Extreme effects in field localization of acoustic wave: super-resonances in dielectric mesoscale sphere immersed in water

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Abstract. By the numerical simulation we predict acoustic super-resonance modes with several tens of thousands of times field-intensity enhancement (order of magnitude: $10^4 - 10^5$) supported by dielectric mesoscale spheres immersed in water. The super-resonances are related to internal scattering at specific values of the Mie and the particle material parameters and they are responsible for generation of giant fields within the particles near its surface. Taking into account the analogy between electromagnetic and acoustic waves this phenomenon is valid in electromagnetic (optical) waveband.

1. Introduction

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

In the acoustic, the scattering of sound from a spherical fluid obstacle of size comparable to a wavelength was considered in [3, 4]. It has been shown that the amplitude of the scattered wave in the backward direction from a fluid sphere a few wavelengths in diameter exceeds twice that from a rigid sphere of the same size for the case of the relative sound velocity 0.8 and density equal to that of the surrounding medium [4]. Focusing effect in the sound scattering by a spherical balloon with high diameter filled with carbon dioxide was investigated in [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 acoustical materials properties is a shear speed of sound, i.e. acoustic materials are anisotropic due to the two speed of sound [10].

In our analysis of acoustojet 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 $5\lambda$ 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 the first approximation in the harmonic case was based on the Helmholtz equation [12]. It was demonstrated [12] the influence of the main parameters of dielectric penetrable spherical cavity, immersed in water, to transformation of whispering gallery mode 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 as a material we have selected Rexolite© that closely match the impedance of water [13, 14]. The main parameters of Rexolite© are: sound velocity 2337 m/s, 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 $R=4\lambda$ (at frequency of 1 MHz in water), relative density contrast is 1.0402 and the speed of sound contrast is 1.570.

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.](image)

Analysis of simulations shown that for a permeable sphere, impedance leads to the dissipation of acoustic power in addition to a phase change in the scattered wave. Figures 2a and 2d shown that the increased focusing properties (acoustojet formation) near the shadow surface in the interference pattern and the hot spot lobes is 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].

Figures 2b and 2d correspond to the conditions for the beginning of the formation of an acoustic jet (Figure 2a shown the generation of a nonresonant acoustojet) immediately before and after superresonance, 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. Characteristic features of superresonance can be seen in Figure 2c, where the two “hot spots” represent the distribution of the field intensity inside a spherical particle with $q = 25.132766$ and with $\ell = 33$ multipole at the super resonance condition ($q$ is size (Mie) parameter defined as $q = 2\pi R / \lambda$). The enhancement factor can be extremely large at these “hot spots”, reaching the order of $10^4 – 10^6$. The pronounced whispering gallery mode and example giant field intensity are clearly visible in Figure 2c. Inside the particle there is high intensity with maximal field intensity enhancement about 125 thousand. It could be noted that at the superresonance condition the hotspot spots has a super resolution about of $0.21...0.23\lambda$, which exceeds solid immersion resolution limit ($\lambda/2n$) of acoustojet. 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

$$Q = k a / \Delta (k a) = q / \Delta q .$$

From the data of Figure 1 it is followed that $Q = 6.7 \times 10^5$.

It could be noted that superresonance 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 superresolution mode can 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 superresonances 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 consider above relative density contrast and the speed of sound contrast. In fact it valid for all dielectric particles but superresonant conditions depends on a function of relative density and the speed of sound contrast and the Mie parameter $q$.

We show giant field enhancement ($10^4…10^6$) can be achieved with mesoscale dielectric sphere immersed in water under super resonance condition. The super-resolution (0.21…0.23$\lambda$) is observed at hot spots. We call this new effect as super resonance effect.

We believe the discovery of superresonance is of important to mesoscale particle super-resolution acoustic imaging [18, 25, 26], biosensors and hold 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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