Quasi-bound States in the Continuum in a Finite Chain of Dielectric Scatterers: Theory and Experiment

M. Balyzin[1], **Z. Sadrieva**[1], **M. Belyakov**[1],
P. Kapitanova[1], **A. Sadreev**[2], **and A. A. Bogdanov**[1]

[1]Department of Nanophotonics and Metamaterials, ITMO University, Saint-Petersburg, Russia
[2]Kirensky Institute of Physics, Federal Research Center KSC SB RAS, Krasnoyarsk, Russia

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 a dielectric rod or slab supports waveguide modes formed under the condition of total internal refection from the waveguide boundaries [1]. The wave numbers of the waveguide modes lie under the light line of the surrounding space making them orthogonal to the radiation continuum. When the dispersion curve crosses the frequency cut-off, the waveguide mode turns into a leaky mode (resonant states) [1]. However, recently it was acknowledged that introduction of periodic modulation of the refractive index along the axis of the rod or slab discretises the radiation continuum, and this could result in complete suppression of radiation losses for leaky modes [2, 3]. Therefore, the resonant state becomes localized, i.e., totally decoupled from the radiation continuum. Such localized solutions are known as *bound states in the continuum* (BICs) [4, 5]. Recently, the immense progress in handling photonic crystals encouraged extensive studies on BICs in various periodic photonic structures [2, 6–10]. These studies are predominantly motivated by potential applications to resonant enhancement [11–14], lasing [15, 16], filtering of light [17, 18] and biosensing [19, 20].

Among variety of the considered designs of photonic structures, the one-dimensional arrays of spheres or disks are peculiar because of the rational symmetry. It gives rise to existence of BICs with predefined angular momentum. In the scattered spectra such a state manifest itself as a scattered field with orbital angular momentum travelling along the array [2, 21–23]. This could be used for generation of *twisted light* and, therefore, for optomechanical manipulations [24], quantum cryptography, and other applications [25]. Theory of BICs in the one-dimensional arrays of spheres and disks is developed in Refs. [3, 26] but, in spite of a variety of potential applications, experimental study is not presented for today.

In this work we report first experimental study of BICs in 1D axially symmetric array of dielectric scatterers. We study transformation of the resonant state into symmetry protected BIC with increase the number of the scatterers by measurement of the transmission characteristic of the chain.

2. TRANSMISSION SPECTRA

The polarization of the mode with $m = 0$ is divided into TE and TM. Therefore, they can be selectively excited via near field by axially symmetric antennas placed coaxially with the chain. The TM modes can be excited by electric dipole antenna, and the TE modes can be excited by magnetic dipole antenna. Since the analyzed symmetry protected BIC is a TE-mode, in the experiment we use two identical shielded-loop antenna [27] placed coaxially with the chain and connected to ports of the vector network analyzer [see Fig. 1(a)]. The antennas with the outer diameter of 10 mm have been fabricated from 086 Semi-rigid Coax Cable. They are placed at the distance $D = 5$ mm away from the faces of the first and last disks. Such a distance provides a weak coupling regime between the antennas and the chain providing making the analysis of the Q factor of the quasi-BIC relevant.

The transmission spectra of the array of 20 disks placed between two loop antenna is shown in Fig. 1(b). Two transmission bands consisting of 20 resonance peaks each are clearly seen. A weak signal at frequencies 2.7–2.9 GHz corresponds to the modes with $m = 1$, which are excited due to non-perfect axial symmetry of the sample. The resonances laying in the green area in Fig. 1(b) corresponds to the waveguide modes of the infinite chain and the resonances in the grey corresponds the leaky modes at the infinite cahin. The intensity of the leaky resonances in the transmission spectrum is very weak because of poor localization and radiative losses. Panel (b) in Fig. 1 shows the zoomed transmission spectra in the region of leaky modes. The blue solid line is the experimental data and the red dotted line is the results of numerical simulation carried out in Comsol Multiphysics. Fig. 1 shows clearly that the width of the last peak in the series is the most narrow. This peak corresponds to quasi-BIC, which transforms into a true BIC as $N \to \infty$.

Each transmission spectra with a fixed number of the disks is measured five times. After each measurement, the disks are extracted from the holder and shuffled. The experimental dependence of the Q factor for two last resonances in the series [see mode 1 and mode 2 in Fig. 1(c)] on the number of the disks is shown in Fig. 2 with rhombus markers. The error bars show the standard deviation in the Q factors. The dotted lines correspond to the simulation. One can see that for small N, when the radiative losses are dominant, the Q factor increases quadratically. However,

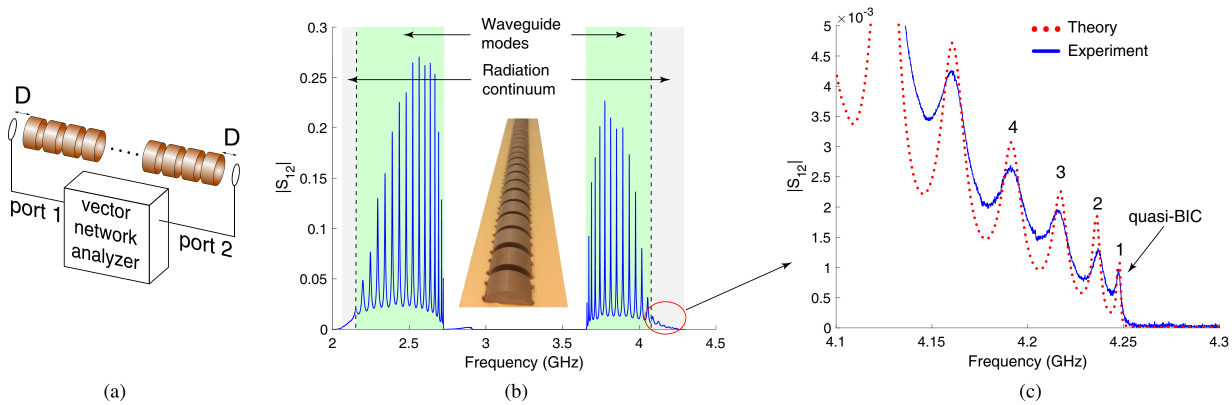

Figure 1: (a) Scheme of the experimental setup for measurement of the transmission trough the chain of the ceramics disks. (b) Transmission spectra of the chain consisting of 20 ceramics disks placed between two coaxially positioned loop antennas. The parameters of the chain is following: permittivity of the ceramic disks is $\varepsilon = 40$, radius of the disks $R = 10.2$ mm and their thickness $h = 10.1$ mm, period of the chain is $L = 15.1$ mm. The green and grey areas correspond to waveguide and leaky modes, respectively. The inset shows the photo of the sample. (c) Zoomed-in view of the transmission spectra shown in panel (b). The dotted line shows the results of numerical simulations carried out in Comsol Multiphysics. The last peak in the series corresponds to quasi-BIC.

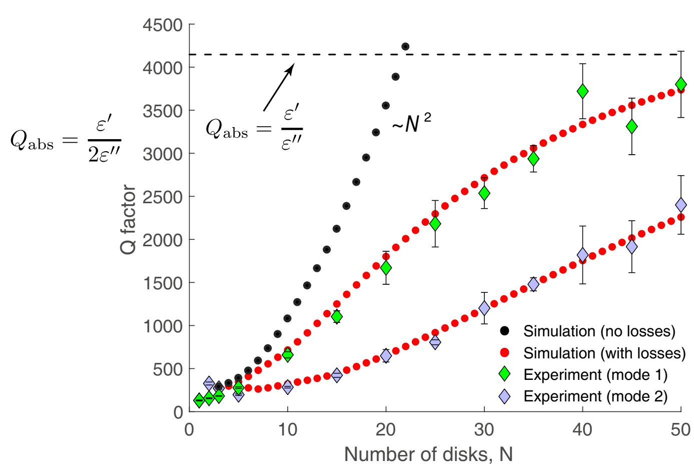

Figure 2: Experimental measured dependence of Q factors of the symmetry protected quisi-BIC (mode 1) and the neighboring resonance (mode 2) on the number of the period N in the chain of ceramics disks. Error bars indicate the standard deviation in the Q factor extracted from the transmission spectra measured five times. After the each measurement, the disks are extracted from the holder and shuffled. Dotted line shows the results of numerical simulation in Comsol Multiphysics.

the deviation from the quadratic behavior becomes essential as $N \sim 20$. Further increase of the number of the disks results in saturation of the total Q factor to the level $Q_{\text{abs}} = \varepsilon'/\varepsilon''$. It is clear that the lower the material losses the bigger number of scatterers necessary to take in order is needed to suppress the radiative losses of quasi-BIC with respect to the material absorption. The analyzed chain of the ceramics disks with $\tan\delta = 2.4 \times 10^{-4}$ behaves as an infinite one when the number of the disks is more than 50.

3. CONCLUSION

We presented the first report of experimental observation of the symmetry protected BIC in the linear array of periodically arranged ceramic disks. Due to the Styrofoam material of the cuvette with permittivity close to an air the system turns out to be close to the system considered in [26] with however a few important aspects which makes difference between theory and experiment. The first aspect is a finite number of disks which altogether with material losses and structural fluctuations brings on agenda a concept of quasi BICs as resonant states with very high Q factor. The measurement of this Q factor was a subject of the paper. The second aspect is related to overlapping of eigenmode subbands of the array which belong different OAM with $m = 0, 1, 2$. That aspect complicates direct observation of quasi BICs in scattering of plane waves as was considered in theory [28]. Nevertheless we are going to resume such kind of experiments for another more favorite choice of disks lengths. However observation of the non symmetry protected BICs with OAM is our high priority.

ACKNOWLEDGMENT

This work was supported by the Russian Foundation for Basic Research (16-37-60064, 17-02-01234, 16-02-00314), the Ministry of Education and Science of the Russian Federation (3.1668.2017/4.6), the President of Russian Federation (MK-403.2018.2).

REFERENCES

1. Adams, M. J., *An Introduction to Optical Waveguides*, Vol. 14, Wiley, New York, 1981.
2. Bulgakov, E. N. and A. F. Sadreev, "Bloch bound states in the radiation continuum in a periodic array of dielectric rods," *Phys. Rev. A*, Vol. 90, No. 5, 053801, 2014.
3. Bulgakov, E. N. and A. F. Sadreev, "Light trapping above the light cone in a one-dimensional array of dielectric spheres," *Phys. Rev. A*, Vol. 92, No. 2, 023816, 2015.
4. Von Neumann, J. and E. P. Wigner, "Über merkwürdige diskrete eigenwerte," *The Collected Works of Eugene Paul Wigner*, 291–293, Springer, 1993.
5. Fonda, L. and G. C. Ghirardi, "Properties of the bound states embedded in the continuum," *Ann. Phys.*, Vol. 26, No. 2, 240–246, 1964.
6. Shipman, S. P. and S. Venakides, "Resonant transmission near nonrobust periodic slab modes," *Phys. Rev. A*, Vol. 71, No. 2, 026611, 2005.
7. Marinica, D., A. Borisov, and S. Shabanov, "Bound states in the continuum in photonics," *Phys. Rev. Lett.*, Vol. 100, No. 18, 183902, 2008.
8. Hsu, C. W., B. Zhen, J. Lee, S.-L. Chua, S. G. Johnson, J. D. Joannopoulos, and M. Soljacić, "Observation of trapped light within the radiation continuum," *Nature*, Vol. 499, No. 7457, 188, 2013.
9. Sadrieva, Z. and A. Bogdanov, "Bound state in the continuum in the one-dimensional photonic crystal slab," *J. Phys. Conf. Ser.*, Vol. 741, No. 1, 012122, IOP Publishing, 2016.
10. Sadrieva, Z. F., I. S. Sinev, K. L. Koshelev, A. Samusev, I. V. Iorsh, O. Takayama, R. Malureanu, A. A. Bogdanov, and A. V. Lavrinenko, "Transition from optical bound states in the continuum to leaky resonances: Role of substrate and roughness," *ACS Photonics*, Vol. 4, No. 4, 723–727, 2017.
11. Magnusson, R. and S. Wang, "New principle for optical filters," *Appl. Phys. Lett.*, Vol. 61, No. 9, 1022–1024, 1992.
12. Zhang, M. and X. Zhang, "Ultrasensitive optical absorption in graphene based on bound states in the continuum," *Sci. Rep.*, Vol. 5, 8266, 2015.
13. Mocella, V. and S. Romano, "Giant field enhancement in photonic resonant lattices," *Phys. Rev. A*, Vol. 92, No. 15, 155117, 2015.
14. Yoon, J. W., S. H. Song, and R. Magnusson, "Critical field enhancement of asymptotic optical bound states in the continuum," *Sci. Rep.*, Vol. 5, 18301, 2015.

15. Kodigala, A., T. Lepetit, Q. Gu, B. Bahari, Y. Fainman, and B. Kanté, "Lasing action from photonic bound states in continuum," *Nature*, Vol. 541, No. 7636, 196, 2017.
16. Bahari, B., F. Vallini, T. Lepetit, R. Tellez-Limon, J. Park, A. Kodigala, Y. Fainman, and B. Kante, "Integrated and steerable vortex lasers using bound states in continuum," *Bulletin of the American Physical Society*, 2018.
17. Foley, J. M., S. M. Young, and J. D. Phillips, "Symmetry-protected mode coupling near normal incidence for narrow-band transmission filtering in a dielectric grating," *Phys. Rev. A*, Vol. 89, No. 16, 165111, 2014.
18. Cui, X., H. Tian, Y. Du, G. Shi, and Z. Zhou, "Normal incidence filters using symmetry-protected modes in dielectric subwavelength gratings," *Sci. Rep.*, Vol. 6, 36066, 2016.
19. Romano, S., S. Torino, G. Coppola, S. Cabrini, and V. Mocella, "Optical sensors based on photonic crystal: A new route," *Optical Sensors 2017*, Vol. 10231, 102312J, International Society for Optics and Photonics, 2017.
20. Liu, Y., W. Zhou, and Y. Sun, "Optical refractive index sensing based on high-q bound states in the continuum in free-space coupled photonic crystal slabs," *Sensors*, Vol. 17, No. 8, 1861, 2017.
21. Bulgakov, E. N. and D. N. Maksimov, "Light guiding above the light line in arrays of dielectric nanospheres," *Opt. Lett.*, Vol. 41, No. 16, 3888–3891, 2016.
22. Yuan, L. and Y. Y. Lu, "Propagating bloch modes above the lightline on a periodic array of cylinders," *J. Phys. B — At. Mol. Opt.*, Vol. 50, No. 5, 05LT01, 2017.
23. Hu, Z. and Y. Y. Lu, "Propagating bound states in the continuum at the surface of a photonic crystal," *JOSA B*, Vol. 34, No. 9, 1878–1883, 2017.
24. Padgett, M. and R. Bowman, "Tweezers with a twist," *Nat. Photonics*, Vol. 5, No. 6, 343, 2011.
25. Torres, J. P. and L. Torner, *Twisted photons: Applications of light with orbital angular momentum*, John Wiley & Sons, 2011.
26. Bulgakov, E. N. and A. F. Sadreev, "Bound states in the continuum with high orbital angular momentum in a dielectric rod with periodically modulated permittivity," *Phys. Rev. A*, Vol. 96, No. 1, 013841, 2017.
27. Whiteside, H. and R. King, "The loop antenna as a probe," *IEEE T. Antenn. Propag*, Vol. 12, No. 3, 291–297, 1964.
28. Bulgakov, E. N. and A. F. Sadreev, "Bound states in the continuum with high orbital angular momentum in a dielectric rod with periodically modulated permittivity," *Phys. Rev. A*, Vol. 96, No. 1, 013841, 2017.