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A magnetoactive metamaterial based on a structured ferrite

Subject and Purpose. *The use of spatially structured ferromagnets is promising for designing materials with unique predetermined electromagnetic properties welcome to the development of magnetically controlled microwave and optical devices. The paper addresses the electromagnetic properties of structured ferrite samples of a different shape (spatial geometry) and is devoted to their research by the method of electron spin resonance (ESR).*

Methods and Methodology*. The research into magnetic properties of structured ferrite samples was performed by the ESR method. The measurements of transmission coefficient spectra were carried out inside a rectangular waveguide with an external magnetic field applied.*

Results. *We have experimentally shown that over a range of external magnetic field strengths, the frequency of the ferromagnetic resonance (FMR) of grooved ferrite samples (groove type spatial geometry) increases with the groove depth. The FMR frequency depends also on the groove orientation relative to the long side of the sample. We have shown that as the external static magnetic field approaches the saturation field of the ferrite, the FMR frequency dependence on the external static magnetic field demonstrates "jump-like" behavior. And as the magnetic field exceeds the ferrite saturation field, the FMR frequency dependence on the groove depth gets a monotonic character and rises with the further growth of the field strength.*

Conclusion. *We have shown that the use of structured ferrites as microwave electronics components becomes reasonable at magnetic field strengths exceeding the saturation field of the ferrite. At these fields, such a ferrite offers a monotonically increasing dependence of the resonant frequency on the external magnetic field and on the depth of grooves on the ferrite surface. Structured ferrites are promising in the microwave range as components of controlled filters, polarizers, anisotropic ferrite resonators since they can provide predetermined effective permeability and anisotropy. Fig. 5. Tabl. 1. Ref.: 12 items.*

Key words: *metamaterial, ferrite, ferromagnetic resonance, microwave frequency range.*

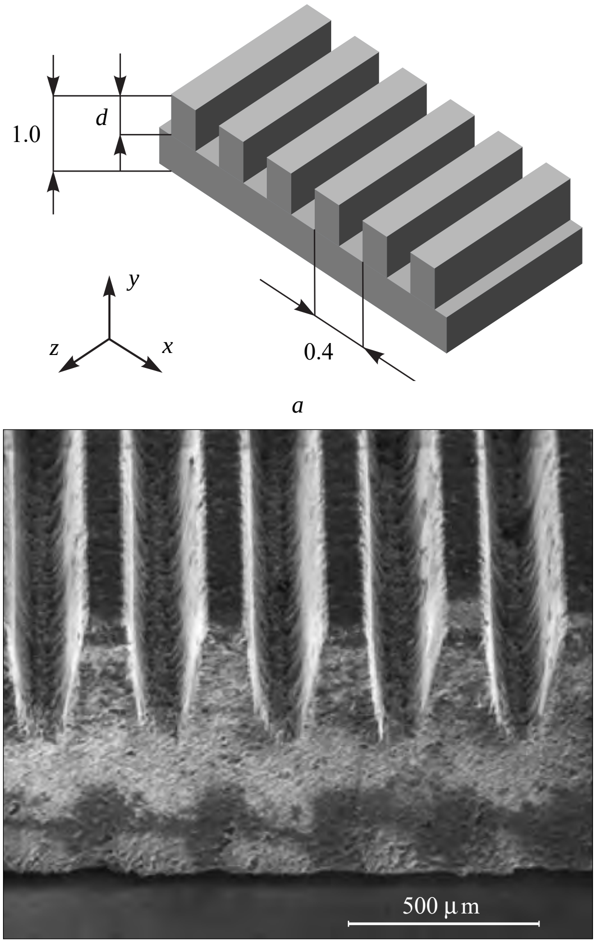
It is well known that magnetoactive metamaterials are prospective base for frequency filters. In addition, magnetoactive metamaterials can find application in computer technology, microwave and optical engineering. The main advantage of the abovementioned filters is wideband-frequency tunability. The filters based on magnetically controlled photonic crystals with their magnetoactive elements constructed of ferromagnetic materials are effective in the microwave and optical ranges [1–8].

However, modern electronics of high and extremely high frequencies requires brand-new filters where application of classical ferrodielectrics is problematic. It is well known that electrical and magnetic properties of ferrodielectrics are determined by the crystal structure. Any modification in the crystal structure leads to a change in its properties. The development of such materials (magnets) requires large costs.

An alternative solution to the problem is the use of spatially structured ferromagnets, such as magnetoactive metamaterials. The electromagnetic properties of a magnetoactive metamaterial depend not only on the properties of the metamaterial constituents but on their spatial arrangement, too. On this basis, the development of materials with predetermined electromagnetic properties (constitutive parameters – permittivity and permeability) is possible. In this case, it is natural to turn attention to magnetoactive metamaterials under electron spin resonance (*ESR*) conditions. For this, a magnetic field of the kOe order should be applied to the magnetoactive metamaterial [9, 10] for the microwave range. The *ESR* area is the most attractive as the frequency dispersion of magnetic permeability is at its maximum there [9, 10]. This structuring contributes to the formation of spatial electrodynamic resonances appearing in the sample and thus greatly controls formation of the effective magnetic permeability of the entire structure. Besides, this structuring modifies demagnetizing factors [9] and substantially transforms the electromagnetic properties (effective constitutive parameters) of the sample. So, the magnetoactive metamaterial research using the *ESR*-method notable for its great sensitivity to magnetic structural changes is really necessary in the frequency range of the metamaterial prospective application.

On this basis, the aim of the work is the *ESR*-method research into the electromagnetic properties of structured ferrite samples of a different shape (spatial geometry).

1. Structures under study and theoretical approach. For the magnetoactive metamaterial research, six parallelepipedic samples of ferrite (1SCh4 brand, $4\pi M_S = 4\,750$ Gs, $g = 2.14$) are used. Each sample is of the size $a \times b \times c = 7.2 \times 3.4 \times 1.0$ mm. By the term "spatial geometry" we mean parallel grooves cut on one side of the sample so that the sample represents a comb structure (Fig. 1, *a*, *b*).



a

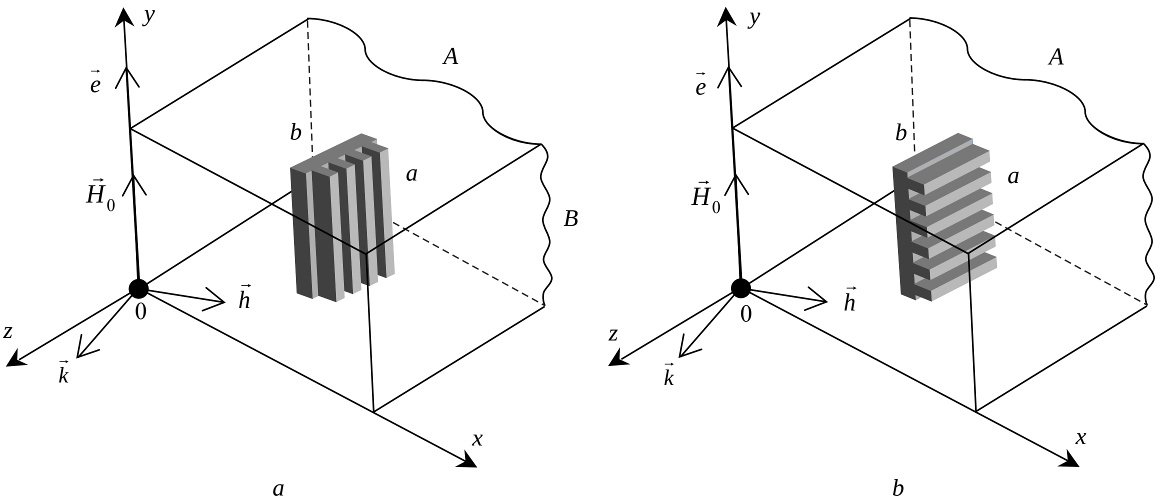
b

Fig. 1. Structured ferrite sample: *a* – schematic view and *b* – scanning electron microscope image showing grooves made with femtosecond laser (45 degree tilt, end view)

Numbers and groove depths *d* of ferrite samples

Series	Sample	*d*, mm
Series 1 – grooves are parallel to side *a* of the sample	No. 1	0.2
	No. 2	0.4
	No. 3	0.6
Series 2 – grooves are perpendicular to side *a* of the sample	No. 4	0.2
	No. 5	0.4
	No. 6	0.6
Ferrite slab	No. 7	0.0

All the samples are separated into two series (see the Table). The first series samples have grooves parallel to the long side (*a*) of the sample (see Fig. 2, *a*). The second series samples have grooves perpendicular to the long side (*a*) of the sample (see Fig. 2, *b*). Within the same series, the samples differ in groove depth, *d*. The reference sample (No. 7) is a ferrite parallelepiped without grooves.



a

b

Fig. 2. Location of structured ferrite samples inside a rectangular waveguide: *a* – series 1 and *b* – series 2

To have samples with a structured surface and avoid thermally-induced demagnetization, we resorted to laser ablation using a femtosecond laser system *Spitfire Pro* 35*F-XP, Spectra-Physics*. The laser system generates 50 fs pulses at a 1 kHz repetition rate, the center wavelength is 800 nm. The resulting laser beam with an average power of 1.4 W is focused on the sample surface using a 50 mm lens. The scanning velocity along the surface is 5 mm/s. The groove period is 0.4 mm, the ridge width is 0.2 mm. The three groove depths are obtained using three dedicated positioning programs.

In the case of collinear magnetic materials, the *ESR* phenomenon observed for ferromagnetic materials is commonly called [9, 11] the Ferromagnetic Resonance (*FMR*) phenomenon described by the motion equation

$$\frac{\partial \vec{M}}{\partial t} = -\gamma(\vec{M} \times \vec{H}_{eff}), \tag{1}$$

where γ is the gyromagnetic ratio, $\vec{M}$ is the magnetization of the sample unit volume, and $\vec{H}_{eff}$ is the total magnetic field with the components [9]

$$\begin{aligned} H_x &= h - N_x M_x, \\ H_y &= H_0 - N_y M_y, \\ H_z &= -N_z M_z, \end{aligned} \tag{2}$$

where H_x, H_y, H_z are the total field components in the *x*, *y*, *z* directions, respectively, with both external and internal fields taken into account, $\vec{H}_0$ is the external static magnetic field directed along the *y*-axis, $\vec{h}$ is the high-frequency alternating magnetic field directed along the *x*-axis, and M_x, M_y, M_z are the components of the alternating magnetization $\vec{M}$. In (2), N_x, N_y, N_z are the components of the effective demagnetizing factor *N* [9, 10] of the sample. *N* governs the *FMR* frequency f_{FMR} and directly depends on the shape of the sample. Since the samples differ in their groove depths, the demagnetizing fields of the structured and unstructured ferrite samples of the same size should differ, too.

A numerical modelling was made in order to determine the *FMR* frequency of the studied samples, with demagnetizing factors and groove depth *d* taken into account.

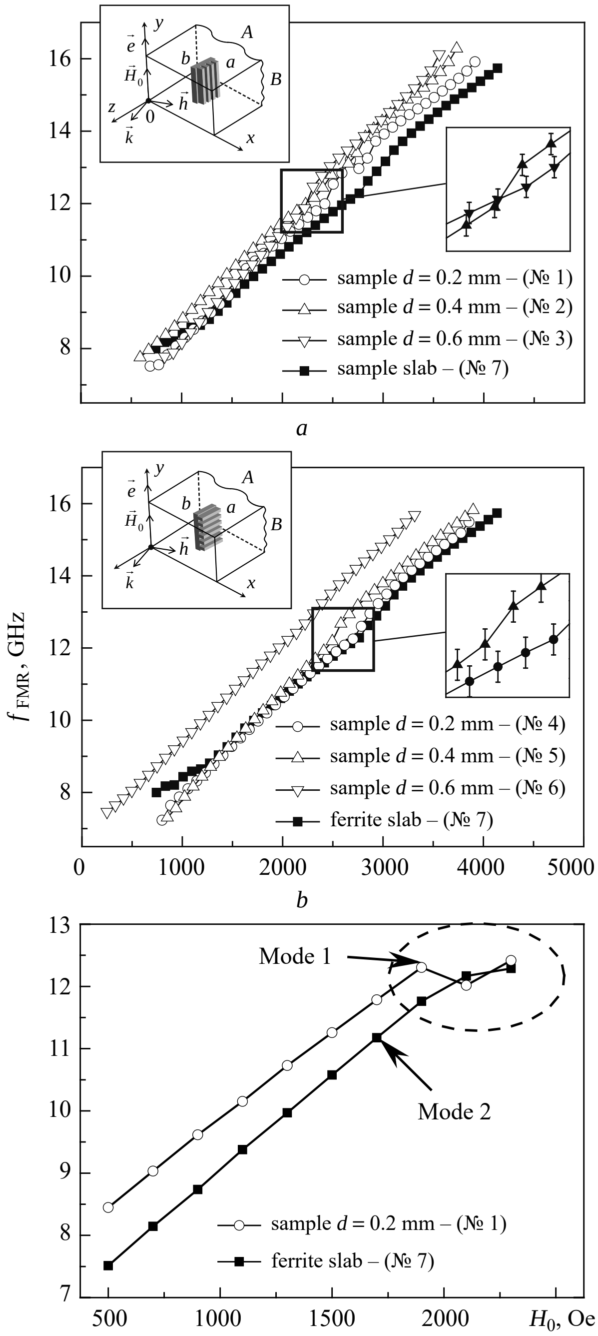
2. Experiment and data analysis. Each sample is placed inside a metal rectangular hollow waveguide. Its cross-section is $A \times B = 23 \times 10$ mm, the main waveguide mode is TE_{10}. The external static magnetic field $\vec{H}_0$ is directed along the *OY* axis (Fig. 2) [6, 7, 11, 12]. The waveguide is positioned so that the sample is located between the electromagnet poles to satisfy the *FMR*-conditions ($\vec{h} \perp \vec{H}_0$) [11]. A *Vector Network Analyzer* N5230A is connected to the waveguide by coaxial cables, the spectrum registration is performed in the frequency domain mode at several values of the static magnetic field strength H_0.

Fig. 3, *a*, *b* shows the experimental f_{FMR} frequency dependences on the external magnetic field H_0 for the samples located as in Fig. 2 (the insets in Fig. 3, *a*, *b*). As seen from Fig. 3, *a*, *b*, the resonant frequency f_{FMR} increases with H_0 for all the considered groove depths d. Besides, f_{FMR} increases as groove depth d increases with H_0 fixed.

For clarity sake, the dependences $f_{FMR} = f_{FMR}(d)$ are shown in Fig. 4. Let us analyze these dependences in more detail. According to Fig. 4, the dependences can be conventionally separated into two – nonmonotonic (grey colored) and monotonic (white colored) – areas. The nonmonotonic behavior can be explained by the fact that the ferrite (in the "grey" area in Fig. 4) is unsaturated, $H_0 < H_{sat}$, where H_{sat} is the saturation field of the ferrite sample [9, 10]. When $H_0 > H_{sat}$, the ferrite passes to the saturated state. As a result, the dependence $f_{FMR} = f_{FMR}(d)$ becomes monotonic (the "white" area in Fig. 4). In other words, when $H_0 > H_{sat}$ and the magnetic saturation occurs in the structured ferrite, the magnet turns out to be collinear. In this case, an internal field is formed inside it, and the magnetic field value substantially exceeds the surface anisotropy field caused by the structuring. In this case, a groove depth change acts as a small magnetic-field perturbation and provides a monotonic $f_{FMR} = f_{FMR}(d)$ dependence. When the magnet is unsaturated, $H_0 < H_{sat}$ (Fig. 4) the internal field is basically determined by the surface anisotropy field caused by the magnet structuring. So, the groove depth d largely perturbs the f_{FMR}, leading to a nonmonotonic nonlinear dependence $f_{FMR} = f_{FMR}(d)$, which is typical for any large perturbation.

It should be noted that the FMR frequency is affected by the groove arrangement relative to the direction of the external static magnetic field, $\vec{H}_0$. The field $\vec{H}_0$ is directed along the OY axis, i.e. parallel to the long side a of the sample. Thus, the value of the FMR frequency for the samples with grooves parallel to the long side a of the sample (series 1, Fig. 2, a) is greater than for the samples with grooves perpendicular to the side a (series 2, Fig. 2, b), compare the FMR frequency values for the curves with $d = 0.2$ mm and $d = 0.4$ mm in Figs. 3, a and b. The observed phenomenon is caused by the action of the demagnetizing fields $N_x M_x$; $N_y M_y$; $N_z M_z$ in the given structured ferrite sample [9].

Note that in Figs. 3, a, b, there are "jumps" on the curve $f_{FMR} = f_{FMR}(H_0)$ (experiment) near $H_0 \approx 2\,500$ Oe. We suggest that the observed "jumps" are caused by the passage from one mode arising in the given electrodynamic structure to another one. This effect occurs when the wavelength is comparable with the sample size. A numerical calculation using the model described by formula (1) has been performed. Fig. 3, c presents the



a

b

c

Fig. 3. Dependence of FMR frequency f_{FMR} on external magnetic field H_0, $f_{FMR} = f_{FMR}(H_0)$, for several groove depths d = 0.2, 0.4, and 0.6 mm and for a slab without grooves (curve 7): a – sample orientation inside a waveguide according to Fig. 2, a (series 1, experiment), b – according to Fig. 2, b (series 2, experiment), and c – according to Fig. 2, a (series 1, numerical modelling)

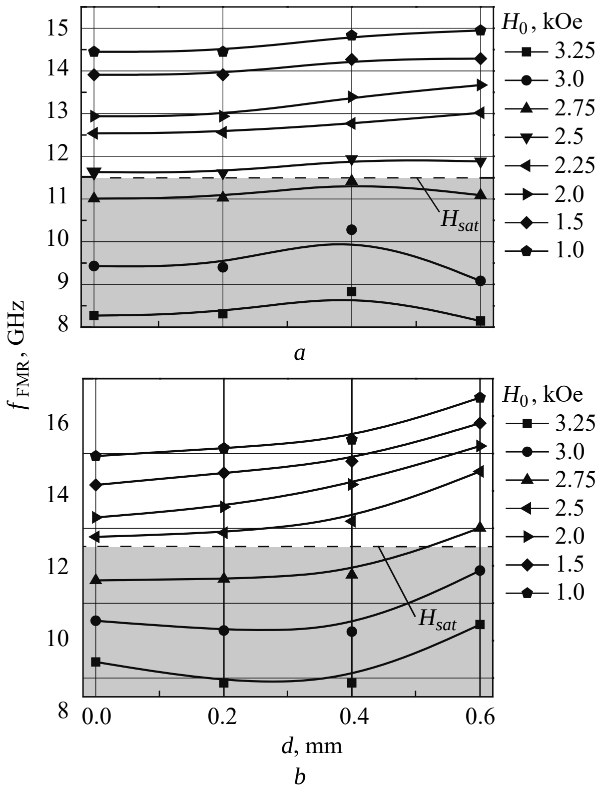


Fig. 4. Dependence of FMR frequency f_{FMR} on groove depth d for several values of magnetic field H_0 and at two sample positions inside a waveguide: *a* – according to Fig. 2, *a* (series 1) and *b* – according to Fig. 2, *b* (series 2)

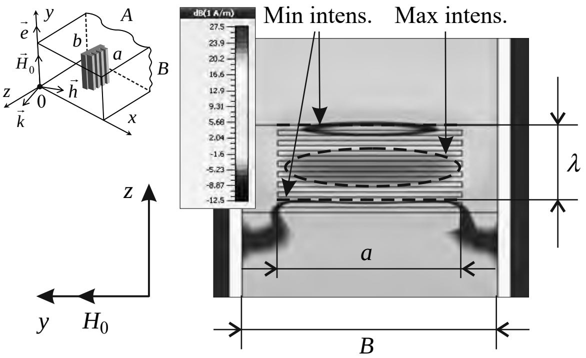


Fig. 5. Electromagnetic field spatial distribution (numerical modelling) for sample No. 3 inside a waveguide (the cross section of the sample is in the middle of the waveguide), H_0 = 1 900 Oe and f_{FMR} = 13.824 GHz

calculated FMR frequency f_{FMR} as a function of the external magnetic field for the $d = 0$ mm and $d = 0.2$ mm samples (the grooves are parallel to the long side a of the sample according to Fig. 2, a). It can be seen that near $H_0 \approx 2\ 000$ Oe the "jumps" are similar to those experimentally observed for the FMR frequency depending on the external magnetic field (marked by the solid-line square in Fig. 3, *a*, *b*). Also, Fig. 3, *c* indicates the passages from "Mode 1" to "Mode 2".

To confirm the assumption above, the spatial distribution of the h_x-component of the electromagnetic field in sample No. 3 is presented in Fig. 5. A numerical modeling was carried out for the mode arising at frequency f_{FMR} = 13.824 GHz and magnetic field intensity $H_0 = 1\ 900$ Oe, the sample location is as in Fig. 2, *a*. From Fig. 5, it can be seen that the wavelength λ in the sample approximately equals the length of its short side *b* at the given frequency (the distance between the two dashed lines).

That is, indeed, the "jumps" on the dependences $f_{FMR} = f_{FMR}\,(H_0)$ in Fig. 3 are observed when the geometric dimensions of the sample are comparable with the wavelength as was assumed earlier.

In other words, at the given magnetic fields, the transitions from one spatial mode (Mode 1) excited in the studied sample to another (Mode 2) (Fig. 3, *c*) occur in the form of "jumps" on the dependences $f_{FMR} = f_{FMR}\ (H_0)$ as observed in the graphs in Fig. 3. That the electromagnetic field spatial distribution shown in Fig. 5 is similar to the electromagnetic field distributions for the other samples at the other resonant frequencies (near the "jumps") and other groove depth *d* values confirms this fact.

Conclusions. We have established that:

1. The *FMR* frequency of the structured ferrite sample depends on the depth of grooves on the ferrite surface. Namely, the *FMR* frequency increases with the groove depth over some range of the external magnetic field.

2. The *FMR* frequency of the investigated structured ferrite depends on the groove orientation relative to the long side of the sample and to the direction of the external magnetic field $\vec{H}_0$. When the grooves are perpendicular to the long side of the sample, the *FMR* frequency is lower than when the grooves are parallel to it due to the influence of the demagnetizing fields of the structured ferrite.

3. When the external magnetic field intensity $H_0 \approx 2.5$ kOe is applied to the structured ferrite sample, the *FMR* frequency dependences on the external static magnetic field demonstrate a "jump-like" behavior. It takes place when the dimensions of the sample are comparable with the wavelength in it.

4. At magnetic fields $H_0 \geq 2.5$ kOe (saturated ferrite), the dependence of the FMR frequency on the groove depth becomes monotonic and increases as the field rises.

Thus, our research shows that the studied structured magnetoactive metamaterials could find application as components of extremely high frequency electronics considering that the magnetic field strength is larger than the saturation field ($H_0 > H_{sat}$). Namely, the ferrite is saturated at this level and has a monotonic increasing dependence of the resonant frequency on the external magnetic field and on the groove depth on its surface.

As for the practical application, it is safe to say that structured ferrites are promising as microwave electronics components with predetermined permeability and electronically tunable anisotropy. The structured ferrites are promising as polarizers and active media for solid-state lasers in the optical range. Also, the structured ferrites can act as memory components in computer technologies.

REFERENCES

1. Zavislyak, I.V., Popov, M.A., Srinivasan, G., 2009. A cut-off millimeter wave resonator technique for mapping magnetic parameters in hexagonal ferrites. *Meas. Sci. Technol.*, **20**(11), pp. 115704 (5 p.). DOI: 10.1088/0957-0233/20/11/115704.
2. Parke, L., Youngs, I.J., Hibbins, A.P., Sambles, J.R., 2014. Broadband impedance-matched electromagnetic structured ferrite composite in the megahertz range. *Appl. Phys. Lett.*, **104**(22), pp. 221905 (4 p.). DOI: 10.1063/1.4881186.
3. Diwekar, M., Kamaev, V., Shi, J., Vardeny, Z.V., 2004. Optical and magneto-optical studies of two-dimensional metallodielectric photonic crystals on cobalt films. *Appl. Phys. Lett.*, **84**(16), pp. 3112–3114. DOI: 10.1063/1.1712027.
4. Kozhaev, M.A., Chernov, A.I., Sylgacheva, D.A., _Shaposhnikov, A.N., Prokopov, A.R., Berzhansky, V.N., Zvezdin, A.K., Belotelov, V.I., 2018. Giant peak of the inverse Faraday effect in the band gap of magnetophotonic crystal. *Sci. Rep.,* **8**(1), pp. 11435 (7 p.). DOI: 10.1038/s41598-018-29294-w.
5. Dong, H.Y., Wang, J., Cui, T.J., 2013. One-way Tamm plasmon polaritons at the interface between magnetophotonic crystals and conducting metal oxides. *Phys. Rev. B*, **87**(4), pp. 045406 (5 p.). DOI: 10.1103/PhysRevB.87.045406.
6. Kharchenko, G.O., Tarapov, S.I., Kalmykova T.V., 2014. Features of the magnetophotonic crystal spectrum in the vicinity of ferromagnetic resonance. *J. Magn. Magn. Mater.*, **373**, pp. 30–32. DOI: 10.1016/j.jmmm.2014.07.011.
7. Kalmykova, T.V., Nedukh, S.V., Polevoy, S.Yu., Kharchenko, A.A., Tarapov, S.I., Belozorov, D.P., Pogorily, A.N., Polek, T.I., Pashchenko, V.A., Bludov, O.M., 2015. Magnetoresonance properties of manganite $La_{1-x}Sr_xMnO_3$ (x = 0.15; 0.225; 0.3; 0.45; 0.6). *Low Temp. Phys.*, **41**(4), pp. 273–278. DOI: 10.1063/1.4918758.
8. Tarapov, S.I., Belozorov, D.P., 2012. Microwaves in dispersive magnetic composite media (Review Article). *Low Temp. Phys.*, **38**(7), pp. 766–792. DOI: 10.1063/1.4733684.
9. Eremenko, V.V., Milner, A.S., Borovik, E.S., 2005. *Lectures on Magnetism*. Moscow: Physmathlit Publ. (in Russian). ISBN-13: 978-5-9221-0577-4.
10. Poole, C., 1997. *Electron Spin Resonance: A comprehensive treatise on experimental techniques*. New York: Dover Publ. ISBN-13: 978-0486694443.
11. Tarapov, S.I., Machekhin, Y.P., Zamkovoy, A.S., 2008. *Magnetic resonance for optoelectronic materials investigating*. Kharkov: Collegium Publ.
12. Vakula, A.S., 2015. Temperature change of the magnetic properties of Fe_3O_4 nanopowders synthesized by different methods in the microwave range. *Radiophys. Electron.*, **20**(3), pp. 62–65 (in Russian). DOI: 10.15407/rej2015.03.062.

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МАГНІТОАКТИВНИЙ МЕТАМАТЕРІАЛ НА ОСНОВІ СТРУКТУРОВАНОГО ФЕРИТУ

Предмет і мета роботи. Використання просторово структурованих феромагнетиків є перспективним для розробки матеріалів із однозначно заданими електромагнітними властивостями. Вони можуть знайти застосування для проєктування магнітокерованих мікрохвильових і оптичних пристроїв. Метою даної роботи є дослідження електромагнітних властивостей зразків структурованих феритів з різною формою (просторовою геометрією) методом електронного спінового резонансу (ЕСР).

Методи і методологія роботи. Магнітні властивості досліджуваних структурованих зразків фериту були досліджені методом ЕСР. Експерименти проводилися в прямокутному хвилеводі шляхом вимірювання спектрів коефіцієнта проходження при заданому зовнішньому магнітному полі.

Результати роботи. В роботі експериментально показано, що для структурованого зразка фериту з канавками частота феромагнітного резонансу (ФМР) збільшується зі збільшенням глибини канавок для деякого діапазону зовнішнього магнітного поля. Частота ФМР також залежить від орієнтації канавок щодо широкої сторони зразка. Показано, що коли зовнішнє постійне магнітне поле стає близьким до поля насичення фериту, залежність частоти ФМР від зовнішнього постійного магнітного поля демонструє «стрибкоподібну» поведінку. У магнітних полях, більших за поле насичення фериту, залежність частоти ФМР від глибини канавки стає монотонною і збільшується з ростом поля.

Висновок. Показано, що застосування структурованих феритів в якості елементів надвисокочастотної електроніки стає прийнятним при напруженості магнітних полів, більших за поле насичення фериту. В цих полях такі ферити мають монотонно зростаючу залежність резонансної частоти від постійного магнітного поля і від глибини канавок на їх поверхні. Структуровані ферити перспективні в мікрохвильовому діапазоні як елементи керованих фільтрів, поляризаторів, анізотропних феритових резонаторів, оскільки в них можна отримати необхідну ефективну магнітну проникність і анізотропію.

Ключові слова: *метаматеріал, ферит, феромагнітний резонанс, НВЧ-діапазон.*