LETTERS TO THE EDITORS

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Once again about supercavity modes

(a response to the letter to the editors of *Physics–Uspekhi* from V V Klimov [*Phys. Usp.* **62** (10) 1058 (2019); *Usp. Fiz. Nauk* **189** (10) 1131 (2019)] with comments on the review by M V Rybin and M F Limonov "Resonance effects in photonic crystals and metamaterials" [*Phys. Usp.* **62** (8) 823 (2019); *Usp. Fiz. Nauk* **189** (8) 881 (2019)])

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Abstract. **In this letter, we demonstrate the fallacy of the provisions and conclusions set forth in the letter to the editors of *Physics–Uspekhi* by V V Klimov [*Phys. Usp.* 62 (10) 1058 (2019)]. The author discusses the review by M V Rybin and M F Limonov [*Phys. Usp.* 62 (8) 823 (2019)] and makes a number of conclusions that have nothing to do with the content of the review and the original work on which the review is based. Also, V V Klimov's conclusions contradict well-known data in the literature.**

Keywords: bound states in the continuum, supercavity modes, quality factor, destructive interference, avoided crossing of eigenmodes

From the editorial board. We give the opportunity to M V Rybin and M F Limonov, the authors of the review "Resonance effects in photonic crystals and metamaterials" [*Phys. Usp.* **62** (8) 823 (2019)], to respond to the criticism presented in V V Klimov's letter "On the existence of 'supercavity modes' in subwavelength dielectric resonators and their relation to bound states in the continuum." According to our practice, we consider further discussion on this topic in *Physics – Uspekhi* inappropriate.

Bound states in the continuum (BICs) are at present one of the intriguing fields in modern photonics widely discussed in the literature. We paid a special attention to this topic in our review "Resonance effects in photonic crystals and metamaterials," published in a special issue of *Physics – Uspekhi* devoted to the 100th anniversary of the Ioffe Institute. Among other literature on BICs, we presented our results with co-authors discussed in three papers [2 – 4] (references [78, 117, 120] in the review, respectively).

V V Klimov's letter to the editors, titled "On the existence of 'supercavity modes' in subwavelength dielectric resonators and their relation to bound states in the continuum," was published in the October issue of *Physics – Uspekhi* [5]. In this letter, the author calls erroneous our results and conclusions [1, 3, 4] concerning 'supercavity' modes. Prior to the main discussion, we will make two remarks. First, V V Klimov writes about our review [1] as if about an original paper in which we have found something and are proving something, although this is not the case. As is accepted in reviews, we only discuss the published results. Second, our key work [2], in which the term 'supercavity' mode is introduced and explained, is not cited in letter [5]. Figure 1 explains the sense of introducing a new concept: because a true BIC with the infinite Q factor cannot be implemented in real finite

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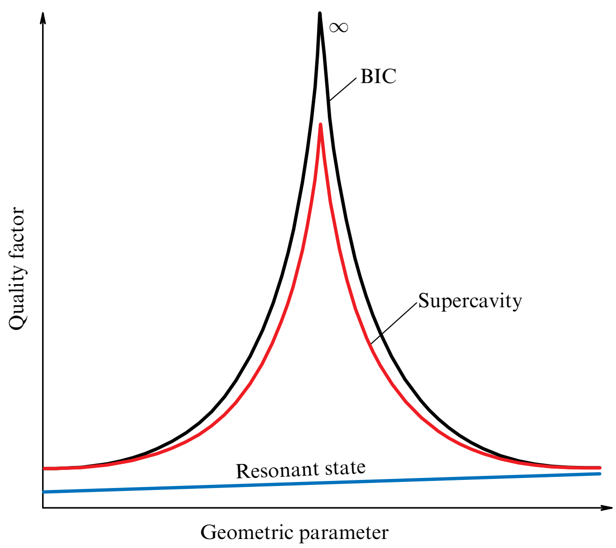

Figure 1. (Color online.) Relation between a true BIC, the supercavity mode, and a usual resonance state. The figure is similar to Fig. 1 from [2].

structures, its resonance analog observed in experiments and coinciding by the formation mechanism but having a finite Q factor was called a supercavity mode [2].

Consider point-by-point the erroneous statements of the author of letter [5].

1. V V Klimov's main error is that he assigns to us the conclusion about the discovery of *new* modes (which we called 'supercavity' modes) *additional to a standard set of the resonator eigenstates*: "It will be shown below that no new 'supercavity' modes were discovered in [10–12]", "the eigenvalues of modes are analytic functions of the resonator shape, and this does not allow one to talk about the appearance of new modes upon changing the shape of a subwavelength resonator (p. 1131)", "for real new modes to appear, a new resonator physics is required (p. 1132)", etc.

In reality, *certainly* we do not write about any additional modes. We studied in [3, 4] the eigenmodes of a finite dielectric cylinder, which are divided into Mie modes (determined by the side walls of the cylinder) and Fabry–Perot modes (determined by the flat ends of the cylinder). The different dependence of the modes of these two families on the aspect ratio r/l leads to numerous anticrossing regions (Fig. 9 in paper [4]) — a well-known effect for the strong coupling case. In the ranges of parameters r/l far from anticrossing regions, the high-frequency oscillations of each of the interfering pairs of Mie–Fabry–Perot modes are manifested as usual leaky modes and are observed in scattering spectra in the form of *broad intense bands* (lines in rectangles in Fig. 2b). Upon approaching an anticrossing region and, correspondingly, upon increasing the mode coupling, the high-frequency bands *narrow down a few orders of magnitude*, resulting in a resonance increase in the Q factor and a transition to the supercavity regime (Fig. 1). For example, for the cylinder permittivity $\varepsilon = 80$, the supercavity regime is observed for the high-frequency mode in a pair of anticrossing oscillations TE_{020} and TE_{012} for $r/l = 0.7$ (Fig. 2b and Fig. 3 in [3]), for a pair of anticrossing oscillations TE_{110} and TE_{111} for $r/l = 0.55$ (Fig. 3 in [4]), etc (Fig. 9 in [4]). In this case, the total number of cylinder eigenmodes remains, naturally, invariable for any values of the aspect ratio r/l. The appearance of *many* supercavity modes is caused by the *destructive interference* of a pair of leaky modes in the strong coupling regime (the anticrossing of two modes) described in [6] (reference [77] in reviews [1]). Such a mechanism of quasi-BIC appearance was observed in a number of papers (see review [7]).

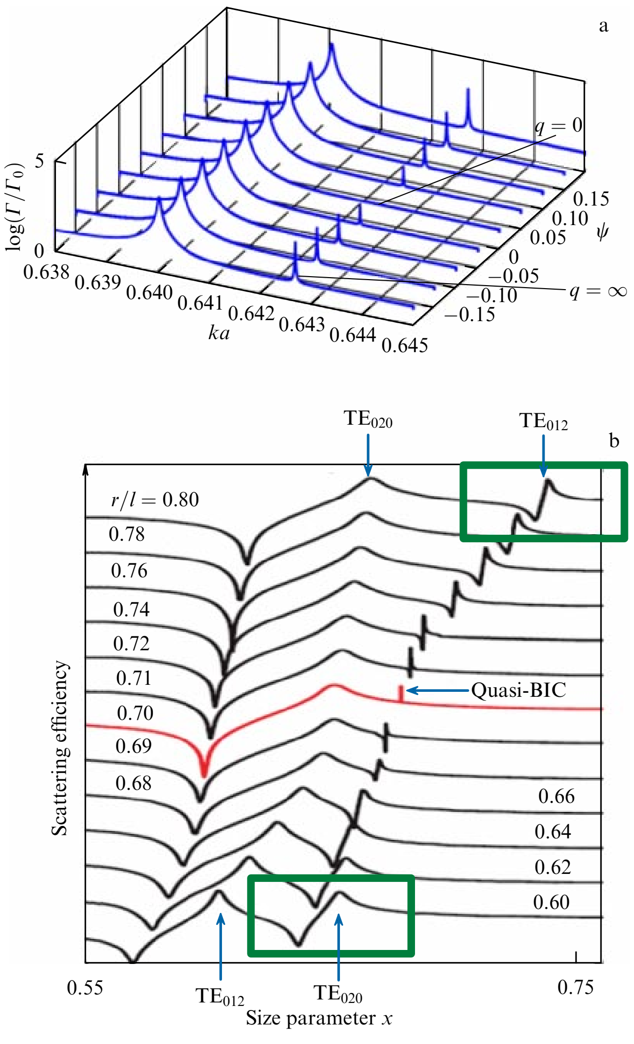

Figure 2. (Color online.) (a) Normalized radiation power of a dielectric sphere as a function of the orientation ψ of the exciting dipole for $\varepsilon = 80$ [5]. (b) Scattering spectra of a finite dielectric cylinder as a function of the structural parameter r/l for the invariable excitation geometry by a TE-polarized plane electromagnetic wave, $\varepsilon = 80$ [3].

2. The next error of the author of letter [5] is the statement that he himself thought up that the excitation conditions for scattering spectra in our papers were changed. We clearly pointed out in our papers that all the spectra in calculations [3, 4] and experiments [4] correspond to the same scattering geometry, namely, to the normal incidence of a plane wave on the side surface of a cylinder. Polarization was also the same for each set of spectra (in particular, the TE polarization was not changed for spectra in Fig. 2b). Having invented the situation with a change in the source orientation, V V Klimov writes: "The obvious fact that a change in excitation conditions can reduce the cross section to zero and lead to the 'vanishing' of modes is illustrated by the dependence of the normalized radiation power Γ/Γ_0 of a dielectric sphere with radius a on the orientation of the exciting dipole" (Fig. 1 in V V Klimov's letter [5] and Fig. 2a in this letter). It is difficult to argue with this conclusion; however, this calculation has no relation to our results. Nevertheless, it allows us to point out again an important feature of a supercavity mode. By comparing Figs 2a and 2b, one can clearly see that in the case of mode vanishing caused by a change in the source parameters its half-width does not change, unlike the linewidth, which demonstrates impressive changes in the supercavity regime.

3. In continuing his criticism, V V Klimov affirms: "in the case of a circular cylinder,... the eigenmodes should be characterized by the distribution of electromagnetic fields exponentially decaying at infinity" (p. 1131). This statement is also erroneous. A dielectric cylinder is an open optical system, as a resonator of any other form, but of a finite size. The fields of eigenmodes of open passive systems, as is well known [8, 9], in the general form diverge exponentially at infinity because of the nonzero imaginary part of the eigenfrequency, but not decrease as is stated in letter [5].

4. Then, the author of letter [5] discusses the Q factor value determined for the supercavity modes of a cylinder in our papers [3, 4] and compares it with the Q factor of modes in a dielectric sphere. It seems that V V Klimov has inattentively read our review, in which we emphasize on page 887: "It is important to emphasize that supercavity modes are not

resonances with an extremely high Q factor, but are modes appearing through a mechanism corresponding to the one appearing in BICs.''

5. The author [5, p. 113] writes: ''It is unlikely that the choice of a cylindrical resonator for searching for high-Q modes can be called fortunate because the presence of edges in the general case leads to the additional scattering of fields and a decrease in the Q factor.'' This statement is meaningless with respect to the subject of publications [2–4] on BICs. First, the Friedrich–Wintgen BIC appearance mechanism [6] represents the destructive interference of two leaky modes in the strong coupling regime and is not determined by the presence or absence of edges. Moreover, many photonic dielectric structures in which bound states in the continuum (more exactly, close to them, i.e., supercavity modes) were observed experimentally or in calculations are formed by cylinders [7]. This is explained, particularly, by the fact that, unlike spherical particles, cylindrical micro- and nanoobjects with a regular geometric shape can be manufactured using technological methods available at present. Structures considered in the literature in which quasi-BICs were observed include a system of cylindrical nanoresonators forming a square lattice [10], a photonic membrane with cylindrical holes (i.e., the structure of inverted cylinders [11]), a chain of dielectric cylinders [12], and a system of two parallel rows formed by cylinders [13].

Note in conclusion that we observed for the first time in [3, 4] the supercavity (quasi-BIC) regime in an isolated cylinder. It is for this reason that our papers attracted great attention and are often cited. At the same time, the main critical remarks presented in letter [5] either have nothing common with the content of our review [1] or the results of our original papers [3, 4] or are erroneous.

We thank our coauthors in papers [2–4] A A Bogdanov, Yu S Kivshar, K L Koshelev, and K B Samusev for discussing this letter.

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