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Peculiarities of Generation of Extreme Electromagnetic Fields in a Dielectric Mesoscale Sphere with the presence of the Environment

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The results of numerical simulation based on the Mie theory of the effect of superresonance (high-order Fano resonance) for a mesoscale dielectric sphere immersed in air are presented, since the environment in the form of a vacuum is an idealization that is almost never realized in nature. Using the example of a particle with a refractive index of 1.5 and a size parameter $q \sim 26$ and $q \sim 38$, it was demonstrated for the first time that a change in the refractive index of the environment by $2.4 \cdot 10^{-4}$ leads to a decrease in the field intensity in the region of the shadow pole of the sphere by an order of magnitude and a shift of the resonant value of the size parameter q to the short-wavelength region. In this case, the relative intensities of the resonant peaks for both the magnetic and electric fields in the vicinity of the poles of the sphere in the optical range can reach values characteristic of a particle in vacuum (of the order of 10^6-10^7), with an appropriate adjustment of the resonant size parameter.

Keywords: high-order Fano resonance, superresonance, mesotronics, field intensity, extreme magnetic field.

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The research into physics of generation of ultrastrong magnetic fields has a long history [1]. At the same time, novel physical principles for the generation of intense magnetic fields (MFs) are still being developed nowadays. The first magnetic dipole resonance is observed in photonics for spherical particles as cavities under the condition of equality of the radiation wavelength inside a particle to its diameter ($q \sim \pi/n$, where q is the so-called Mie size parameter that is written as $q = 2\pi a/\lambda$, a is the particle radius, and λ is the irradiating wavelength). Specifically, the enhancement of MF intensity was below 500 in [2] for cylindrical sub-wavelength particles with $q \sim 0.5$ and a high refraction index.

Among the recently discovered intriguing optical effects in dielectric particles [3,4], magnetic light, photonic jets, and optical nanovortices deserve a mention in this context. Nanovortices are crucial for MF generation. Since the characteristic scale of such vortices is well below λ [5], the possibility of generation of strong MFs follows from the Biot−Savart law. A high-order Fano resonance [5] is an alternative approach to the generation of extreme electromagnetic fields in optics, since the degree of localization of vortices increases in transition to higher multipole orders [3,5–9] and induces specific optical phenomena driven by interference between a wide spectrum of all internal modes and a single high-order internal resonance mode [7–10]. It has been shown recently that extremely strong fields with intensity enhancement factors on the order of 10^5-10^7 for both magnetic and electric components may be produced in the vicinity of the inner surface of a mesoscale dielectric sphere in vacuum due to a high-order Fano resonance [7–9] induced by near-field interference effects. The characteristic asymmetric shape of resonance lines typical of Fano resonances has also been demonstrated in these studies. However, the parameters of generated fields are very sensitive both to the particle size parameter and to dissipative losses in its material [7,8].

As far as we know, no studies demonstrating the effect of the environment on the generation of extremely strong fields in a dielectric sphere in the visible wavelength range have been proposed yet. A vacuum environment is an idealization that is almost never encountered in nature. However, the environment cannot vanish completely. Below, we use the approach that was proposed in our earlier studies [7–9]. We demonstrate that when a dielectric mesoscale sphere is surrounded by air, resonance particle size q shifts toward shorter wavelengths and the intensity of fields in the vicinity of the particle poles becomes extremely sensitive to the refraction index of the medium. As before, we rely on the rigorous Mie theory [7–9,11], reveal the contribution of an individual mode, and confirm that, with a proper correction of resonance size parameter q of a particle, high-order Fano resonances with a giant (up to 10^7-10^8) enhancement of intensities of magnetic and electric fields may be excited in it.

A refraction index of 1.5, which is typical of dielectrics in the optical range, is used for a spherical particle. In contrast to previous studies [7–9], the sphere is surrounded by air with refraction index $n = 1.000241307$ [12]. Note that the particle size parameter in the Mie theory includes the wavelength in the environment, and the refraction index of a particle is always assumed to be relative. However,

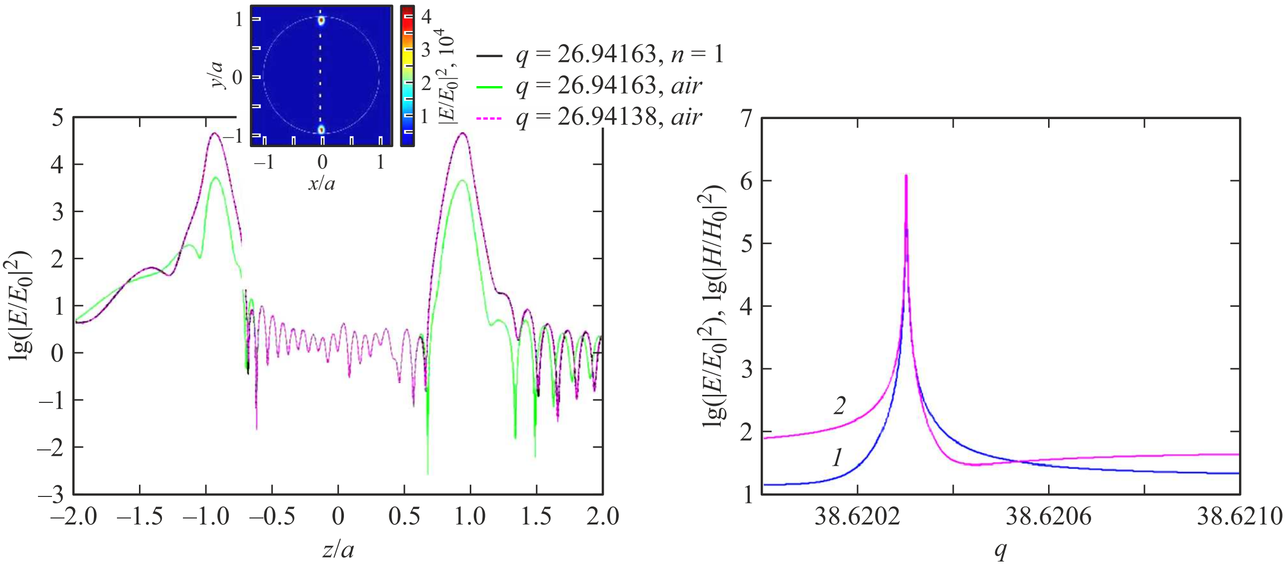

Figure 1. Distributions of the electric field intensity for a spherical particle with $q = 26.94163$ and $n = 1.5$ in vacuum (black curve) [7] and air (green curve) along the sphere diameter (denoted by the light dotted line in the inset). The corresponding field intensity distribution for a different resonance value ($q = 26.94138$) of a sphere in air is represented by the magenta curve. The positions of hot spots on the sphere poles are indicated in the inset. An example of the shape of resonance lines with a characteristic asymmetric Fano profile for the intensities of electric (*1*) and magnetic (*2*) fields and a particle with size parameter $q \sim 38.6203$ is presented on the right. A color version of the figure is provided in the online version of the paper.

a simple recalculation of modeling data for a particle in vacuum [7–9] into the data for a particle in a certain environment (performed by substituting the refraction index of this particle with an equivalent one with consideration to the contrast between the refraction indices of the particle and the environment) yields erroneous results. This is due to the fact that the relative refraction index enters into the so-called Mie scattering coefficients [11] in a complex way, and these coefficients depend qualitatively differently on various parameters of the problem at different values of such parameters [13].

The effect of environment on the electromagnetic field intensity near the poles of a spherical particle is illustrated in Fig. 1. The particle parameters were taken from [7] and correspond to the resonance TM mode $l = 35$ and resonance value $q = 26.94163$ for vacuum. Analyzing these results, one finds that a $2.4 \cdot 10^{-4}$ variation of the refraction index of the environment (from $n = 1$ for vacuum to $n = 1.000241307$ for air) results in an order-of-magnitude reduction in the field intensity at hot spots and a reduction in the resonance value of the particle size parameter, which drops from $q = 26.94163$ to 26.94138. Note that the corresponding dependences for the magnetic field are completely identical. The minimum full width at half-maximum (FWHM) values for the field intensity distribution at hot spots for the sphere in vacuum and in air are roughly equal ($\mathrm{FWHM}_{air} = 0.2058\lambda$ and $\mathrm{FWHM}_{vac} = 0.20967\lambda$, respectively) and remain below the diffraction limit $\lambda/(2n) = 0.333\lambda$ in both cases.

The mode theory [7,9,11,14] provides an explanation for the fairly high sensitivity of the intensity of hot spots to the refraction index of the environment. Specifically, the variation of coefficient A (directly proportional to Mie coefficient dn [9,11]) of the resonance TM mode $l = 35$ with refraction index n of the medium surrounding the considered sphere is illustrated in Fig. 2, *a*. It can be seen that the maximum field intensity at the hot spot and the amplitude of resonance coefficient A decrease sharply when the refraction index of the medium changes by about $\delta n \sim 10^{-5}$. Figure 2, *b* presents the variation of the resonance coefficient corresponding to the TM mode $l = 35$ with refraction index n of the environment.

In the case of higher-order modes ($l = 51$) of the Fano resonance of a spherical particle with size parameter $q = 38.6203$ (see the typical asymmetric Fano resonance profile for a particle with size parameter $q \sim 38.6203$ on the right panel of Fig. 1), a change in the refraction index of the environment may both reduce the maximum intensity at hot spots and alter the wav structure in the vicinity of this particle. Figure 3 shows the MF intensity distributions for such a particle in vacuum and in air. It can be seen that a $2.4 \cdot 10^{-4}$ change in the refraction index of the medium both reduces the maximum MF intensity by two orders of magnitude from the initial value of $2 \cdot 10^6$ and alters the field structure, which turns from a super-resonance to a non-resonance one typical of a photonic jet (Figs. 3, *b*, *c*). The latter change is attributable to the disruption of constructive interference of a single partial wave with the TE mode $l = 51$ in a particle with other modes. Note that with the particle size parameter corrected for the presence air, the minimum magnetic hot spot FWHM is approximately 0.205λ at a maximum MF intensity of about $1.8 \cdot 10^6$.

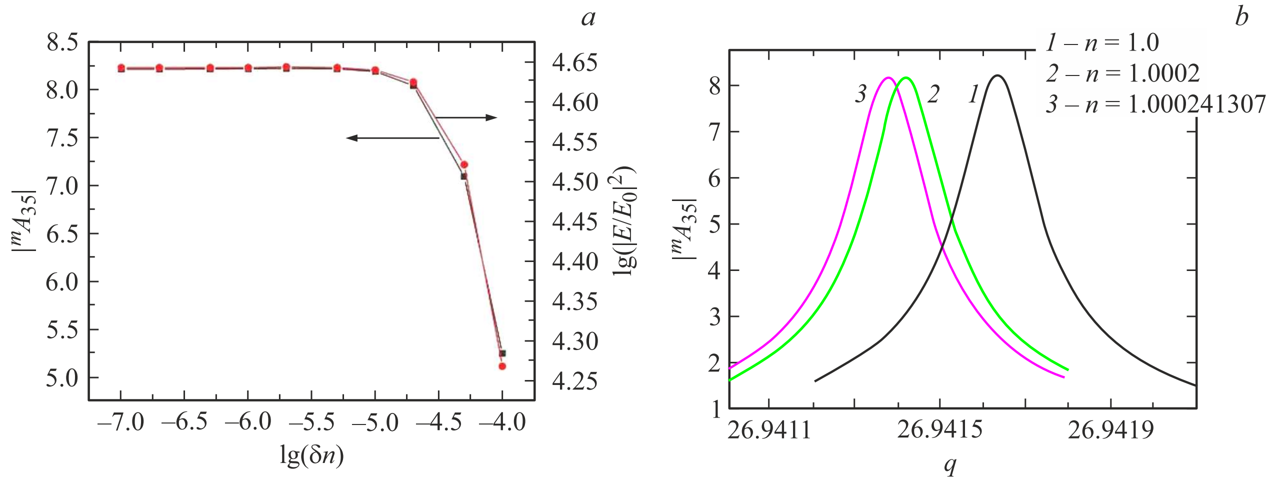

Figure 2. *a* — Dependence of the electric field amplitude and the Mie scattering coefficient of the resonance TM mode with $l = 35$ on the refraction index of the medium. *b* — Dependences of the Mie scattering coefficient of the TM resonance mode $l = 35$ on the resonance value of size parameter q for different refraction indices of the medium.

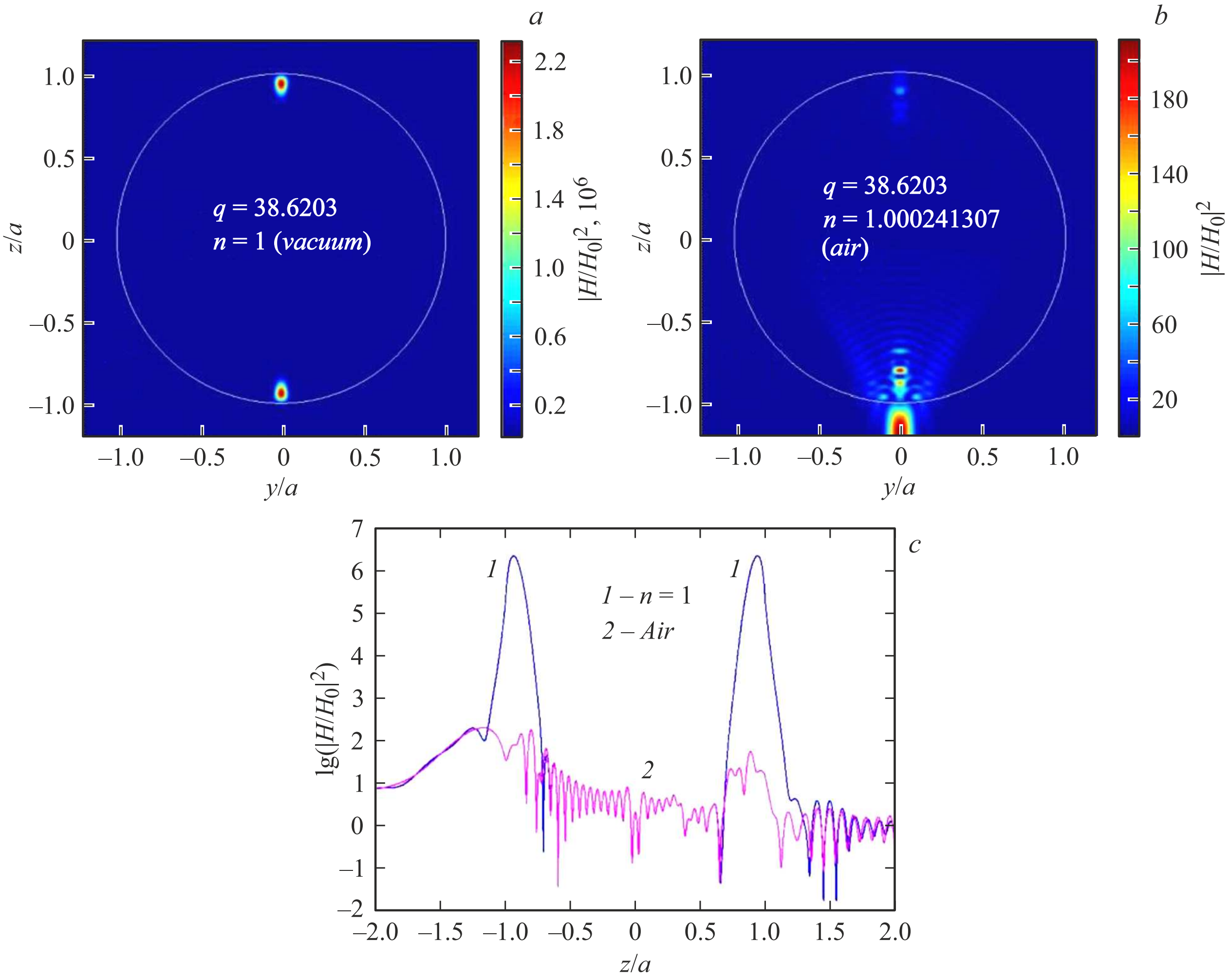

Figure 3. Magnetic field intensity for a spherical particle with size parameter $q = 38.6203$ and refraction index $n = 1.5$ corresponding to the resonance TE mode $l = 51$, in vacuum (*a*) and air (*b*). *c* — Field intensity distribution $|H/H_0|^2$ along the principal particle diameter on a logarithmic scale.

Thus, the excitation of higher-order Fano resonances is not a trivial task, since one needs both to adjust the size parameter of a sphere to match precisely the specified refraction index of its material and to take the environmental parameters into account. We have demonstrated that a slight $(2.4 \cdot 10^{-4})$ change in the refraction index of the medium leads to an order-of-magnitude reduction in the field intensity at the shadow pole of a sphere and to a marked shift of the resonance value of the size parameter toward shorter wavelengths. Therefore, studies of a spherical particle in vacuum performed without regard to the parameters of the surrounding medium are mostly academic in nature. At the same time, the excitation of the super-resonance of a spherical particle in a medium provides an opportunity for precision control over the variation of the refraction index of this medium for various sensors. The influence of surface roughness of a particle, scattering off inhomogeneities of its material, surface asphericity, etc., needs to be examined in future studies to determine the maximum achievable parameters of electromagnetic fields generated based on high-order Fano resonances. For example, the resonance line width under super-resonance conditions is on the order of λ/Q ($Q \sim 10^5 - 10^7$ [9] is the Q-factor), which is rather hard to measure in optics. Any inhomogeneities of this magnitude will shift and disrupt the resonance. In addition, since the resonance parameters are highly sensitive to the environmental parameters, the latter may require further efforts for stabilization. At the same time, this may be used as a threshold detector of variation of environmental parameters in certain applications (see, e.g., [15]). We plan to continue research in these directions.

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Conflict of interest

The authors declare that they have no conflict of interest.

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