

## Confirmation of the generation of strong magnetic fields in a dielectric sphere with a high refractive index in the microwave range

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The previously theoretically predicted generation of instantaneous local magnetic fields during resonant scattering of a plane microwave by Rayleigh weakly dissipative spherical dielectric particles with a high refractive index has been experimentally confirmed. The generated magnetic fields are comparable in strength to those in neutron stars. This resonance effect provides a promising basis for a number of interesting applications, including laboratory modeling of magnetic fields in neutron stars.

**Keywords:** magnetic field, magnetic dipole resonance, Fano resonance, spherical particle.

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The generation of strong magnetic fields (in particular, their optical generation) has remained a pressing issue for many years. At present; the maximum intensities achieved at the focus of a laser beam are on the order of  $I \sim 10^{23}$  W/cm<sup>2</sup> [1]. According to the Biot–Savart law, the magnetic field amplitude in a current loop may be increased by reducing the size of the loop down to the nanometer scale. Specifically, gold split-ring resonators with a gap of 35 nm feature a fundamental magnetic resonance excited by the electric field of an incident wave, which results in a magnetic dipole moment [2].

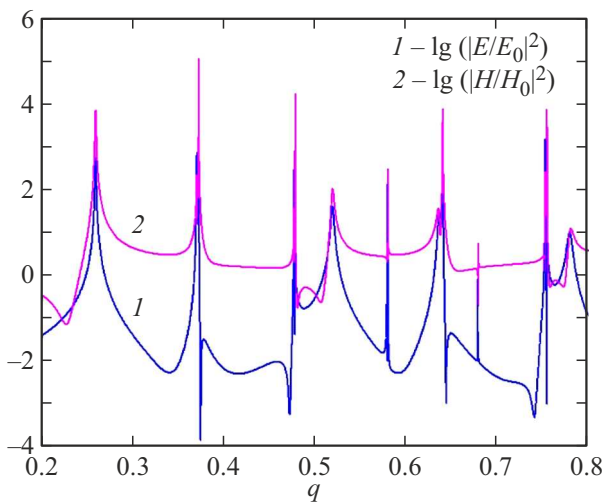
At the same time, it is known that light scattering by plasmonic nanoparticles allows one to produce optical nanovortices with scale  $r \ll \lambda$  around singularities where the Poynting vector tends to zero [3]. It has been demonstrated later [4] that subwavelength particles with high permittivity  $\varepsilon$  may also induce a strong magnetic response. In the case of dipole resonance, the radius of an optical vortex is inversely proportional to the refraction index of the sphere material:  $r \approx \lambda/4\sqrt{\varepsilon}$  [4]. All-dielectric resonant nanostructures are used widely in certain fields of nanophotonics [5,6].

The focusing capacity of dielectric spheres comparable in size to (or larger than) the wavelength has been known since ancient times. Such mesoscale dielectric spheres may support strong electromagnetic fields [7] (magnetic ones included [8]). According to one hypothesis, the generation of strong magnetic fields is attributable not only to the intensities of displacement currents, but also to the superoscillation effect [9]: the formation of local fields with large magnitudes of the wave vector inside a particle in the vicinity of singularities with steep phase gradients [10,11]. Optical nanovortices with a markedly subwavelength scale  $r \ll \lambda$  emerging around singularities may enable the generation of strong magnetic fields. However, even small losses in the spherical particle material may suppress these effects

to a significant degree [8]. Optical subwavelength vortices in a spherical dielectric particle are vortices of the Poynting vector field [8]. According to an alternative theory [12], they do not correspond to magnetic field vortices in the general case. This theory postulates that the magnetic field is smoothly zeroed out (or even remains constant) at the singularity points of the Poynting vector field.

Thus, although the phenomenon of generation of strong electromagnetic fields under optical illumination of a dielectric sphere is known, its mechanism remains open to question. Magnetic Mie modes inside a spherical particle are induced by the „twisting“ of displacement currents, which produce secondary magnetic fields in the transverse direction, enhancing the internal magnetic field. At the same time, there are a number of materials with low losses and high permittivity in the microwave range. This provides an opportunity to confirm experimentally both the fact of magnetic field generation and the validity of achievable magnetic field amplification levels through the example of Rayleigh spherical particles with a high refraction index. The wavelength of radiation in the material of a dielectric particle is  $n$  times shorter than the incident wavelength. Therefore, when the particle diameter is comparable to the wavelength within the sphere, the mode of the spherical particle with a relatively high refraction index is a magnetic dipole mode, which is associated with the excitation of a circulating polarization current inside this particle [4,8].

The polarizability of the particle increases with an increase in refraction index (coupled with low dissipation in the material of the sphere), leading to an enhancement of resonant amplitude of modes the natural frequency of which matches the frequency of an irradiating electromagnetic wave. The resonant lines of different natural modes overlap weakly in this case. Thus, it is possible to excite individual natural modes by choosing proper values of the Mie sphere size parameter and the refraction index [4]. Therefore,



**Figure 1.** Maximum intensities of electric (1) and magnetic (2) fields for a spherical particle as functions of Mie size parameter  $0.2 \leq q \leq 0.8$  on a logarithmic scale.

a significant enhancement of magnetic fields in high-permittivity materials in the GHz range is to be expected even in the region of the first Fano resonances [8,11,13]. Note that the enhancement of the magnetic field intensity relative to the electric one (i.e.,  $(H/E)^2$ ) may be adjusted by perforating the particle (e.g., with a through cylindrical channel).

Following [11,13], we identify the contribution of an individual mode using rigorous Lorenz–Mie modeling. The corresponding scattering spectrum for a spherical particle with  $\varepsilon = 142.1$  as a function of Mie size parameter  $q = 2\pi R/\lambda$  is shown in Fig. 1.

The presented dependences indicate that the line of high-order resonances becomes increasingly narrow; i.e., quality factor  $Q$  of resonances increases with the growth of their order. The amplitudes of all but one modes are quite small. The exception is the resonant mode (see the table), which depends on Mie size parameter  $q$ , with an amplitude that is approximately tens of times greater (such a high value of the Mie coefficient is due to the constructive interference of a single partial wave of the resonant mode with a wide spectrum of other modes inside the particle). Note

that amplitudes  $|^m A_n|$  increase with increasing refraction index. Here,  $|^m A_n|$  is the amplitude of the coefficient of the electromagnetic field component proportional to Mie coefficient  $d_n$ ,  $n$  is the mode number, and the superscript in front of amplitude  $A$  denotes the mode type: magnetic ( $m$ ) or electric ( $e$ ) [13].

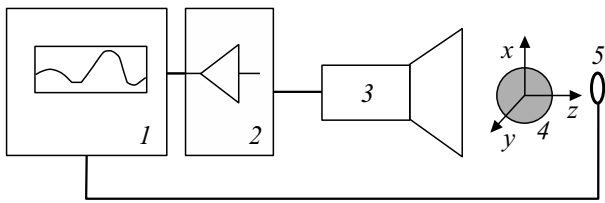
As was already noted, the main hypothesis regarding the generation of strong magnetic fields in dielectrics is the formation of highly localized optical vortices in the sphere material. These vortices may be observed in electric field fluxes in particles, where the electric field/displacement current distribution for the magnetic dipole resonance has a circular shape. Magnetic fields are excited by resonant eddy displacement currents that are proportional to the rate of change of the electric field.

Comparing the distributions of electric  $(E/E_0)^2$  and magnetic  $(H/H_0)^2$  fields inside the particle for magnetic dipole, magnetic quadrupole, and hexapole modes, one finds [14] that the magnetic fields inside the particle may reach high levels of  $H^2 \sim 10^6$  (even with a low specified accuracy [7] of localization of Mie size parameter  $\Delta q \sim 10^{-4}$ ).

The scale invariance of Maxwell's equations guarantees the identity of scattering processes for any geometrically similar bodies with the same optical characteristics of the material (refraction and absorption index) and characteristic dimensions of the scatterer (in wavelengths of incident radiation). In other words, the amplification of electromagnetic fields depends on the relation between the Mie size parameter and the dielectric properties of the particle material. Therefore, the results obtained on millimeter and centimeter scales may be carried over to a different (e.g., optical) spectral range. An experimental setup similar to the one discussed in [15] was used as a basis for measurements of local magnetic fields near a dielectric sphere with a high refraction index (Fig. 2). It was demonstrated experimentally in the mentioned study that the maximum resonant response for an incident plane electromagnetic wave corresponds to dipole magnetic resonances for flat dielectric ring structures in the THz range. However, it should be noted that no measurements of magnetic fields of spherical particles were carried out in [15]; as is known [8,13], the corresponding resonances are not observed for two-dimensional structures and, consequently, the effect examined in the present study is nonexistent.

Parameters of resonant scattering by a spherical particle with a high refraction index

Mie size parameter $q$	Resonant value of the Mie coefficient amplitude and mode number	$\max(E/E_0)^2$	$\max(H/H_0)^2$
0.2595	$ ^m A_1  = 71.37$	971.2	$3.275 \cdot 10^5$
0.3727	$ ^m A_2  = 98.84$	8077.5	$6.509 \cdot 10^5$
0.4785	$ ^m A_3  = 21.49$	993.3	$5.842 \cdot 10^4$
0.6404	$ ^m A_2  = 35.83$ $ ^e A_1  = 13.88$	1210.4	$1.362 \cdot 10^5$
0.7550	$ ^m A_3  = 33.79$	2330.0	$1.059 \cdot 10^5$



**Figure 2.** Diagram of the experimental setup. 1 — Radio frequency circuit analyzer, 2 — broadband amplifier, 3 — horn antenna, 4 — dielectric sphere with a diameter of 14 mm, and 5 — magnetic field probe.

A sphere made of standard STP-130 ceramics [16] was used in our experiments (Fig. 2). Since even small losses in the spherical particle material may suppress resonant effects to a significant degree [8], the exact values of optical constants of the particle material, the refraction index, and the loss tangent at the measurement frequencies are crucial for the interpretation and repeatability of the results. The measurement of relative permittivity of the ceramic material (on the order of  $\varepsilon \approx 142.1$  within the frequency range of 1–10 GHz) and dielectric loss tangent  $\text{tg } \delta \approx 0.0004$  was based on the measurement of natural resonant frequencies and quality factors of electromagnetic oscillations  $H_{0n\delta}$  of the waveguide-dielectric resonator type [17]. Such optical constants of the spherical particle material agree closely with the results reported in [8], where it was demonstrated that magnetic superresonances excited in a mesoscale sphere with a permittivity on the order of  $\varepsilon \approx 16$  and zero dissipation lead to an enhancement of intensity of magnetic field  $H^2 \approx 10^7$ , which decreases to  $H^2 \approx 10^5$  with dissipation  $\text{tg } \delta \approx 10^{-5}$  and vanishes with dissipation  $\text{tg } \delta \approx 10^{-3}$  (it should be taken into account that a mesoscale sphere is more sensitive to the magnitude of dissipation in its material than a Rayleigh one). A plane wave polarized linearly along the  $x$  axis propagated along the  $z$  axis. A sensor based on a metal loop, which allows one to measure the magnetic field component perpendicular to the plane of this loop [15], was used to determine the local field structure around the spherical particle. The sensor was positioned at a distance of approximately  $R/3.5$  mm from the shadow surface of the sphere. An AKIP-6605/2 vector network analyzer with an operating frequency range extending from 100 kHz to 26.5 GHz was used to generate signals in a given frequency range and detect the electrical signal of the magnetic probe. A plane linearly polarized wave was formed by an AIR-18M measuring horn with an operating frequency range of 0.75–18 GHz and a gain of 3–18 dB. An additional TOP3M9037-LNA radio frequency amplifier with a gain of 20 dB was used to increase the signal-to-noise ratio in the 100 MHz–6 GHz frequency band. Following [15], we measured the relative coefficient of signal power attenuation  $I[\text{dB}] = 10 \lg(W_1/W_0)$  without the spherical particle ( $W_0$ ) and with it ( $W_1$ ) near the resonant value of the incident field frequency.

The measured values of relative signal power (Fig. 3, a) reveal a giant (approximately five orders of magnitude) increase in magnetic intensity  $H^2$  for the magnetic dipole resonance at a frequency of 2.452 GHz. The asymmetry of the corresponding resonance distribution is evident. These results are consistent with the theoretical values of magnetic field enhancement for mesoscale spheres predicted earlier in [8].

Figure 3, b shows the distribution of magnetic field strength near the spherical particle with the above parameters at a magnetic dipole resonance frequency of 2.452 GHz. Dotted lines indicate the boundaries of the sphere, the solid curve corresponds to the magnetic field strength determined based on the Mie theory, and squares represent experimental data. It is evident that the Mie theory calculations and the experimental data agree closely; minor deviations from the Mie theory are attributable to the finite size of the probe and the accuracy of its positioning. The Mie theory estimate and extrapolation of the experimentally measured values of magnetic field near the surface of the sphere yield a maximum magnetic field strength inside the particle in excess of  $H^2 = 5.7 \cdot 10^5$  (second row in the table). The slight deviation of the experimentally determined Mie size parameter may be attributed to experimental errors and the lack of control of the uniformity of refraction index of the sphere material throughout its volume. The upper limit of the maximum magnetic field intensity depends on dissipative losses in the material of the spherical particle and the accuracy of its manufacture with regard to relative size  $q$  [7].

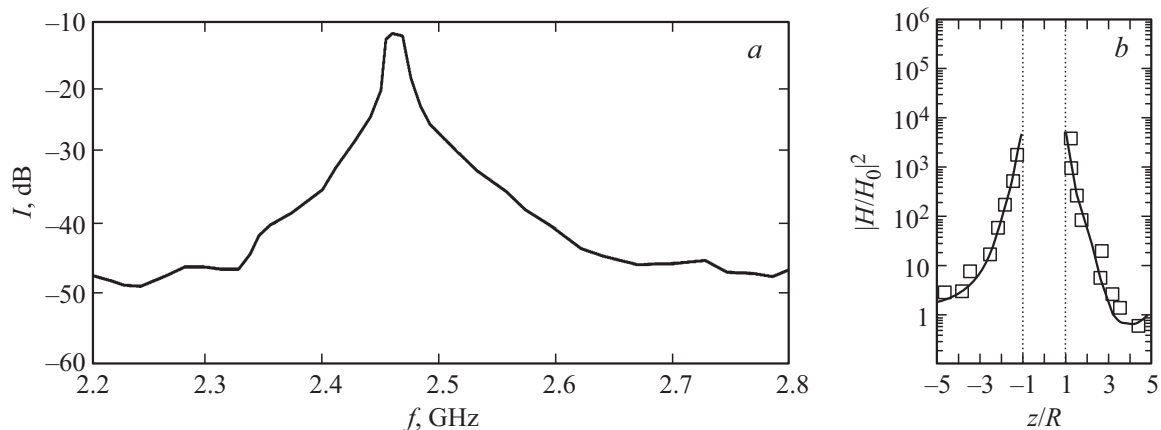
Thus, the effect of giant enhancement of magnetic field (on the order of  $10^5$  compared to the magnetic field in an incident plane electromagnetic wave) inside and around spherical Rayleigh particles with a high refraction index ( $\varepsilon \approx 100$  and  $\text{tg } \delta \approx 10^{-4}$ ) upon excitation of low-order (dipole) resonances in these particles was confirmed experimentally. Consequently, extremely high levels of amplification (up to four to five orders of magnitude) of magnetic intensity may be achieved even in the lowest order (magnetic dipole resonance). In the optical range, the loss tangent may be sufficiently small for a number of materials (e.g., BK7 glass [13]). Resonant effects of this kind form a solid basis for a number of promising applications, such as magnetic ablation, enhanced absorption, magnetic nonlinear optics, study of the effect of strong magnetic fields on materials (semiconductors) and microcircuits, etc.

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## Conflict of interest

The authors declare that they have no conflict of interest.



**Figure 3.** *a* — Distribution of relative signal power for the magnetic dipole resonance at a frequency of 2.452 GHz. *b* — Distribution of magnetic field strength near a spherical particle along axis  $z$  at  $x = y = 0$ . The solid curve represents the distribution of magnetic field strength near a particle plotted in accordance with the Mie theory. Experimental data are represented by squares. According to the Mie theory, the maximum magnetic field enhancement at the particle center exceeds  $H^2 = 5 \cdot 10^5$ .

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