Technical Physics Letters, 2024, Vol. 50, No. 10

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The possibility of magnetic noise generation in the optical range

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Received May 14, 2024
Revised June 22, 2024
Accepted June 22, 2024

Magnetic noise in magnetic systems has been known over a hundred years ago, but the possibility of observing opticalrange magnetic noise in non-magnetic systems has not been reported so far. As shown by simulation, the timedependent Fano resonance associated with internal Mie modes may be observed at a certain stage of the spherical water droplet freezing from outside to inside. In natural precipitation there exists an ensemble of differentsize water droplets randomly distributed in space. Therefore, such particles (being irradiated by laser radiation) will randomly generate during freezing strong electromagnetic fields depending on the droplet size and freezing time. Such a cloud of freezing droplets may be regarded as a natural magnetic noise generator.

Keywords: magnetic noise, Fano resonance, mesotronics, freezing water droplet.

DOI: 10.61011/0000000000

A freezing water droplet that is a combination of water (core) and ice shell opens new possibilities in photonics. However, an extremely limited number of studies have so far been devoted to research in optical phenomena in a freezing water droplet. Problems of this class relate to studying the features of electromagnetic waves interaction with bodies having timedependent dielectric parameters. Some nonresonant optical effects occurring in a freezing mesoscale water droplet have recently been considered in [1,2].

Excitation of highorder Fano resonances in monolithic mesoscale spheres [3–5] allows reducing the resonance line width and thereby increasing the sensitivity of resonance structures. In addition, irradiation of those spheres with electromagnetic waves gives rise to giant magnetic and electric fields inside the particle.

Mesoscale spherical droplets consisting of water and thin ice shell are resonators that can create highorder Fano resonance at a certain stage of droplet freezing: at a certain ice shell thickness, the droplet emits a strong magnetic pulse; when the droplet is illuminated by optical radiation, such particles act as a scattered light generator. One of the main goals of this study was to predict the possibility of the existence of magnetic noise generated by an ensemble of naturally occurring freezing water droplets illuminated by optical radiation. Until now, nobody has reported on the possibility of observing the phenomenon of opticalrange magnetic noise in nonmagnetic (dielectric) systems.

Recent experimental studies [6–8] (see also the references cited in those papers) have shown that the phase transition in small droplets of supercooled water is an extremely complex, fast and multistage process. However, the models adopted in the above-mentioned studies do not include effects associated with magnetic fields formed in a freezing droplet. Therefore, it seems relevant to theoretically evaluate the effects of magnetic response in a freezing water droplet (an element of an ensemble of individual droplets) as a source of magnetic noise.

The droplet freezing consists of two main processes: cooling the droplet to the phasetransition temperature and then freezing of the ice shell spherical layer. Experimental measurements of the size distribution of raindrops show that the main part of the droplets is concentrated in the diameter range below 0.2 mm, while in warm (or socalled low) clouds particles $0.1-10\,\mu$m in size prevail [9]. The shape of a water droplet $R \ll 2.5$ mm in radius [1,2,10], i.e. at a low Bond number, may be considered spherical. Water droplets less than $50\,\mu$m in radii are not expected to explode because of water expansion in freezing [11].

Scattering of light in the water droplet with ice shell (Fig. 1) was simulated using the COMSOL Multiphysics code. An incident linearly polarized plane wave with electric field $|\mathbf{E}_0| = 1$ V/m propagates along axis z (the reference frame origin being in the droplet center). As the boundary condition, a perfectly matched layer was used. As in [1,2], the water and solid ice refractive indices at wavelength $\lambda = 589$ nm were chosen to be 1.334 and 1.301, respectively. The mesh sizes inside and outside the water–ice droplet were $\lambda/20$ and $\lambda/10$, respectively. To visualize the effect, a droplet with external modal diameter $D = 6\,\mu$m (corresponding to Mie size parameter $q = \frac{D\pi}{\lambda} \sim 32$, where λ is the wavelength of the optical radiation illuminating the drop) was located in air ($n = 1$). R_{core} is the particle water core radius, δ is the spherical ice

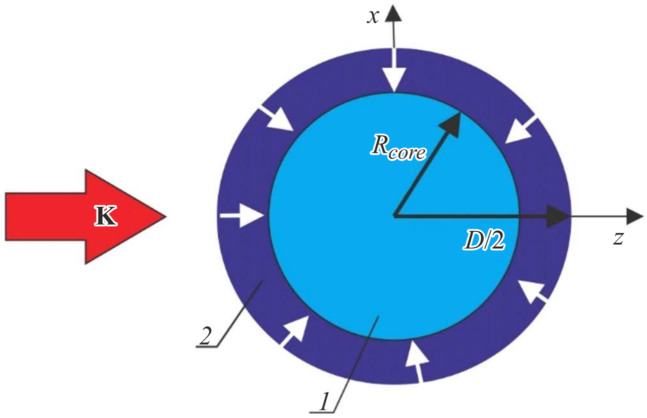

Figure 1. The problem geometry and schematic illustration of the water droplet freezing from outside to inside. *1* — water, *2* — ice. White arrows indicate the propagation direction of the ice−water interface.

shell thickness depending on the freezing time. The problem definition is described in more detail in [12].

Dynamics of the droplet freezing is a multistage process which is still not completely clarified [6–8,11]. We have assumed the simplest scenario of the droplet freezing from outside to inside, in which the ice−water interface moves symmetrically into the liquid. The effects of ice expansion and compression in the droplet with a low Bond number may be neglected [11].

Fig. 2 demonstrates normalized distributions of electric and magnetic field intensities inside the freezing droplet and in the vicinity of its shadow surface for the resonant value of parameter δ. Analysis shows that the Fano resonance occurs inside the water droplet at small ice shell thicknesses $160 < \delta < 180$ nm. These resonances correspond to a whispering gallery wave with $l = 76$, where l is the resonant mode number (Fig. 2). Note that in the millimeter wavelength range the effect of ice clearing is also observed, which is probably caused by the fact that a thin layer of water molecules is in an unstable state [13].

The possibility of the Fano resonance occurrence stems from low dissipation in water droplet in the optical range. The field structure inside the freezing droplet is typical of the case when a highorder mode interferes with loworder ones, which leads to the characteristic Fano shape for magnetic and electric field spectra in the vicinity of the droplet poles (Fig. 2, *c*). Note that the resonant mode amplitude is several orders of magnitude higher than the coherent sum of all other modes. As a result, the field distribution inside the particle is determined by this resonant mode regardless of the phases of other modes [3–5], as clearly shown in Fig. 2, *c*.

The magnetic field in resonance exceeds the electric field at pole hot spots of the droplet with $\delta = 171$ nm by approximately 1.3 times (Fig. 2). Intensity of electric field $|\mathbf{E}/\mathbf{E}_0|^2$ in resonance gets enhanced by 350 times, while the magnetic field intensity $|\mathbf{H}/\mathbf{H}_0|^2$ increases by 450 times. Note that the magnitudes of the electromagnetic field amplification that are several times lower in Fano resonance for spherical nanoparticles with the Mie size parameter of about 5 and high (GaP) refractive index were previously observed theoretically in [14]. Note also that far from Fano resonance, e. g. when the ice shell is $\delta = 180$ nm thick, intensities of both the magnetic and electric fields in the photonic jet focus exceed the maximum intensities at hot spots inside the droplet.

The magnetic field strengthening occurs because at a certain Mie size parameter of a water droplet, core and shell refractive indices and shell thickness, optical vortices arise inside the droplet as a result of light interference in the vicinity of singular points [15] with zero Umov−Poynting vector [4]. This complies with emergence of relevant circular currents just which, according to the Biot−Savart law, create magnetic fields [4,5]. Distributions of electric and magnetic field intensities along the axis of radiation propagation inside the droplet (axis z) in Fano resonance are shown in Fig. 3.

Asymmetric shape of the highorder Fano line (Fig. 3) is observed for the magnetic and electric field spectra at the pole on the droplet shadow side ($x = 0, y = 0, z = R$). The minimum relative field intensity is observed near the ice shell thickness of about $\delta = 171$ nm. As per [5], an increase in the resonant mode number and enhancement of the electromagnetic field amplification with increasing freezing droplet diameter should be expected.

Depending on the freezing conditions [11,16–18], a water droplet about 10 μm in size gets frozen in approximately 2.4 ms. The average speed of the ice−water interface propagation in a freezing water droplet about 10 μm in outer diameter is approximately 0.028 m/s [11,16]. The results given in Fig. 3 show that the Fano resonance line width at half maximum is close to 10 nm. Hence, the Fano resonance lifetime in the outsidetoinside freezing of the above-considered water droplet 6 μm in diameter is about 0.35 μs.

Variations in the ice shell thickness in the freezing water droplet result in significant variations in the electric and magnetic field intensities inside the laserirradiated droplet. In a freezing water droplet of an arbitrary radius (provided the Bond parameter is small), there will always be an ice shell thickness at which Fano resonance occurs, i. e., as the water droplet gets frozen, it adjusts itself to the resonance values due to variations in the ratio of the radius of the water core of liquid to ice shell thickness. Since formation and freezing of droplets is a stochastic process, at a certain stage of water droplet freezing there will always be an optimal thickness of the ice surface layer at which the interference of a highorder mode with loworder modes creates inside the droplet the Fano resonance with timedependent parameters. This resonance causes a significant increase in the electric and magnetic fields at hot spots at the droplet poles. As a result, the optical field distribution inside and outside the droplet undergoes variations, which gives rise at a certain stage of the droplet freezing to timedependent Fano resonances of the freezing water droplet; therewith,

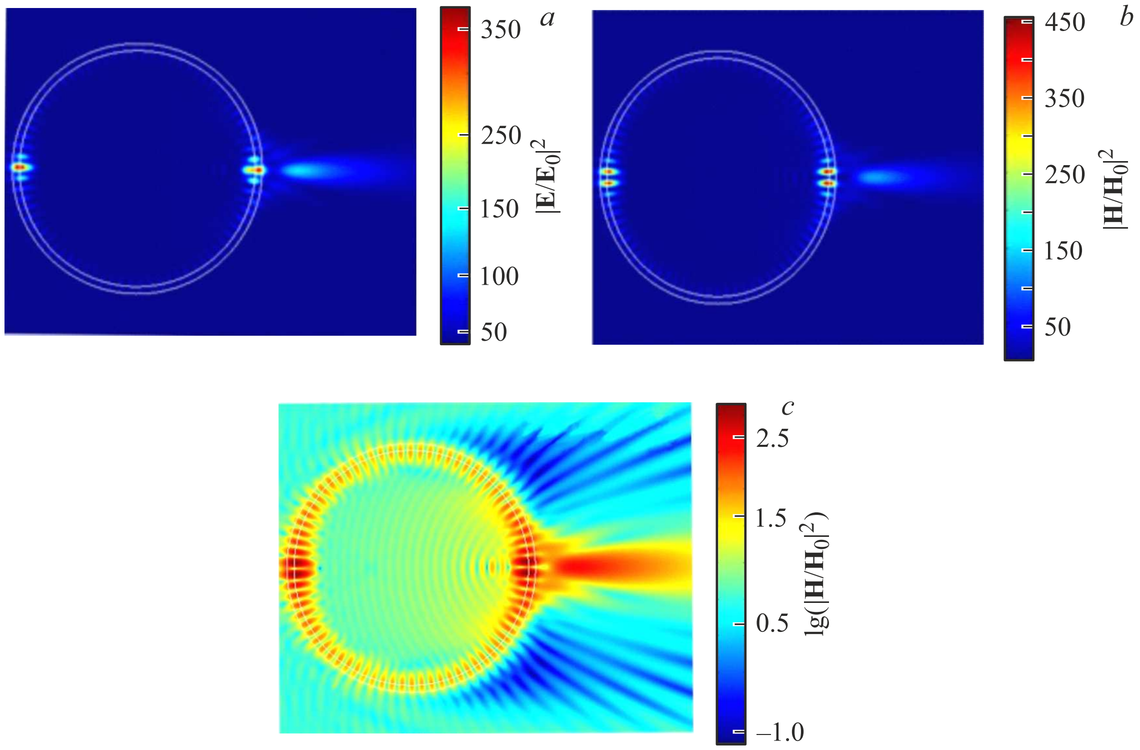

Figure 2. Distributions of the electric $|\mathbf{E}/\mathbf{E}_0|^2$ (a) and magnetic $|\mathbf{H}/\mathbf{H}_0|^2$ (b) field intensities (c — on the logarithmic scale) at the ice shell resonant value $\delta = 171$ nm. The distributions are normalized to the values for the incident wave.

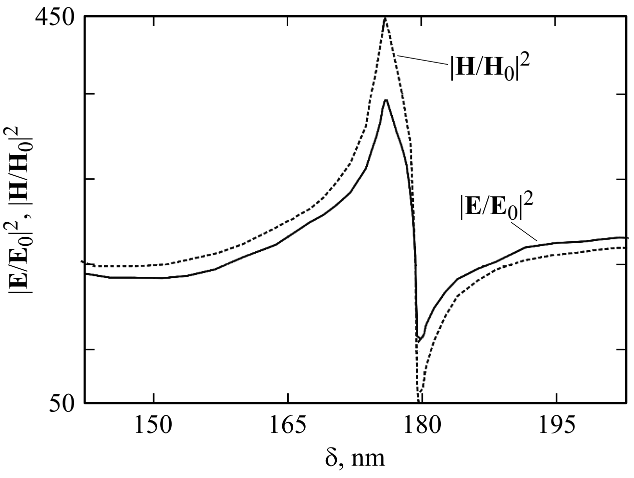

Figure 3. Distributions of normalized intensities of electric and magnetic fields in the vicinity of the freezing droplet shadow hot spot depending on ice shell thickness δ in the region of resonance.

a significant increase in the magnetic field is observed: being illuminated by laser radiation, such particles act as a source of highpower electromagnetic field. In this case, it is possible to consider the cloud of freezing droplets as a diffusion medium with variable resonant characteristics. Therefore, being laser-irradiated, such a cloud of individual freezing droplets may be regarded as a natural optical generator of magnetic noise which has never been reported before.

Generation of submicrosecond electromagnetic pulses may also serve as a basis for studying the initial stage of water droplet freezing, since variations in the ice shell thickness during the water droplet freezing from outside to inside allows monitoring in time formation of an asymmetric shape of the Fano resonance line inside the droplet; the relevant electromagnetic noise provides information on the droplet spatialphase restructuring.

Funding

The study was partially supported by the Tomsk Polytechnic University Development Program.

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] O.V. Minin, I.V. Minin, Y. Cao, Sci. Rep., **13**, 7732 (2023). DOI: 10.1038/s41598-023-34946-7

[2] O.V. Minin, Y. Cao, I.V. Minin, Nanomaterials, **13**, 2168 (2023). DOI: 10.3390/nano13152168

[3] I.V. Minin, O.V. Minin, Optika atmosfery i okeana, **37** (3), 187 (2024). DOI: 10.15372/AOO20240301 (in Russian)

[4] Z. Wan, B. Luk'yanchuk, L. Yue, B. Yan, J. Monks, R. Dhama, O.V. Minin, I.V. Minin, S. Huang, A. Fedyanin, Sci. Rep., **9**, 20293 (2019). DOI: 10.1038/s41598-019-56783-3

[5] I.V. Minin, O.V. Minin, Z. Song, JETP Lett., **116** (3), 144 (2022). DOI: 10.1134/S002136402260121X.

[6] A. Kalita, M. Mrozek-McCourt, T.F. Kaldawi, P.R. Willmott, N.D. Loh, S. Marte, R.G. Sierra, H. Laksmono, J.E. Koglin, M.J. Hayes, R.H. Paul, S.A.H. Guillet, A.L. Aquila, M. Liang, S. Boutet, C.A. Stan, Nature, **620**, 557 (2023). DOI: 10.1038/s41586-023-06283-2

[7] A. Hakimian, M. Mohebinia, M. Nazari, A. Davoodabadi, S. Nazifi, Z. Huang, J. Bao, H. Ghasemi, Nat. Commun., **12**, 6973 (2021). DOI: 10.1038/s41467-021-27346-w

[8] F. Chu, S. Li, C. Zhao, Y. Feng, Y. Lin, X. Wu, X. Yan, N. Miljkovic, Nat. Commun., **15**, 2249 (2024). DOI: 10.1038/s41467-024-46518-y

[9] H. Yu, X. Sun, R. Ti, B. Tu, Y. Fan, Y. Wang, Z. Wang, Y. Wei, X. Liu, H. Huang, Y. Li, Y. Wang, Opt. Express, **32**, 17738 (2024). DOI: 10.1364/OE.518266

[10] A. Starostin, V. Strelnikov, L.A. Dombrovsky, S. Shoval, O. Gendelman, E. Bormashenko, J. Colloid Interface Sci., **620**, 179 (2022). DOI: 10.1016/j.jcis.2022.04.019

[11] S. Wildeman, S. Sterl, C. Sun, D. Lohse, Phys. Rev. Lett., **118**, 084101 (2017). DOI: 10.1103/PhysRevLett.118.084101

[12] O.V. Minin, S. Zhou, I.V. Minin, *High order unconventional Fano resonance in the time domain for a freezing water microdroplet*, preprint (Optical Society of America, 2023). DOI: 10.1364/opticaopen.24320959

[13] G.S. Bordonskiy, Tech. Phys. Lett., **50** (5), 30 (2024). DOI: 10.61011/TPL.2024.05.58417.19587].

[14] M. Tribelsky, A. Miroshnichenko, Phys. Rev. A, **93**, 053837 (2016). DOI: 10.1103/PhysRevA.93.053837

[15] M.V. Berry, Sci. Appl., **12**, 238 (2023). DOI: 10.1038/s41377-023-01270-8

[16] Z. Meng, P. Zhang, Int. J. Heat Mass Transfer, **193**, 122955 (2022). DOI: 10.1016/j.ijheatmasstransfer.2022.122955

[17] V.T.J. Phillips, A. Khain, N. Benmoshe, E. Ilotoviz, A. Ryzhkov, J. Atmos. Sci., **72**, 262 (2015). DOI: 10.1175/JAS-D-13-0376.1

[18] L. Karlsson, H. Lycksam, A. Ljung, P. Gren, T.S. Lundström, Exp. Fluids, **60**, 182 (2019). DOI: 10.1007/s00348-019-2823-1

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