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Super-resonances in a dielectric mesoscale sphere immersed in water: effects in extreme field localization of acoustic wave

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We predict acoustic super resonance modes with a field-intensity enhancement several tens of thousands of times higher (order of magnitude: 10^4 -10^5) with the support of dielectric mesoscale spheres submerged in water, by means of numerical simulations. The super resonances are related to the internal dispersion in specific values of both Mie and particle material parameters, being responsible for the generation of giant fields within the particles and near its surface. Taking into account the analogy between electromagnetic and acoustic waves, this phenomenon is valid in the electromagnetic (optical) wave band.

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1. Introduction

The phenomenon of photonic nanojet is now well known from the optical [1] and THz [2] bands; allow forming localized light in subwavelength area by scattering of light on low loss dielectric particle.

In acoustics, the scattering of sound from a spherical fluid obstacle of size comparable to a wavelength was considered in Refs. [3, 4]. It has been shown that the amplitude of the scattered wave in the backward direction from a fluid sphere of a few wavelengths diameter size, exceeds twice that from a rigid sphere of the same size when the relative sound velocity is 0.8 and the density is equal to that of the surrounding medium [4]. The focusing effect in sound scattered by a spherical balloon with large diameter filled with carbon dioxide was investigated in Refs. [5, 6].

Recently, it has been theoretically demonstrated for the first time [7, 8] that an existence of acoustic analogue of photonic jet phenomenon [9], providing for subwavelength localization of acoustic field in shadow area of arbitrary 3D penetrable mesoscale particle, is possible. It is important to note that the principle difference between optical and solid acoustical materials properties is a shear speed of sound, i.e. acoustic solid materials exhibits two speed of sound, a longitudinal one and a degenerated shear one even when they are isotropic. [10]. Therefore, the direct transfer of results from optics to acoustics will not be correct.

In our analysis of acoustojets phenomenon [7], in simulations we use the rigorous partial-wave expansion method [11], which depends on the beam-shape and scattering coefficients, to obtain the scattered pressure around the solid elastic spherical particle where both compressional and shear waves were taken into account. Simulations show [10] that for a 5λ radius sphere with relative refractive index of about 1.6, the acoustic jet remains under the diffraction limit by approximately few wavelengths in depth, with an intensity gain close to 20 dB relative to the incident intensity. Some of the examples of acoustojet by a homogeneous sphere made of lead; polyethylene and silver were illustrated and characterized according to subwavelength beam waist, intensity gain, and propagation depth.

The simulation, in first approximation, in the harmonic case was based on the Helmholtz equation [12]. It was demonstrated [12] that, the influence of the main parameters of dielectric penetrable spherical cavity immersed in water to transformation of Whispering Gallery Mode (WGM) into acoustojet (acoustic jets) by interaction of acoustic plane wave scatterer. For investigation of resonant scattering of ultrasound in dielectric spherical cavity immersed in water, we have selected Rexolite© as a material due to its impedance is not excessively different from that of water (the impedance of Rexolite is 1.62 times that of water) [13, 14].

The main parameters of Rexolite© are sound velocity 2337 m/s and density 1.04 g/cm^3. According to [12], the initial parameters of the particle near WGM resonance (sometimes also referred to as a morphology-dependent resonance) were selected as: radius of particle R=4λ (at frequency of 1 MHz in water), relative density contrast is 1.0402 and the speed of sound contrast is 1.570.

It could be noted that the effect of absorption in sphere material should lead to a decrease in the quality factor; however, this is the subject of further research and is not considered in this paper.

2. Results of investigation

Lord Rayleigh first reported on circumferentially circulating acoustical resonances that he named "whispering gallery modes [15]." In a whispering gallery mode, acoustic waves do not penetrate particle close to the center but bounce around the circumference of the sphere.

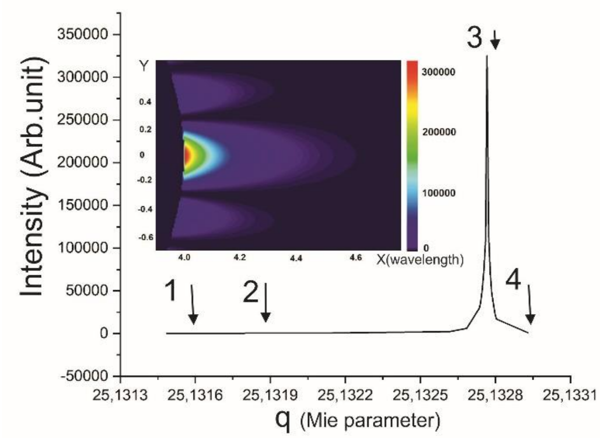

Figure 1. Resonant scattering on Rexolite© sphere immersed in water. In the insert, the structure of "hot spot" at the resonant frequency is shown. Maximal field intensity at the points 1-4 are: 325 (1), 2500 (2), 325000 (3), 1000 (4).

Analysis of simulations show that for a permeable sphere, impedance leads to the dissipation of acoustic power in addition to a phase change in the scattered wave. From Fig.1 it is followed that for spherical particle with $q = 25.132766$ and with $\ell = 33$ multipole at the super resonance condition (q is size (Mie) parameter defined as q=2πR/λ and ℓ the mode number). The enhancement factor can be extremely large at these "hot spots", reaching the order of 10^4 -10^5. It could be noted that at the super-resonance condition, the hot spot has a super resolution about of 0.21λ-0.23λ, which exceeds solid immersion resolution limit (λ/2n) of acoustojet, where n is an effective refractive index of surrounding medium (water).

Fig.2 shows the internal structure of one type of resonance for Rexolite© particle immersed in water. Simulation was made by Comsol software.

Figs.3(a) and (d) show that the increased focusing properties (acoustojet formation) near the shadow surface in the interference pattern. The hot spot lobes are due to that for the uniformly dielectric sphere a positive impedance phase angle significantly increases the contribution both the octopole and the quadrupole modes, and decreases the contribution of the dipole mode [16].

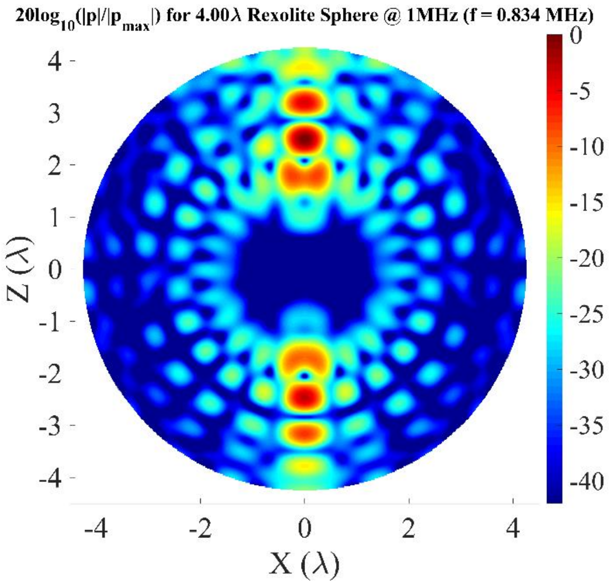

Figure 2. Internal structure of one type of the resonance mode for the Rexolite© sphere immersed in water due to internal scattering at specific values of the Mie and the particle material parameters.

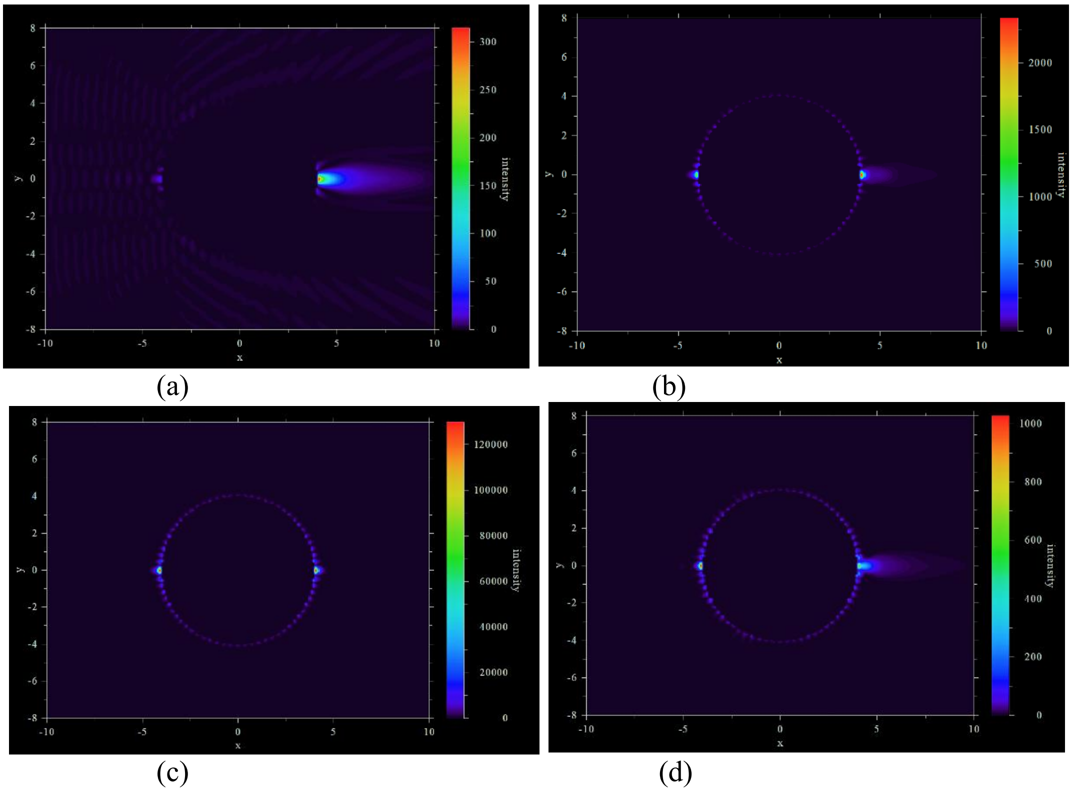

Figure 3. Near superresonant scattering on Rexolite© sphere immersed in water. The particle illuminated from the left to right. The labels of (a-d) corresponds to points of (1-4) from Fig.1, respectively. Maximal field intensity are: 325 (a), 2500 (b), 325000 (c), 1000 (d). Fig.3(c) visualizes the near-field intensity of the resonance mode of the Rexolite sphere in water.

Fig. 3(b) and Fig. 3(d) correspond to the conditions for the beginning of the formation of an acoustic jet. Fig.3(a) shows the generation of a non-resonant acoustojet immediately before and after super-resonance, respectively. The normalization is relative to the illumination.

A giant field enhancement mode caused by microsphere's internal partial waves we define as a 'super-resonance' effect. The enhancement factor can be extremely large at these "hot spots", reaching the order of 10^4 -10^5. The pronounced whispering gallery mode and example giant field intensity are clearly visible in Fig.3c and Fig.1. Inside the particle there is high intensity with maximal field intensity enhancement about 325 thousand. It is noticeable that the field in the resonance mode band passes fleetingly from the spherical particle to the background water environment.

The quality factor of resonator by analogy with simple oscillator can be defined as

$$Q=ka/\Delta(ka)=q/\Delta q.$$

From the data of Fig.1 it is followed that $Q=2.1\text{x}10^6$.

It could be noted that super-resonance mode exist only in 3D case (microspheres) in contrast to WGM which can be excited in both cylinder (2D case) and sphere.

3. Conclusion

In this work, it was shown that the giant localization of the field and the super-resolution mode could be excited in a mesoscale sphere submerged under water under certain conditions of resonance. This effect is observed in the parameter area, next to those characteristic of an acoustojet.

Studies of such super-resonances are of interest for the following main reasons:

- It gave the ability to create highly localized acoustic fields, both, inside and outside the particle near it surface.
- It is a possibility for optimization of several applications e.g. in acoustojet [7, 8], surface optomechanics [17], acoustic superlens microscopy [18,19] and surface-enhanced acoustic Raman spectroscopy [20,21], etc.

- Optimization of the whispering gallery mode at super resonance is of interest for optofluidic resonators [22] where such microfluidic cavities were made in the form of a water submerged solid micro resonator [23,24].
- This effect is not limited to the considered above relative density contrast and speed of sound contrast. In fact it is valid for all dielectric particles but super-resonant conditions depends on a function of relative density and the speed of sound contrast and the Mie parameter $q=2\pi R/\lambda$.

We show giant field enhancement (10^4-10^5) can be achieved with mesoscale dielectric sphere immersed in water under super resonance condition. The super-resolution (0.21λ-0.23λ) is observed at hot spots. We call this new effect as super resonance effect.

We believe the discovery of super-resonance is important to mesoscale particle super-resolution acoustic imaging [18, 25, 26], biosensors and holds new promise for applications in different scientific directions.

It could be noted that the effective refractive index of the polymer sphere increases when it is immersed in water due to the water molecules adsorbed on its surface, which increases the penetration depth of the evanescent wave and the effective radius of sphere [27].

In common, taking into account the analogy between electromagnetic and acoustic waves [28, 29], this phenomenon is valid in electromagnetic (optical) waveband [30]. However, in the scattering by elastic penetrable solid particles, the presence of two different sound velocities, the longitudinal and transverse ones, strongly affects the modal characteristics within the scatterer due to mode conversion. Therefore, the effect of the ratio of these two speeds on the super resonance effect is the subject of further research.

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