https://doi.org/10.15407/ujpe70.7.487

YU.M. POPLAVKO, YU.V. DIDENKO, D.D. TATARCHUK

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
(37, Beresteiskyi Ave., Kyiv 03056, Ukraine)

METAMATERIALS IN RELATION TO MICROWAVES

Metamaterials are defined as artificial materials composed of periodic structural units to obtain their unusual properties that are not usually found in nature. Of particular interest in the microwave range are materials that interact with the electromagnetic field, as if they would have negative permittivity and/or magnetic permeability. In ordinary materials, negative permittivity or magnetic permeability is possible in the frequency range of antiresonances of polarization or magnetization. The paper examines the possibility to classify metamaterials by the negative values of their susceptibilities, since just these parameters characterize the antiphase response of substance to the applied electromagnetic field. Therefore, there are certain grounds for expanding the usual concept of metamaterials in relation to their use in microwaves.

Keywords: dielectric and magnetic susceptibility, metamaterials, microwave protective materials.

1. Introduction

In the microwave range, metamaterials are used to form the antenna pattern and reduce radar beam reflection from the protected object, where the metamaterial matches the high wave resistance of the dielectric medium (air) with the low wave resistance of the metal surface. Negative permittivity or magnetic permeability is observed in conventional dielectrics and magnets, so given consideration of the physical mechanisms of this phenomenon can be useful for developers of artificial metamaterials for microwave range.

To classify metamaterials, the values of permittivity (ε) and magnetic permeability (μ) are usually used, which enter into Maxwell's equations as $D = \varepsilon_0\varepsilon E$ and $B = \mu_0\mu H$. In a vacuum, the relative parameters $\varepsilon = 1$ and $\mu = 1$, so their true values (including negative ones) are created by electric polarization $P = \varepsilon_0\chi E$ and magnetization $M = \mu_0\varkappa H$, therefore $\varepsilon = 1 + \chi$ and $\mu = 1 + \varkappa$. Thus, really effective parameters must serve the dielectric χ and magnetic $\varkappa$ *susceptibilities*, since χ reflects the ability to electric polarization, and æ characterizes the magnetic response of the substance to the applied EM field. Therefore, for a metamaterial, it is more natural to consider negative values of dielectric and magnetic susceptibilities (i.e., $\chi < 0$ and $\varkappa < 0$).

When overlook discuss various applications of microwave shielding composites and antenna guide elements, it can be assumed that metamaterials include not only traditional doubly negative materials, where $\varepsilon < 0$ and $\mu < 0$ [1–3], but also two types of *single* negative materials: the substances with negative induced polarization (in which $\chi < 0$ and $\varepsilon < 1$, but positive $\varkappa > 0$ and $\mu > 1$) and the substances with negative induced magnetization (where $\varkappa < 0$ and $\mu < 1$, but positive $\chi > 0$, $\varepsilon > 1$). Such an extension of the well-known concept to the cases of single quasi-metamaterials does not contradict traditional understanding.

2. Interaction of EM Waves with Various Substances

When considering the propagation EM waves in diversified media, many various combinations of their electromagnetic parameters are possible. Figure 1 conditionally shows four possible cases, presented in the rectangular coordinate system, in which, as coordinate axes, the dielectric and magnetic susceptibilities χ and $\varkappa$ are plotted (under assumption that these parameters are isotropic).

Almost all *natural* materials, whose electromagnetic parameters are located *outside* quadrant I, can

Citation: Poplavko Yu.M., Didenko Yu.V., Tatarchuk D.D. Metamaterials in relation to microwaves. *Ukr. J. Phys.* **70**, No. 7, 487 (2025). https://doi.org/10.15407/ujpe70.7.487.

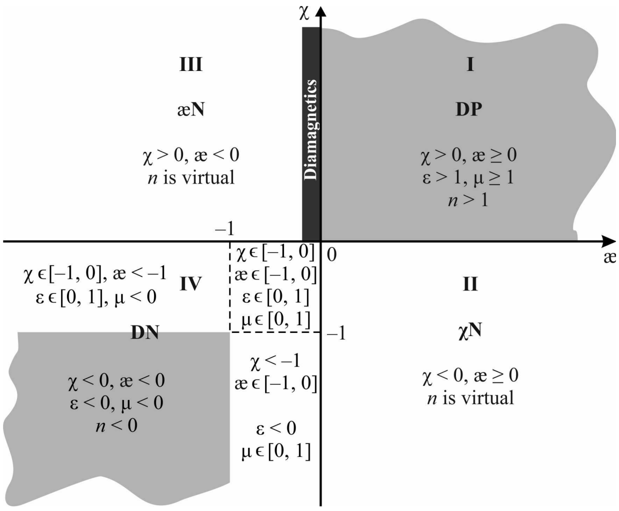


Fig. 1. Classification of varios media behavior in relation to EM impact: I quadrant (DP is a double positive media) corresponding to EM characteristics of ordinary materials; II quadrant for negative induced polarization (χN); III quadrant for negative induced magnetization ($\varkappa N$); IV quadrant for double negative media (DN) corresponding to materials with negative reaction of polarization and magnetization to EM field

be conditionally classified as various manifestations of quasi-metamaterials, although they are not metamaterials by their nature. The fact is that, in a certain narrow frequency interval (namely, above the resonant frequency of polarization or magnetization) the ordinary substances in the region of anti-resonances look like single negative quasi-metamaterials (these manifestations will be described in more details in sections 3 and 4). In dielectrics these can be resonances of some polarization mechanisms or piezoelectric resonances, while, in magnetics, the domain or spin-orbital resonances of magnetization are possible.

The concept of negative susceptibilities corresponds to the fact that when a material is exposed to an alternating EM field in a certain frequency range, the phase of the variable polarization (or magnetization) is opposite to the phase of the field acting on the material. The capacitive current (reflecting the electric polarization) leads the phase of the EM field by $\pi/2$, while the inductive current (corresponding to magnetization) lags the phase of the applied field by $\pi/2$. When the frequency ω of the EM field changes and resonance is approached, the phase difference between the electric (or magnetic) response and the EM effect decreases, so that, at the resonant frequency, their phases coincide and a maximum of $\varepsilon(\omega)$ or $\mu(\omega)$ is observed. But immediately above the resonant frequency, the phases of the EM effect and the quasi-elastic response become opposite, so the polarization (or magnetization) is negative, so the susceptibility must also be negative. To achieve this, electrically charged or magnetic particles oscillating in an electromagnetic field must have inertia, which causes them to move in the direction of the applied force.

2.1. Double positive materials (DP)

In the quadrant I of Fig. 1 symbolically all common materials are placed, which are not related to the metamaterials. They possess positive values for both $\chi > 0$ and $\varkappa > 0$ which means that, in them $\varepsilon > 1$ and $\mu \geq 1$, i.e., their refractive index of the EM wave, incident from a vacuum onto material and partially propagating in medium, is positive ($n > 1$). In any dielectric there are some regions of EM spectrum (usually located in the far infrared and optical parts of the spectrum), where $\chi(\omega) < 0$ due to delayed reaction of polarization; so, in this exceptional case, this material would be located in the II quadrant. Similarly, negative parameter $\varkappa(\omega)$ of ferromagnetics, conditional by the domains or spin-lattice resonances, may appear in the quadrant III in the area of magnetic resonances.

When an EM wave falls on the surface of a dielectric, polarization occurs, causing secondary waves to radiate in all directions (like a dipole antenna). All these waves add up and, in accordance with the Huygens–Fresnel principle, lead to partial reflection and refraction. When an EM wave falls on the surface of a conductor, internal oscillations of electrons occur, generating an electromagnetic field that tends to compensate for this effect, which leads to almost complete reflection of the EM wave from the conductor. All this applies to homogeneous materials.

2.2. Double negative materials (DN)

Figure 1 in quadrant IV corresponds to the ancestors of metamaterial that are most discussed and applied [2,3]. They possess both negative susceptibilities ($\chi <$ < 0 and $\varkappa < 0$) in a certain frequency range, while, usually, these materials are characterized by $\varepsilon < 0$ and $\mu < 0$ and have negative value of refractive index $n = -\sqrt{\varepsilon\mu} < 0$.

The unshaded areas in quadrant IV correspond to situations, when negative values of susceptibilities do not reach value "–1", and therefore it is difficult to judge the sign of refractive index since the dielectric permittivity and/or magnetic permeability in these unshaded areas can change their sign. As for the shaded area, these materials are described in hundreds of works and have many applications, so that do not make sense to repeat here.

3. Phenomena of Negative Electric Polarization

In the quadrant II of Fig. 1, such peculiar case is shown, when electric polarization changes with time in the opposite phase to driving electric field. Therefore, a negative value of dielectric susceptibility is seen: $\chi < 0$ and $\varepsilon < 1$, but with a positive value of magnetic susceptibility: $\varkappa > 0$ and $\mu > 1$. At that, the refractive index n has the imaginary value, so, large absorption with nearly full reflection of EM waves are observed.

In the dielectrics, negative parameter $\chi < 0$ corresponds to such frequency range, in which dielectric dispersion of resonant polarization occurs, Fig. 2, *a*. At radio frequencies, this may be a piezoelectric resonance, in the microwave range such resonance (but damped) may be possessed by ferroelectrics, and in ionic crystals at far infrared frequencies, the resonance of lattice polarization is happening.

In resonant dielectric dispersion, the permittivity passes through a maximum and a minimum, and an effective conductivity appears in the form of a sharp maximum $\sigma(\omega)$ at the resonant frequency ω_0: $\sigma_{\max} = \varepsilon_0 \Delta\varepsilon\omega_0/\Gamma$, where Γ is the attenuation coefficient, and $\Delta\varepsilon$ is the dielectric contribution of a given polarization [4]. The effective conductivity increases due to the weakening of the elastic bonds between the ions of the crystal lattice when approaching resonance. Usually, the ionic lattice resonances are observed at far infrared range, but, in the case of piezoelectric resonances, the frequency depends on the size of the piezoelectric element. To apply these resonances to microwaves, piezoelectric resonators must have a size of several micrometers, which is feasible in microelectronics.

3.1. Features of plasma resonance

Plasma is created by highly mobile electrons moving in the cation lattice of metals and semiconductors. Electronic plasma in conductors exhibits quasi-resonance characteristics: due to the inertia of charge carriers conductivity decreases to zero at a frequency

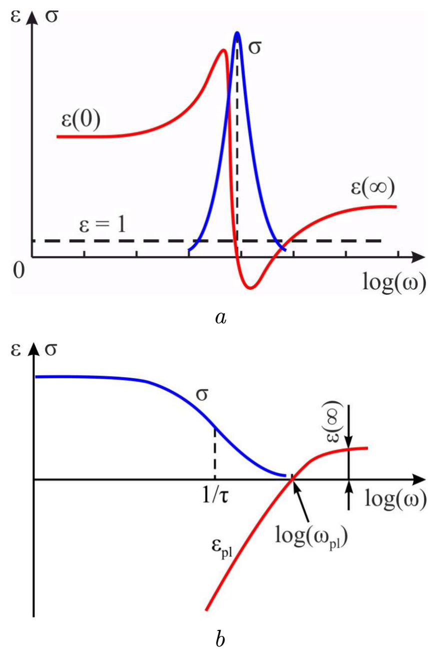


Fig. 2. Frequency dependence of dielectric permittivity ε and conductivity σ; (*a*) is a resonance polarization dispersion in dielectric, $\varepsilon(0)$ is a permittivity before dispersion, $\varepsilon(\infty)$ is a permittivity after dispersion; (*b*) is a plasma resonance in metals, τ is a relaxation time, $\omega_{\rm pl}$ is a frequency of plasma resonance

above 10^{16} Hz, Fig. 2, *a*. In this case, a negative contribution to the effective permittivity appears, which increases above the plasma resonance frequency ($\omega_{\rm pl}$) to a positive value ε_∞. This is polarization of electronic shells, which, for various metals, is characterized by $\varepsilon_\infty = 4...8$. Provided that limiting dielectric constant of metal is $\varepsilon_\infty = 1$, the plasma frequency can be estimated by value $\omega_{\rm pl} = \sqrt{(ne^2/m\varepsilon_0)}$ [4].

Being excited by the applied field, electron of a metal begins its accelerated motion along the free path, but this movement is certainly interrupted by the collision of electron with a dissipation of its acquired energy. As the frequency increases, a moment must come, when the electric field changes its direction before the electron's collision occurs. So, it moves for some time in the anti-phase to applied alternating field, and this process repeats. Conductivity dispersion of the metal is described as

$$\sigma'(\omega) = \frac{\sigma(0)}{1+\omega^2\tau^2};$$

$$\sigma''(\omega) = -\frac{\sigma(0)\omega\tau}{1+\omega^2\tau^2};$$

$$\sigma(0) = \frac{ne^2\tau}{m}.$$

where τ is the relaxation time of electrons, n is their concentration, e is their charge, and m is their mass. The complex conductivity $\sigma^*(\omega) = \sigma'(\omega) + i\sigma''(\omega)$ is related to the complex permittivity $\varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega)$ with regard for the ultraviolet contribution to permittivity ε_∞ shown in Fig. 2, *b*:

$$\varepsilon^*(\omega) = \varepsilon_\infty - \frac{ne^2}{m\varepsilon_0(\omega^2 - i\omega\gamma)} = \varepsilon_\infty - \frac{\omega_{\rm pl}^2}{\omega^2 - i\omega\gamma},$$

where $\varepsilon^*(\omega)$ is expressed in terms of plasma frequency $\omega_{\rm pl}$ while the damping coefficient γ of plasma oscillations is the reciprocal of relaxation time: $\gamma = 1/\tau$. Microwave measurements show that negative permittivity of highly conductive metals approaches several thousands [4], while it is only a few hundred for low-conducting magnetic metals.

At the end of $\sigma(\omega)$ optical dispersion, as can be seen from Fig. 2, *b*, the conductivity decreases so much that it no longer screens the effect of electric field on electronic shells of ions, therefore, the role of their polarization, characterized by the value ε_∞, becomes significant. In nano-sized metallic particles, these processes are noticeable even at microwaves. At that, the nanotechnology makes it possible to control the EM properties of matter. Absorption and transmission characteristics change especially strongly, when moving to nano-sized metal particles. However, in metals with reduced electrical conductivity and, especially, in the finely dispersed 1D, 2D, and 3D metallic particles (which are precisely used as fillers for absorbing microwave composites), the inertia of conduction electrons becomes noticeable already at millimeter and even at centimeter waves, which leads to microwave absorption.

A reduction in the real part of conductivity shown in Fig. 2, *b* is due to the delay of drifting motion of electrons. Just this leads to negative permittivity of metals $\varepsilon'(\omega) = \sigma''(\omega)/(\varepsilon_0\omega)$, associated with imaginary part of conductivity. This behavior of electronic gas in metals in a very high-frequency EM field requires the introduction of plasma frequency concept.

Artificially created ε-negative media can be realized in the composite metamaterials, based predominantly on *metallic* components. In principle, the *dielectric* spheres, cylinders, *etc.*, at microwave frequencies also can be components of metamaterials for instance, as dielectric resonators (DR). They can be implemented using dielectrics with increased permittivity ($\varepsilon \geq 20$), provided at condition that DR's size is multiples of half a wave in dielectric; however, DRs as metamaterials did not find noticeable distribution.

Against, in order to create the artificial resonant structures, the *metallic* elements of different shapes, having dimensions commensurate with the wavelength, are most widespread used. This is favored by the fact that the metal has highly mobile electrons, which react almost inertia-free to a rapidly changing EM field. By a special selection of the shape, size, and suitable design of metallic elements, both positive and negative so-called "dielectric constant" can be obtained.

This technique has been used for a long time to obtain, in aves, the artificial media containing metal components, which in a certain frequency range demonstrate one or another kind of "dielectric polarization" by specific reaction of metaatoms forming a composite. In this case, used to control microwaves structures are very reminiscent of those composite materials which now are called as metamaterials. Various phenomena of EM waves passage through such ones made of metallic components "dielectric structure" have been experimentally realized and widely applied [5]. By this way, the real substance in a certain frequency range is replaced by one or another spatial lattice of metallic elements. At that, when appropriate parameters selecting for particular wavelength λ, they proceed from the principles of similarity, i.e., the distance between elements and dimetions of elements should be small as compared to λ.

The components that make up the metamaterial must have a certain amount of capacitance and inductance. In order to create capacitance (providing the accumulation of electrical charge) or inductance (providing the directional movement of charges) in certain elements, it is necessary to use a material with high mobility of free electrons – that is, a metal. To understand the design development of metaatoms allotted for various purposes, it is advisable to first consider the calculation of elementary capacitances (inductances will be discussed later).

The capacitance of a conductor depends on all its dimensions, i.e., capacity of a wire depends not only on its length and bending, but also on its thickness, while the capacitance of surface area (strip) depends not only on its length and width, but also on its

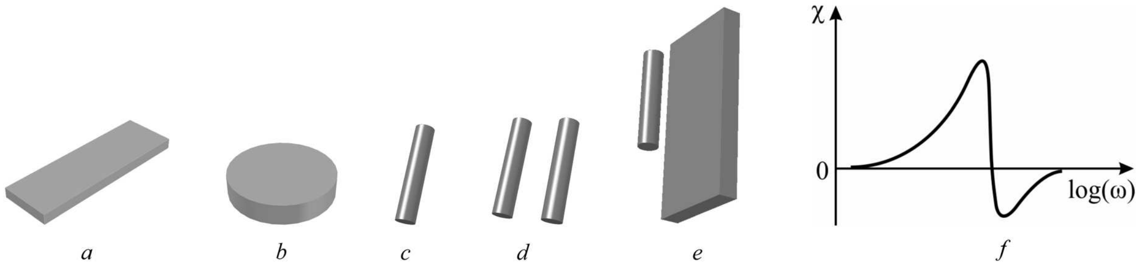


Fig. 3. Capacity of metal fragments: a flat strip (a), $C = S/(4\pi h)$, S is an area, h is a thickness; a disc (b), $C = 2r/\pi$ (r is a radius); a piece of wire (c), $C \approx l/(2\ln(l/r))$, r is a radius, l is a length; two parallel wires (d), $C = l/4\text{arcosh}(d/2r)$, r is a radius, l is a length, d is a distance; a wire near the wall (e), $C = l/2\text{arcosh}(d/r)$, r is a radius, l is a length, d is a distance; a capacitance included in resonant circuit simulates dielectric susceptibility (f)

thickness. Therefore, when scaling (i.e., transferring certain construction of metaatom from one frequency range to r one), it is necessary to consider the thickness of capacitive elements (for example, when scaling with decrease in 100 times, thickness of metal strip increases by the same amount).

The capacitance of a conductor indicates its ability to store electrical charge: $C = q/\varphi$ ($[C] = C$(coulomb)/V(volt) = F(farad)). For example, the capacity of a metallic sphere is $C = 4\pi\varepsilon_0\varepsilon r$, i.e. in the CGS it equals to sphere radius: $C = r$ cm (1 pF = = 0.9 cm). In Fig. 3 some cases are considered with calculation data in centimeters (in accordance with CGS system where 1 cm = 1.1 pF). If the elements are located in the dielectric medium (for example in the polymer composite), then calculation formulas should be multiplied by relative permittivity ε.

Conventionally, metaatoms of composite (consisting of similar metallic elements) are considered as a physical model of the atoms of a crystal: lattice of small scattering particles (modeling atoms) must have period much smaller than EM wavelength. In a certain (sufficiently narrow) frequency interval, such a grating can play the role of "continuous medium". But to obtain the desired effect, certain requirements must be met, at that, main thing is to account that the dimensions of elements themselves and the distance between them in the grating must be less than wavelength. Currently, such requirements are typical of the selection of metamaterials.

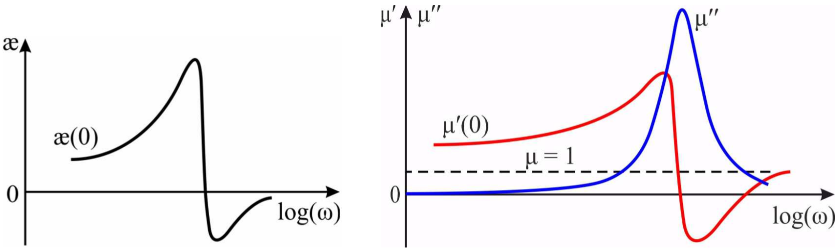
4. Negative Magnetization Phenomena

Quadrant III shown in Fig. 1 characterizes special cases where some materials in a certain frequency range exhibit a negative value of magnetic susceptibility: $\varkappa < 0$ and $\mu < 1$, while simultaneously have positive permittivity $\chi > 0$ and $\varepsilon > 1$. It should be noted that, in most natural substances, the magnetic susceptibility is very small, and, therefore, $\mu \approx 1$. That is why, no noticeable deviations in the interaction with EM waves are observed. Only in the case of magnetics where can be $\mu < 0$ the refractive index for EM waves might have an imaginary value.

The ***natural materials***, in which *at any* frequencies parameter $\varkappa < 0$ (but $\mu > 0$) are different types diamagnetics. The first negative magnetization mechanism exists in any material: the diamagnetism conditional by the orbital electronic moments of atoms. The second mechanism is the Landau diamagnetism due to quantization of electronic gas oscillations, which, in some metals,s can dominant over usual paramagnetism of electrons. However, from the point of view of microwave applications, both these effects are negligible.

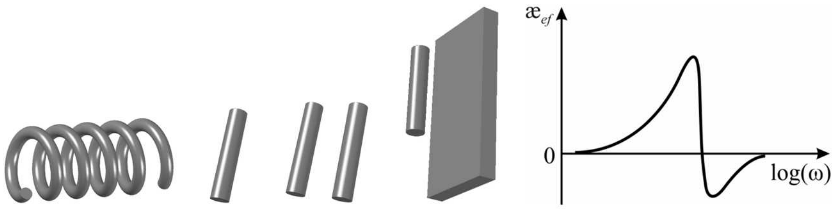
Another event of $\varkappa < 0$, possible in natural materials, can be observed in certain frequency range in the ferromagnetics (most of them are metals), in the antiferromagnetics (most of them are dielectrics) and ferrites, where ferromagnetism and antiferromagnetism coexist, and conductivity is not very high.

In electronics in some cases, it is possible to use the resonance of magnetic domains (taking place in megahertz range), while in microwaves a very important mechanism is the spin-orbital resonance in ferrites. In the ferromagnetics and ferrites the value of susceptibility reaches several hundreds because of consistent orientation of electronic spins associated with crystal lattice that gives quasi-elastic nature of high magnetization. Any resonance (as well as ferromagnetic resonance) is possible only when there is elastic connection in a system; therefore, inertia of magnetization mechanism is conditioned by the in-



a *b*

Fig. 4. Frequency dependence of: a magnetic susceptibility $\varkappa$ (*a*), and a permeability μ for resonance magnetization dispersion (*b*): $\varkappa(0)$ and $\mu(0)$ are susceptibility and permeability before dispersion; $\mu = 1$ is a permeability after dispersion



a *b* *c* *d* *e*

Fig. 5. Inductance of metallic fragments: a solenoid with length l and diameter $D < l$, number of turns N, cross-section S: $L = \mu_0 N^2 S/l$ (*a*); a straight wire with length l, radius r: $L = \mu_0 l(\ln l/r + 1/4)/(2\pi)$ (*b*); two parallel wires with length l, radius r, distance between them $d \geq 2r$: $L = \mu_0 l(\text{arcosh}(d/2r))/(2\pi)$ (*c*); a wire parallel conducting wall with length l, radius r, distance to wall $d \geq r$: $L = \mu_0 l \log(2d/r)/(2\pi)$ (*d*); a inductance included in resonant circuit simulates effective magnetic susceptibility (*e*)

ertia in certain vibrations of the crystal lattice associated with electronic spins. In most magnetics, their resonance frequency is located at the beginning of microwave range, and it is noteworthy that frequency f_{FMR} is the lower the greater initial magnetic susceptibility $\varkappa(0)$, Fig. 4, *a*, which reveals the essence of spin-orbial magnetic resonance.

The frequency f_{FMR} should be lower that corresponds to larger $\mu(0)$; this implies the limitation for ferromagnetic material applicability in microwaves (which is called as Snoek's law) [6]. It claims that the product of the low-frequency magnetic susceptibility and the frequency of ferromagnetic resonance is a constant value for given ferromagnetic: $\varkappa(0) f_{\text{FMR}} = K_S$. The Snoek's constant K_S is determined mostly by the composition of a material, and only a little depends on its structure [2]. Most ferrites are characterized by Snoek's constant ranging from 2 to 5 GHz, but some of ferromagnetic metals and alloys can have much higher K_S due to high saturation of magnetization; for example, for iron $K_S \approx 40$ GHz. However, this rule applies to bulk material, while in microwave absorbers only a very small particles of ferromagnetic metals are applicable: in form of a powders or films.

It should be noted also that despite the similarity of resonance curves in Fig. 4 and Fig. 2, the magnetic absorption mechanism is not equivalent to electrical absorption maximum since there are no magnetic charges in a nature, and the idea of effective conductivity in this case would be incorrect. Energy absorption during magnetic resonance is determined by the fact that the EM field excites special vibrations of magnetic crystal (magnons), which are associated with electronic spins connected to the lattice through orbital magnetism and leading to electromagnetic resonance. Due to the inevitable anharmonicity of the vibrations, their energy is partially transferred to the "thermal reservoir" of the chaotically vibrating crystal lattice.

The ***artificial magnetic materials*** use to control the value and sign of effective parameter $\mu_{\text{ef}}(\omega)$. This parameter is different to natural "true" magnetism. At the same time, the increasing of magnetic response by artificial metaatoms is very important for some microwave devices (although this is possible in a rather narrow frequency interval).

Discussing the possibilities of developing an absorbing microwave composite, it should be noted that the growth in its permittivity leads to an undesirable increase in the reflection coefficient of EM waves; on the contrary, adding a magnetic component to the composite leads to a significant decrease in their reflection because permeability compensates for permittivity (ideal case when $\varepsilon = \mu$). Therefore, it is desirable to increase the magnetic "permeability" of the composite, at least due to artificial "magnetic" inclusions. The magnetic component of meta-atoms (as well as dielectric ones) can be obtained not necessarily from a magnetic, but from any metal with a small $\varkappa$ with $\mu \approx 1$. Some miniature metal elements with their own inductance are shown in Fig. 5. These can be circuits consisting of open turns, or other structures with resonant properties. As the frequency increases above the resonant one, the effective magnetic permeability becomes negative.

Therefore, in both II and III quadrants shown in Fig. 1, the single negative metamaterials are presented. They can be described by either negative ε or negative μ. In natural materials, these cases occur in a certain frequency range, and are due to the resonant dispersion of either permittivity or permeability. This dispersion is inevitably accompanied by the absorption of EM energy, then in a certain frequency range. In media with EM dispersion, electromagnetic waves decay according to an exponential law. Therefore, such materials are practically opaque to EM radiation, if their thickness exceeds characteristic exponential decay length of EM waves. When metamaterials elaboration, many compromise solutions are possible, because electromagnetic resonances are artificially excited by small elements, which can use nonmagnetic material.

5. Conclusions

The article presents an unconventional approach to metamaterial-like structures by analyzing the interaction of EM waves with various media. The fact is that, for microwave technolsogies, not only metamaterials with simultaneously negative permittivity and magnetic permeability are of interest, but also structures with only ε-negative or only μ-negative parameters. The possibility of classifying such materials by the values of permittivity and magnetic susceptibility is considered. Consideration of the features of the interaction of EM waves with various media makes it possible to indicate cases of a negative reaction of both electric polarization and magnetization to the applied electromagnetic field. At the same time, not only in composites, but also in natural materials in a certain frequency range, the same substance in certain frequency ranges can look like a completely different electromagnetic medium. The described resonance phenomena in natural materials can be important in the development of artificial structures from metaatoms capable of simulating permittivity and magnetic resonances, providing negative values of permittivity and magnetic permeability.

1. K. Sun, R. Fan, X. Zhang, Z. Zhang, Z. Shi, N. Wang, P. Xie, Z. Wang, G. Fan, H. Liu, C. Liu, T. Li, C. Yan, Z. Guo. An overview of metamaterials and their achievements in wireless power transfer. *J. Mater. Chem. C* **6**, 2925 (2018).
2. J.B. Pendry, A.J. Holden, D.J. Robbins, W.J. Stewart. Magnetism from conductors and enhanced nonlinear phenomena. *IEEE T. Microw. Theory* **47** (11), 2075 (1999).
3. N. Engheta, R.W. Ziolkowski. *Metamaterials. Physics and Engineering Explorations* (Wiley, 2006) [ISBN: 978-0-471-76102-0].
4. Y. Poplavko, Y. Yakymenko. *Functional Dielectrics for Electronics. Fundamentals of Conversion Properties* (Elsevier, 2020) [ISBN: 978-0-128-18835-4].
5. J. Kruželák, A. Kvasničáková, K. Hložeková, I. Hudec. Progress in polymers and polymer composites used as efficient materials for EMI shielding. *Nanoscale Adv.* **3** (1), 123 (2021).
6. O. Acher, S. Dubourg. Generalization of Snoek's law to ferromagnetic films and composites. *Phys. Rev. B* **77** (10), 104440 (2008).

Received 06.04.25

Ю.М. Поплавко, Ю.В. Діденко, Д.Д. Татарчук

МЕТАМАТЕРІАЛИ У МІКРОХВИЛЬОВОМУ ДІАПАЗОНІ ЧАСТОТ

Метаматеріали визначаються як штучні матеріали, що складаються з періодичних структурних одиниць та мають незвичайні властивості, які зазвичай не зустрічаються в природі. Особливий інтерес у мікрохвильовому діапазоні частот становлять матеріали, які взаємодіють з електромагнітним полем так, ніби вони мають негативну діелектричну проникність та/або магнітну проникність. У звичайних матеріалах негативна діелектрична або магнітна проникність можлива в діапазоні частот антирезонансів поляризації або намагніченості. У статті розглядається можливість класифікації метаматеріалів за негативними значеннями їх сприйнятливостей, оскільки саме ці параметри характеризують протифазну реакцію речовини на прикладене електромагнітне поле. Тому є певні підстави для розширення звичайного поняття метаматеріалів стосовно їх використання в мікрохвильовому діапазоні частот.

Ключові слова: діелектрична сприйнятливість, магнітна сприйнятливість, метаматеріали, мікрохвильові захисні матеріали.