Scattering spectra of dielectric ring: microwave experiments

Nikolay Solodovchenko a) and Mikhail Sidorenko
Department of Physics and Engineering, ITMO University, Saint Petersburg 197101, Russia

a)E-mail: n.solodovechenko@metalab.ifmo.ru

Abstract. In recent years, dielectric ring resonators (RRs) have become an essential part of integrated optical circuits. This determines the growing interest in the study of the fundamental electromagnetic properties of these objects, which is far from complete. In particular, in the literature it is difficult to find information about light scattering spectrum, which should demonstrate a strong resonance character when the probe wavelength is comparable to the geometric dimensions of the RR, taking into account its dielectric constant. In this work, we present the results of an experimental study of the electromagnetic properties of a dielectric RR in the microwave range of the spectrum. The results of numerical calculations of the scattering spectrum are also presented, which demonstrate excellent agreement with the experimental data. In addition to the expected resonance character of the spectrum, we report the effects of strong light confinement, which are associated with Fano resonances between the eigenmodes and the component of the electromagnetic field scattered by the ring.

1. Introduction
Dielectric ring stands out among the most important structural elements of modern photonics, along with the sphere and the cylinder [1]. First of all, a RR is distinguished as the main element of an add-drop filter, on which modern integrated optical circuits are based [2, 3]. However, along with their use in optoelectronic devices, dielectric rings are a classical object of fundamental research. It should be noted that dielectric rings are used in a wide variety of areas of physics, among which the study of an interplay of two types of spontaneous symmetry breaking in optical RRs [4], strong nonlinear coupling in a Si3N4 RR [5], an observation of the multidimensional Purcell effect in an ytterbium-doped RR [6] and a generation of quantum-correlated photon pairs using electrically tunable ring resonators and passive Bragg reflectors [7] and many others.

Despite the great activity of researchers studying various effects associated with RR, as far as we know, neither the calculated nor experimentally measured spectra of light scattering by a dielectric ring in a wide spectral range were presented in the original articles or in reviews [3,8] or books [9]. Therefore, the goal of this work was to study experimentally the scattering spectra of electromagnetic waves from a dielectric ring in the far field, as well as to study the resonant eigenmodes of the ring using the near-field spectroscopy. The studies were carried out in the microwave spectral range, and taking into account the scaling of Maxwell's equations, the results obtained are valid for any spectral range.
2. Experimental setup
For our experiments, a RR was chosen with the dimensions of the inner diameter \( d = 93 \text{ mm} \) and the outer diameter \( D = 115 \text{ mm} \) and the height \( h = 7 \text{ mm} \) and was made of microwave ceramics. The average dielectric constant \(<\varepsilon>\) in the investigated frequency range (1-10 GHz) is 44. The radar cross-section (RCS) scattering measurements of the RR were performed in an anechoic chamber [10]. We use a rectangular horn antenna connected to a transmitting port of the vector network analyzer Rohde&Schwarz ZVB20 to approximate a plane-wave excitation. The transmitting antenna, fixed at the same level as the receiving antenna, illuminates the RR. The RR is located in the center of the measuring station on a stand made of polystyrene foam, interaction with which is neglected. It should be noted that the transmitting antenna is oriented so that the incident electric field is in the plane of the ring (TE polarization). The antennas are located at a distance of about 3 meters from the center.

In such an installation, both the magnitude and the phase are measured, which makes it possible to obtain a complex value of the electric field. To calculate the RCS of a ring, two measurements are needed: the electric field with the ring and empty space. Further, RCS is calculated by the optical theorem (Fig. 1).

The RR eigenmode sequence can be experimentally investigated in the near field. For operation in the near field, a radiating horn antenna is used, and a metal ring located close to the RR surface acts as a signal receiver, which fixes one component of the magnetic field at a given point in space. Thus, in three passes, you can get complete information (real and imaginary part) about the magnetic field near the RR surface (insert in Fig. 1).

![Figure 1. Experimental results of measurements of the RR in the far field (blue solid line) and numerical CST calculation for RR with a dielectric constant \( \varepsilon \) equal to 44 over the entire frequency range (orange solid line) of the ring resonator. The real part (a, d), imaginary part (b, e) and phase (c, f) of the z component of the magnetic field. Each insert (a-f) has its own intensity scale. The insert (g) is a photography of the sample](image)

3. Experimental observation of light trapping in dielectric ring
Among the results obtained, we highlight the experimental observation of the effect of light trapping in several relatively narrow regions of the investigated spectrum. The scattering spectrum shown in Fig. 1 consists of background scattering, the approximate level of which is marked by a green dashed straight line, a number of resonance bands of different widths and intensities, as well as several regions in which the level of scattered light decreases sharply and, in particular, drops to almost zero
in the 5 GHz frequency range. Since the incident electromagnetic wave is normalized in intensity over the entire spectral range, the absence of scattering means the capture of electromagnetic energy by the resonator at the corresponding frequencies. This effect can be associated with destructive interference in the far zone of two waves, one of which is associated with the intrinsic resonance of the ring, and the other with scattering at the ring as a whole. This effect is characteristic of the Fano resonance [10] observed in many of the simplest dielectric structures, in particular on a sphere [11] and a cylinder [12]. Another striking effect leading to the light confining by the resonant structure is bound states in the continuum (BIC) [13], which were also observed in the case of a separate dielectric cylinder [14]. However, the difference between the BIC regime and the effect observed in this work is that in the case of BIC, a sharp narrowing and decrease in the intensity of the resonance scattering line was observed, while in our case scattering does not occur at all.

The absence of scattered light when illuminating an object is equivalent to its invisibility. This phenomenon was studied theoretically earlier in the case of light scattering by a dielectric cylinder in the Fano resonance regime [15]. However, in this work, we succeeded to observe this phenomenon experimentally. Figure 1 shows the distribution of the electromagnetic field inside and around the ring obtained as a result of processing the experimental data: the spatial distribution of the real and imaginary magnetic components of the field and its phase for two frequencies - 4.75 and 5 GHz. It is clearly seen, especially by the example of the phase distribution, that the incident TE-polarized electromagnetic wave with a frequency of 5 GHz passes the ring practically without distortion, leaving the ring invisible from any angle of observation.

4. Conclusion
In this work, for the first time, as far as we know, an experimental study of light scattering by a dielectric ring was carried out. The far and near field scattering was investigated. In addition, the scattering spectra were calculated numerically, and excellent agreement between the calculated and experimental data was demonstrated.

The data obtained allow us to conclude that the eigenmodes of the dielectric ring are fundamentally different from the whispering gallery modes, since they do not form a quasi-equidistant sequence characteristic of the whispering gallery modes. In addition, we observed spectral regions in which there is no light scattering, that is, electromagnetic energy is confined by the resonator. This effect will be studied in detail in our next works.

Acknowledgments
The authors acknowledge fruitful discussions with Mikhail Limonov, Kirill Samusev, and Timur Seidov. This work was supported by the Russian Foundation for Basic Research (Grant No. 20-02-00785a).

References
[1] K. J. Vahala, *Nature* **424**, 839 (2003)
[2] A. Li and W. Bogaerts, *Laser Photonics Rev.* **13**, 1800244 (2019)
[3] P. Pintus, M. Hofbauer, C. L. Manganelli, M. Fournier, S. Gundavarapu, O. Lemonnier, F. Gambini, L. Adelmini, C. Meinhart, C. Kopp, F. Testa, H. Zimmermann, and C. J. Oton, *Laser Photonics Rev.* **13**, 1600219. (2019)
[4] F. Copie, M. T. M. Woodley, L. Del Bino, J. M. Silver, S. Zhang, and P. Del’Haye, *Phys. Rev. Lett.* **122**, 013905 (2019)
[5] S. Ramelow, A. Farsi, Z. Vernon, S. Clemmen, X. Ji, J. E. Sipe, M. Liscidini, M. Lipson, and A. L. Gaeta, *Phys. Rev. Lett.* **122**, 153906 (2019)
[6] D. Ding, L. M. C. Pereira, J. F. Bauters, M. J. R. Heck, G. Welker, A. Vantomme, J. E. Bowers, M. J. A. de Dood, and D. Bouwmeester, *Nat. Photonics* **10**, 385 (2016)
[7] N. C. Harris, D. Grassani, A. Simbula, M. Pant, M. Galli, T. Baehr-Jones, M. Hochberg, D. Englund, D. Bajoni, and C. Galland, *Phys. Rev. X* 4, 041047 (2014)

[8] W. Bogaerts, P. De Heyn, T. Van Vaerenbergh, K. DeVos, S. K. Selvaraja, T. Claeys, P. Duman, P. Bienstman, D. Van Thourhout, and R. Baets, *Laser Photonics Rev.* 6, 47 (2012)

[9] J. Heebner, R. Grover, T. Ibrahim, and T. A. Ibrahim 2008 *Optical microresonators: theory, fabrication, and applications* (New York: Springer Science & Business Media)

[10] C. Larsson, C. Sohl, M. Gustafsson, and G. Kristensson 2009 3rd European Conference on Antennas and Propagation (Berlin: IEEE) pp. 3633-3636

[11] M. F. Limonov, M. V. Rybin, A. N. Poddubny, and Y. S. Kivshar, *Nat. Photonics* 11, 543 (2017)

[12] M. I. Tribelsky and A. E. Miroshnichenko, *Phys. Rev. A* 93, 053837 (2016)

[13] M. V. Rybin, K. B. Samusev, I. S. Sinev, G. Semouchkin, E. Semouchkina, Yu. S. Kivshar, and M.F. Limonov, *Opt. Express* 21, 30107 (2013)

[14] C. W. Hsu, B. Zhen, A. D. Stone, J. D. Joannopoulos, and M. Soljačić, *Nat. Rev. Mater.* 1, 16048 (2016)

[15] A. A. Bogdanov, K. L. Koshelv, P. V. Kapitanova, M. V. Rybin, S. A. Gladyshev, Z. F. Sadrieva, K. B. Samusev, Y. S. Kivshar, and M. F. Limonov, *Adv. Photonics* 1, 016001 (2019)

[16] M. V. Rybin, D. S. Filonov, P. A. Belov, Yu. S. Kivshar, and M. F. Limonov, *Sci. Rep.* 5, 8774 (2015)