectrum of S_{12} amplitude. The insets shows the experimental sample. (c) Zoomed part of panel (b) showing the resonances in the transmission spectra corresponding to leaky modes.

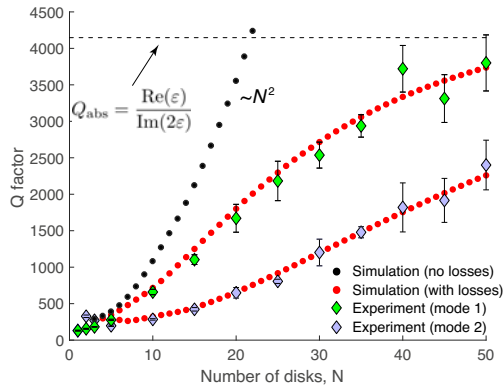


Figure 2. Experimental measured dependence of Q factors of the symmetry protected quasi-BIC (mode 1) and the neighbour resonance (mode 2) on the number of the period N in the chain of ceramics disks. Numeration of the resonances is shown in Fig. 1(c). Dotted line shows the results of numerical simulation in Comsol Multiphysics.

To fix the disks a custom holder with groves was fabricated from a styrofoam material with a permittivity close to 1.1 at the microwave frequencies. The refractive indexes of the holder is close to the refractive index of air that justifies a neglecting of effect of substrate onto the BIC. The fabricated prototype is shown in the inset of Fig. 1(b).

To analyse the resonances of the system, we measure its transmission spectra S_{12} . Here we focus on BIC with zero angular momentum. Thus, to avoid excitation of the states with nonzero angular momentum we use two identical shielded-loop antennas placed concentric with the axis of the array [see Fig. 1(a)]. Both antennas were connected to the ports of the vector network analyser (VNA). The shielded-loop antennas with the outer diameter of 10 mm have been fabricated from 086 Semi-rigid Coax Cable. The antennas have been placed at the distance 5 mm away from the edges. This distance is enough to provide a weak coupling with the array and not distort Q factors of the resonances.

3. Results

The transmission spectra $|S_{12}|$ of the array consisting of 20 disks placed between two loop antenna is shown in Fig. 1(b). The vertical dashed line separates regions of true leaky resonances and quasi-guided modes, which turn into guided modes as number of disks N tends to infinity. One can see that amplitude of the leaky resonances is much less that one of the quasi-guided modes. Figure 1(c) shows zoomed part of Fig. 1(b). The red dotted line shows the results of the simulation carried out in Comsol Multiphysics. The last peak in the series (with the highest frequency) corresponds to quasi-BIC, which turns into symmetry protected BIC as $N \rightarrow \infty$.

The simulated dependence of its Q factor on the N in absence of material losses is shown in Fig. 2 by black dotted lines. We found that $Q \sim N^2$ at small number of disks and then Q saturates due to material losses. The maximal Q factor can be estimated as $Re(\varepsilon)/Im(2\varepsilon)$. The dependance of Q factor on N for two last resonances extracted from the experimental spectra is shown in Fig. 2 by green and blue squares. The experimental results are in good agreement with the results of the simulations.

4. Conclusions

We report the first experimental observation of the symmetry protected BIC in 1D periodic array of dielectric scatterers. We analyze the dependence of Q factor of quasi-BIC on the number of the disks in the array. We observe quadratic growth of Q with N at small number of the disks and following saturation at the level $Q_{max} = Re(\varepsilon)/Im(2\varepsilon)$ at N of several tens.

Acknowledgments

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