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Investigation of the microwave chiral metamaterial based on a uniform set of C-shaped conductive inclusions

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Abstract – The paper considers an artificial chiral metamaterial created on a homogeneous container basefrom foamed dielectric, in which flat conducting S-shaped microelements are evenly placed and arbitrarily oriented. To describe the metamaterial, a particular mathematical model was constructed that takes into account chirality, dispersion, and heterogeneity of the structure. The Maxwell Garnett model was used to account for heterogeneity. To take into account the dispersion of the chirality parameter, the Condon model known from the theory of optically active media was used. The partial domain method was used to solve the problem of the incidence of a plane electromagnetic wave of linear polarization on a planar layer created on the base of the investigated chiral metamaterial. The solution of the problem was reduced to an inhomogeneous system of linear algebraic equations for unknown reflection and transmission coefficients, taking into account the cross-polarization of the electromagnetic field. An analysis of the numerical results showed that the structure has pronounced frequency selective properties, in particular, as in the case of chiral metamaterial based on three-dimensional conductive elements, discrete frequencies were determined at which the structure is transparent to microwave radiation. Chiral metamaterial based on C-shaped microelements can be used to create narrow-band frequency-selective microwave energy concentrators of planar type.
Keywords – chiral media; chiral metamaterial; metamaterial; metastructure; C-element; spatial dispersion; frequency selectivity; Maxwell Garnett model; Condon model; microwave energy.

Introduction

Interest in metamaterials, which is associated with the detection of new properties of the interaction between electromagnetic fields and artificial matter, is increasing every year. A large number of scientific publications on the electrodynamics of metamaterials [1–5] discuss various structures and their electromagnetic properties. Any metamaterial consists of electromagnetic resonant particles (inclusions) that are placed in various ways in a substance of another type (container medium). Inclusions form a two-dimensional or three-dimensional matrix, which changes the values of the dielectric and/or magnetic permeability of the metamaterial as a whole. As a result, the geometric and material parameters of inclusions and the container medium at the metamaterial development stage can be varied to obtain specific electromagnetic properties. In scientific works, considerable attention has been focused on the development of metamaterials to obtain negative refractive properties (Veselago media) [6–8], frequency-selective "invisibility" of objects covered with metamaterial [9], frequency-selective concentration of microwave energy [10–12], and polarization transformation. Currently, metamaterials have been synthesized in the frequency range of 1–100 GHz. The use of metamaterials in microwave technology is also diverse, including microwave filters, phase shifters, polarizing devices, couplers, and transmission lines [13–15]. A significant number of studies have focused on metamaterials in antenna technology, including MIMO devices [16–18].

A special type of metamaterial is chiral medium [19–23], which is characterized by mirror asymmetric conductive composites. Examples of chiral (mirror asymmetric) inclusions are Tellegen elements, thin-wire three-dimensional and plane spirals, S-shaped elements, strip gammadions, multi-start spiral elements, and single and double open rings. In such structures, normal waves are waves with right-handed and left-handed circular polarizations (RCP and LCP, respectively) and different phase velocities. Another property of chiral metamaterials (CMMs) is the cross-polarization of the reflected and transmitted fields.

To describe the electromagnetic properties of CMMs and consider the properties of chirality, a third material parameter, called the chirality parameter, which refers to a certain coupling coefficient between electrical and magnetic processes in an artificial environment, is introduced. Any mirror asymmetric element has an inextricable composition of elementary electric (thin-wire and strip conductor with current) and magnetic (open loop with current) dipoles because of its unique shape.

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In most cases, to describe the CMM, material equations with the following forms are used (Lindell–Sivola formalism) [19]:

$$\vec{\mathbf{D}} = \varepsilon\vec{\mathbf{E}} \mp i\chi\vec{\mathbf{H}}, \quad \vec{\mathbf{B}} = \mu\vec{\mathbf{H}} \pm i\chi\vec{\mathbf{E}}, \tag{1}$$

where $\vec{\mathbf{E}}$, $\vec{\mathbf{H}}$, $\vec{\mathbf{D}}$, and $\vec{\mathbf{B}}$ are the complex amplitudes of the vectors of intensity and induction of electric and magnetic fields, respectively, and i is the imaginary unit. In Eq. (1), the upper signs correspond to the CMM based on mirror asymmetric components with a right twist (right-handed forms of the components), and the lower signs correspond to the CMM based on mirror asymmetric components with a left twist (left-handed forms of the components). Eq. (1) is expressed with the Gaussian system of units and written under the assumption of harmonic dependence of the electromagnetic field vectors on time.

Notably, to describe the interaction between an electromagnetic field and a chiral medium, along with the relative dielectric ε and magnetic μ permeabilities, a dimensionless chirality parameter χ is introduced. For real cases, all functions are frequency dependent, that is, $\varepsilon = \varepsilon(\omega)$, $\mu = \mu(\omega)$, and $\chi = \chi(\omega)$.

Refs. [12, 24] showed the possibility of using CMMs based on thin-wire conductive single-start and multi-start spiral elements for the frequency-selective concentration of microwave energy. In Refs. [10, 11], similar effects were theoretically predicted for a planar layer of a chiral medium based on composite thin-wire spiral elements and strip gammadions. Several mathematical models of the CMM are described in Refs. [32–34].

This study proposes a method for constructing a mathematical model of a CMM based on C-shaped elements, which are placed in a volumetric container made of foam dielectric. When constructing a mathematical model of the investigated CMM, the main properties of the material, namely, chirality, dispersion of material parameters, and heterogeneity, are considered. As an example of the use of the constructed mathematical model, the solution to the problem of reflection of a flat electromagnetic model of linear polarization from a planar layer of a CMM based on conductive C-shaped inclusions, uniformly placed and randomly oriented in a dielectric container, is considered.

1. Development of a particular mathematical model of a CMM

The currently used mathematical models of CMMs in most cases are insufficiently generalized because they do not consider all of the basic properties of metamaterials. In particular, only a few publications considered the heterogeneity of metamaterials as a whole. Here, we discuss the fact that, in most cases, the metamaterial is described by frequency-dependent effective dielectric permeability $\varepsilon(\omega)$.

Let us consider the generalized structure of the arbitrary metamaterial shown in Fig. 1. The CMM consists of a dielectric container (A) with relative permeabilities ε_c and μ_c, where chiral metal inclusions (B) are placed. The areas comprising mirror-like asymmetric elements have relative permeabilities ε_s and μ_s. The linear dimension of the areas is d, and the distance between adjacent elements is l.

Notably, the effective dielectric and magnetic permeabilities of CMMs in the general case depend on the corresponding parameters of the container and the areas where the conductive mirror asymmetric microelements are placed, that is, $\varepsilon = \varepsilon(\varepsilon_c, \varepsilon_s)$ and $\mu = \mu(\mu_c, \mu_s)$. In future work, a foam dielectric will be used as a container medium, in which $\mu = 1$.

To describe heterogeneous properties in physics, several different models (e.g., Maxwell Garnett, Bruggeman, and Odoevsky models) are used [25–27]. In this study, we consider the Maxwell Garnett model, which leads to the following relationship for the effective dielectric permeability of the CMM:

$$\varepsilon = \varepsilon_c \frac{1 + 2\alpha\varepsilon_x}{1 - \alpha\varepsilon_x}; \quad \varepsilon_x = \frac{\varepsilon_s - \varepsilon_c}{\varepsilon_s + 2\varepsilon_c}, \tag{3}$$

where ε is the relative effective dielectric permeability of the CMM, ε_c is the relative dielectric permeability of the dielectric container (A), ε_s is the relative dielectric permeability of regions occupied by chiral inclusions (B), and α is the volume concentration.

In studies conducted by other authors [28], the use of the Maxwell Garnett and Bruggeman models is equivalent at low concentrations of inclusions.

To consider the dispersion of the dielectric permeability of Region B, we use the Drude–Lorentz model:

$$\varepsilon_s(\omega) = \varepsilon_\infty + \frac{(\varepsilon_c - \varepsilon_\infty)\omega_p^2}{\omega_0^2 + 2i\delta_e\omega - \omega^2}, \tag{4}$$

where ε_∞ is the asymptotic value of the dielectric permeability at $\omega \to \infty$, δ_e is the damping coefficient, ω_p^2 is the resonant frequency of absorption, and ω_0^2 is the resonant frequency of the microelement, which is calculated for a specific chiral microelement in a quasi-stationary approximation.

To describe the frequency dependence of the chirality parameter, this study uses the Condon model,

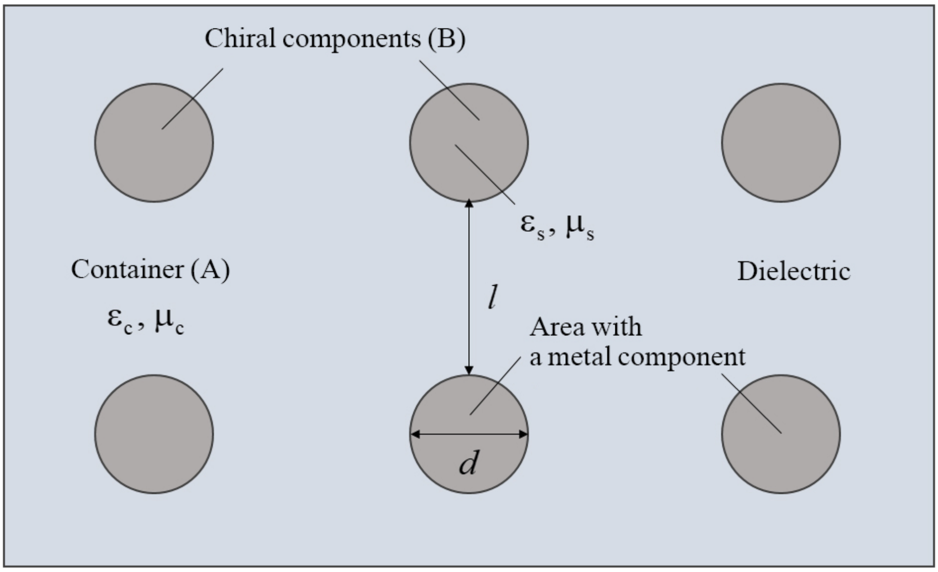

Fig. 1. Generalized structure of an arbitrary CMM
Рис. 1. Обобщенная структура произвольного КММ

which was initially applied in the theory of optically active media [29, 30]:

$$\chi(\omega) = \frac{\omega_0^2 \beta_0 \omega}{\omega_0^2 + 2i\delta_x \omega_0 \omega - \omega^2}, \tag{5}$$

where β_0 is a constant with an inverse time dimension and describes the degree of mirror asymmetry of the microelement and δ_x is the damping coefficient of the chirality parameter.

By substituting Eq. (4) into Eq. (3), we obtain the following equation for the frequency-dependent effective dielectric permeability in the Maxwell Garnett model:

$$\varepsilon(\omega) = \varepsilon_c \frac{1 + 2\alpha\varepsilon_x(\omega)}{1 - \alpha\varepsilon_x(\omega)}; \tag{6}$$

$$\varepsilon_x = \frac{\varepsilon_\infty + \dfrac{(\varepsilon_c - \varepsilon_\infty)\omega_p^2}{\omega_0^2 + 2i\delta_e\omega - \omega^2} - \varepsilon_c}{\varepsilon_\infty + \dfrac{(\varepsilon_c - \varepsilon_\infty)\omega_p^2}{\omega_0^2 + 2i\delta_e\omega - \omega^2} + 2\varepsilon_c}.$$

In Eq. (6), the relative dielectric permeability of the container medium is considered frequency-independent.

Thus, the generalized mathematical model of the CMM in the considered formalism, considering Eqs. (1), (5), and (6), has the following form:

$$\vec{\mathbf{D}} = \varepsilon(\omega)\vec{\mathbf{E}} \mp i\chi(\omega)\vec{\mathbf{H}}, \quad \vec{\mathbf{B}} = \mu\vec{\mathbf{H}} \pm i\chi(\omega)\vec{\mathbf{E}}; \tag{7}$$

$$\varepsilon(\omega) = \varepsilon_c \frac{1 + 2\alpha\varepsilon_x(\omega)}{1 - \alpha\varepsilon_x(\omega)}; \quad \chi(\omega) = \frac{\omega_0^2 \beta_0 \omega}{\omega_0^2 + 2i\delta_x \omega_0 \omega - \omega^2};$$

$$\varepsilon_x = \frac{\varepsilon_s(\omega) - \varepsilon_c}{\varepsilon_s(\omega) + 2\varepsilon_c}; \quad \varepsilon_s(\omega) = \varepsilon_\infty + \frac{(\varepsilon_c - \varepsilon_\infty)\omega_p^2}{\omega_0^2 + 2i\delta_e\omega - \omega^2}.$$

The mathematical model of Eq. (7) is valid for the case when all chiral microelements have identical shapes and linear dimensions, are located equidistantly and chaotically oriented, and the magnetic permeability of the CMM is frequency-independent.

Based on Eq. (7), a particular mathematical model of a CMM is constructed based on a specific type of mirror asymmetric element.

Let us consider the calculation of the resonant frequency of a C-shaped element using a quasi-stationary approximation.

The structure of a CMM cell based on a C-shaped element is shown in Fig. 2. The C-shaped element is described by the outer radius R and inner radius r of the conductive strip. All elements are located at equal distances l from each other. In this case, the C-shaped elements can be rotated relative to their geometric centers in both vertical and horizontal planes.

In the quasi-static approximation, the chiral element is replaced by an inductive–capacitive circuit. To calculate the resonant frequency, we use Thomson's equation:

$$\omega_0 = \frac{1}{\sqrt{LC}}, \tag{8}$$

where L is the total inductance of the chiral component and C is the capacity of the chiral component.

The capacity of the C-shaped element, considering its connection with the four adjacent inclusions, is determined as follows:

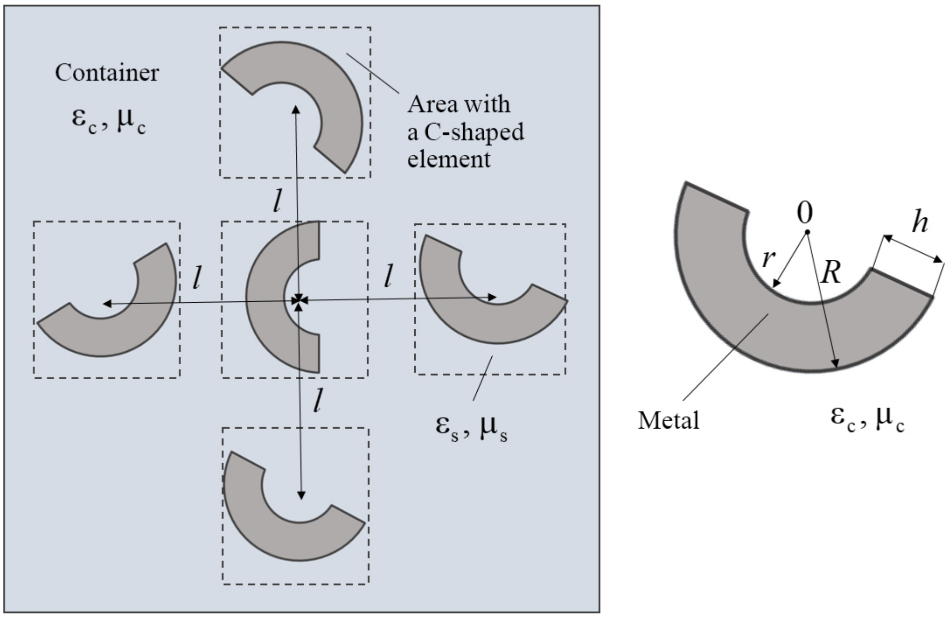

Fig. 2. Structure of a CMM cell based on a C-shaped element
Рис. 2. Структура ячейки КММ на основе С-образного элемента

$$C = C_e + C_{ie}, \tag{9}$$

that is, in the form of a superposition of the capacitances of the element C_e and the inter-element capacitance C_{ie}.

The intrinsic capacity of a C-shaped element is defined as follows:

$$C_e = \varepsilon_c \frac{\pi\left(R^2 - r^2\right)}{2h}, \tag{10}$$

where h is the thickness of the metamaterial container. During recording, we assume that the baseline of the C-shaped element is the middle line with the radius of the semicircle $R' = \left(R + r\right)/2$ and the width of the strip is $h = R - r$.

The inter-element capacitance is determined using the following equation:

$$C_{мэ} = \varepsilon_c \frac{\pi\left(R^2 - r^2\right)}{8l}, \tag{11}$$

where l is the distance between the centers of adjacent areas in which the C-shaped elements are inscribed.

As a result, the equation for the total capacity of the N-start gammadion has the following form:

$$C = \frac{\varepsilon_c \pi\left(R^2 - r^2\right)}{2h}\left[1 + \frac{h}{4l}\right]. \tag{12}$$

The inductance of a C-shaped element is determined using the following equation:

$$L = \mu_c \frac{\sqrt{2}\left(\frac{R + r}{2}\right)^2}{R - r} = \mu_c \frac{\sqrt{2}\left(R + r\right)^2}{4\left(R - r\right)}. \tag{13}$$

Using Thomson's equation (Eq. (8)) and considering Eqs. (12) and (13), the equation for the resonant frequency of the C-shaped element is derived as follows:

$$\omega_0 = \frac{1}{\sqrt{\varepsilon_c \mu_c}} \frac{1}{\sqrt{\frac{\sqrt{2}\pi}{8h}\left[1 + \frac{h}{4l}\right]\left(R + r\right)^3}}. \tag{14}$$

Eq. (14) was obtained using the quasi-static approximation, and its use is possible only in the range $\omega \in \left(0;\ \omega_{max}\right)$, where ω_{max} is the maximum frequency at which the elements can be considered quasi-stationary $cT \gg 1$ (where c is the speed of light and T is the period of the electromagnetic field oscillation).

Thus, a particular mathematical model of a CMM based on a uniform set of C-shaped elements considering Eqs. (1), (7), and (14) has the following form:

$$\vec{\mathbf{D}} = \varepsilon\left(\omega\right)\vec{\mathbf{E}} \mp i\chi\left(\omega\right)\vec{\mathbf{H}}, \quad \vec{\mathbf{B}} = \mu\vec{\mathbf{H}} \pm i\chi\left(\omega\right)\vec{\mathbf{E}}; \tag{7}$$

$$\varepsilon\left(\omega\right) = \varepsilon_c \frac{1 + 2\alpha\varepsilon_x\left(\omega\right)}{1 - \alpha\varepsilon_x\left(\omega\right)};$$

$$\chi\left(\omega\right) = \frac{\omega_0^2 \beta_0 \omega}{\omega_0^2 + 2i\delta_x\omega_0\omega - \omega^2};$$

$$\varepsilon_x = \frac{\varepsilon_s\left(\omega\right) - \varepsilon_c}{\varepsilon_s\left(\omega\right) + 2\varepsilon_c};$$

$$\varepsilon_s\left(\omega\right) = \varepsilon_\infty + \frac{\left(\varepsilon_c - \varepsilon_\infty\right)\omega_p^2}{\omega_0^2 + 2i\delta_e\omega - \omega^2};$$

$$\omega_0 = \frac{1}{\sqrt{\varepsilon_c \mu_c}} \frac{1}{\sqrt{\frac{\sqrt{2}\pi}{8h}\left[1 + \frac{h}{4l}\right]\left(R + r\right)^3}}.$$

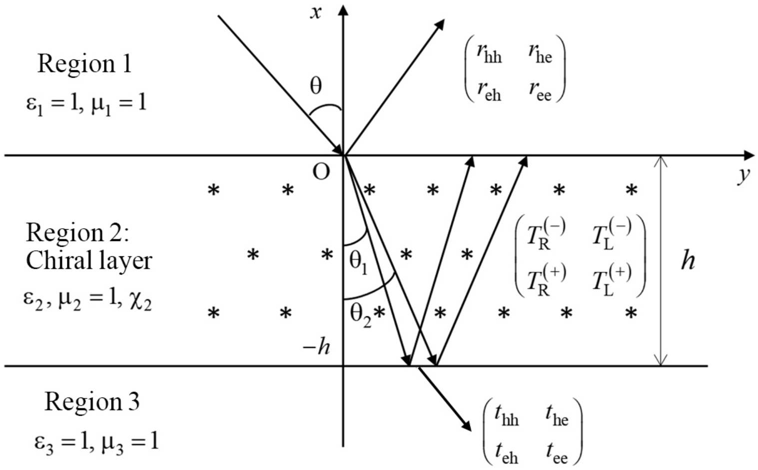

Fig. 3. Geometry of the problem
Рис. 3. Геометрия задачи

2. Problem of the incidence of a plane electromagnetic wave on a planar CMM layer based on a uniform set of C-shaped elements

Let us consider the problem of the incidence of a plane electromagnetic wave with linear E- or H-polarization on a planar layer of CMM based on a uniform set of C-shaped elements. The problem geometry is shown in Fig. 3.

A plane electromagnetic wave is incident on a layer of metamaterial at an angle θ. Region 1 is a dielectric with dielectric and magnetic permeabilities ε_1 and μ_1. The chiral layer (Region 2) is described by material parameters ε_2, μ_2, and χ_2 within the proposed mathematical model of Eq. (7). The concentration of chiral inclusions in Region 2 is equal to α_2. The thickness of the metamaterial layer is h. Region 3 is a dielectric with dielectric and magnetic permeabilities ε_3 and μ_3. When solving the problem, we assume that the planar layer is indefinitely extended along the axis Oz and consider the phenomenon of cross-polarization that occurs when an electromagnetic wave is reflected (passed) from a layer of CMM, that is, when a wave with E-polarization is incident, components of the reflected and transmitted electromagnetic fields with H-polarization, and vice versa, will appear.

The reflection coefficients from the planar metamaterial layer can be written as a 2 × 2 matrix:

$$\hat{\mathbf{R}} = \begin{pmatrix} r_{\text{hh}} & r_{\text{he}} \\ r_{\text{eh}} & r_{\text{ee}} \end{pmatrix}, \tag{8}$$

where r_{hh} is the reflection coefficient of the wave field with H-polarization when a wave with H-polarization is incident, r_{he} is the reflection coefficient of the wave field with H-polarization when a wave with E-polarization is incident, r_{ee} is the reflection coefficient of the wave field with E-polarization when a wave with E-polarization is incident, and r_{eh} is the reflection coefficient of the wave field with E-polarization when a wave with H-polarization is incident.

Similarly, the transmission coefficients in Region 3 are described by the following matrix:

$$\hat{\mathbf{T}} = \begin{pmatrix} t_{\text{hh}} & t_{\text{he}} \\ t_{\text{eh}} & t_{\text{ee}} \end{pmatrix}, \tag{9}$$

where t_{hh} is the transmission coefficient of the wave field with H-polarization when a wave with H-polarization is incident, t_{he} is the transmission coefficient of the wave field with H-polarization when a wave with E-polarization is incident, t_{ee} is the transmission coefficient of the wave field with E-polarization when a wave with E-polarization is incident, and t_{eh} is the transmission coefficient of the wave field with E-polarization when a wave with H-polarization is incident.

Inside Region 2, according to the general properties of the chiral medium, electromagnetic waves propagate with RCP and LCP refracted from Regions 1 and 2 and reflected from the interface with Region 3.

The reflection and transmission coefficients of the RCP and LCP waves in Region 2 are described by the following matrix:

$$\hat{\mathbf{S}} = \begin{pmatrix} T_{\text{R}}^{(-)} & T_{\text{L}}^{(-)} \\ T_{\text{R}}^{(+)} & T_{\text{L}}^{(+)} \end{pmatrix}. \tag{10}$$

Thus, the matrices of the reflection and transmission coefficients of the main and cross-polarized field components expressed in Eqs. (8) to (10) need to be determined. To solve this problem, we use the method of partial areas.

A layer of CMM based on C-shaped elements is described by the material equation (Eq. (1)) [19]:

$$\vec{\mathbf{D}}^{(2)} = \varepsilon_2(\omega)\vec{\mathbf{E}}^{(2)} \mp i\chi_2(\omega)\vec{\mathbf{H}}^{(2)}; \quad (11)$$

$$\vec{\mathbf{B}}^{(2)} = \mu_2 \vec{\mathbf{H}}^{(2)} \pm i\chi_2(\omega)\vec{\mathbf{E}}^{(2)}.$$

where the upper and lower signs determine the right or left shape of the mirror asymmetric components. The relationship in Eq. (13) is expressed with the Gaussian system of units.

To describe the electromagnetic properties of the metamaterial under study, a particular mathematical model of Eq. (7) is used.

Vectors of the electric and magnetic field strengths of a chiral medium are determined using a system of second-order differential equations with the following form [19]:

$$\nabla^2\vec{\mathbf{E}}^{(2)} + k_0^2\left[\varepsilon_2(\omega)\mu_2 + \chi_2^2(\omega)\right]\vec{\mathbf{E}}^{(2)} - \quad (12)$$

$$- 2i k_0^2\mu_2\chi_2(\omega)\vec{\mathbf{H}}^{(2)} = 0;$$

$$\nabla^2\vec{\mathbf{H}}^{(2)} + k_0^2\left[\varepsilon_2(\omega)\mu_2 + \chi_2^2(\omega)\right]\vec{\mathbf{H}}^{(2)} +$$

$$+ 2i k_0^2\varepsilon_2(\omega)\chi_2(\omega)\vec{\mathbf{E}}^{(2)} = 0,$$

where k_0 is the wave number of a plane homogeneous wave in free space.

Vectors of the electric and magnetic field strengths of a chiral medium are written in the form of a superposition of wave fields with circular polarizations [19]:

$$\vec{\mathbf{E}}^{(2)} = \vec{\mathbf{E}}_R + \vec{\mathbf{E}}_L; \quad \vec{\mathbf{H}}^{(2)} = i\sqrt{\frac{\varepsilon_2(\omega)}{\mu_2}}\left(\vec{\mathbf{E}}_R - \vec{\mathbf{E}}_L\right). \quad (13)$$

Thus, with respect to $\vec{\mathbf{E}}_R$ and $\vec{\mathbf{E}}_L$, the homogeneous Helmholtz equation can be expressed as follows [19]:

$$\nabla^2\vec{\mathbf{E}}_{R,L} \pm k_{R,L}^2\vec{\mathbf{E}}_{R,L} = 0, \quad (14)$$

where $\vec{\mathbf{E}}_R$ is the electric field strength of a wave with RCP, $\vec{\mathbf{E}}_L$ is the electric field strength of a wave with LCP, and $k_{R,L} = k_0\left[\sqrt{\varepsilon_2(\omega)\mu_2} \pm \chi_2(\omega)\right]$ is the wave number for RCP and LCP waves in an unbounded chiral medium.

The solutions to Eq. (14) have the following form and determine the fields of four waves with RCP and LCP propagating in Region 2 [31]:

$$E_z^{(2)} = T_R^{(-)}e^{-ik_R(\vec{\mathbf{s}}_R^-,\vec{\mathbf{r}})} + T_R^{(+)}e^{-ik_R(\vec{\mathbf{s}}_R^+,\vec{\mathbf{r}})} + \quad (15)$$

$$+ T_L^{(-)}e^{-ik_L(\vec{\mathbf{s}}_L^-,\vec{\mathbf{r}})} + T_L^{(+)}e^{-ik_L(\vec{\mathbf{s}}_L^+,\vec{\mathbf{r}})};$$

$$H_z^{(2)} = \frac{i}{\eta_2}\left[T_R^{(-)}e^{-ik_R(\vec{\mathbf{s}}_R^-,\vec{\mathbf{r}})} + T_R^{(+)}e^{-ik_R(\vec{\mathbf{s}}_R^+,\vec{\mathbf{r}})} - \right.$$

$$\left. - T_L^{(-)}e^{-ik_L(\vec{\mathbf{s}}_L^-,\vec{\mathbf{r}})} - T_L^{(+)}e^{-ik_L(\vec{\mathbf{s}}_L^+,\vec{\mathbf{r}})}\right],$$

where $\vec{\mathbf{s}}_{R,L}^- = \left\{-\cos\theta_{R,L}, \sin\theta_{R,L}\right\}$ is the unit vector along which the waves propagate into Region 2 from Region 1, $\vec{\mathbf{s}}_{R,L}^+ = \left\{\cos\theta_{R,L}, \sin\theta_{R,L}\right\}$ is the unit vector along which the waves reflected from Region 3 to Region 2 propagate, $\theta_{R,L}$ is the angle of refraction of the RCP and LCP waves, $\eta_2 = \sqrt{\mu_2/\varepsilon_2}$ is the impedance of the CMM layer, $k_{R,L} = k_0(n_2 \pm \chi_2)$ is a constant of the propagation of the RCP and LCP waves in chiral region 2, and $n_2 = \sqrt{\varepsilon_2\mu_2}$ is the relative refractive index for Region 2.

This work considered cases of the incidence of a plane electromagnetic wave with E-polarization [31]:

$$E_z^{(1)} = e^{-ik_1(\vec{\mathbf{s}}_{ind},\vec{\mathbf{r}})} + r_{ee}\, e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})}; \quad (16)$$

$$H_y^{(1)} = \frac{\cos\theta}{\eta_1}e^{-ik_1(\vec{\mathbf{s}}_{ind},\vec{\mathbf{r}})} - r_{ee}\frac{\cos\theta}{\eta_1}e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})};$$

$$H_z^{(1)} = r_{eh}\, e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})};$$

$$E_y^{(1)} = r_{eh}\eta_1\cos\theta\, e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})}$$

and the incidence of a plane electromagnetic wave with H-polarization:

$$H_z^{(1)} = e^{-ik_1(\vec{\mathbf{s}}_{ind},\vec{\mathbf{r}})} + r_{hh}\, e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})}; \quad (17)$$

$$E_y^{(1)} = -\eta_1\cos\theta\, e^{-ik_1(\vec{\mathbf{s}}_{ind},\vec{\mathbf{r}})} + r_{hh}\cos\theta\, e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})};$$

$$E_z^{(1)} = r_{he}\, e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})};$$

$$H_y^{(1)} = -r_{he}\frac{\cos\theta}{\eta_1}\, e^{-ik_1(\vec{\mathbf{s}}_{ref},\vec{\mathbf{r}})}.$$

The following notations are introduced in Eqs. (16) and (17): $k_1 = k_0\sqrt{\varepsilon_1\mu_1}$ is the wave number for a plane homogeneous wave in Region 1, $\vec{\mathbf{s}}_{ref} = \{\cos\theta, \sin\theta\}$ is the unit vector that determines the direction of propagation of the incident wave, $\eta_1 = \sqrt{\mu_1/\varepsilon_1}$ is the impedance of Region 3, and $\vec{\mathbf{s}}_{ind} = \{-\cos\theta, \sin\theta\}$ is the unit vector that determines the direction of propagation of the incident wave.

The electromagnetic field in the region expressed in Eq. (3) has the following form for the case of the incidence of a plane electromagnetic wave with E-polarization [31]:

$$E_z^{(3)} = t_{ee}\, e^{-ik_3(\vec{\mathbf{s}}_{tr},\vec{\mathbf{r}})}; \quad (18)$$

$$H_y^{(3)} = -t_{ee}\frac{\cos\theta_3}{\eta_3}e^{-ik_3(\vec{\mathbf{s}}_{tr},\vec{\mathbf{r}})};$$

$$H_z^{(3)} = t_{eh}\, e^{-ik_3(\vec{s}_{tr},\vec{r})};$$
$$E_y^{(3)} = t_{eh}\eta_3 \cos\theta_3\; e^{-ik_2(\vec{s}_{tr},\vec{r})}$$

and for the case of the incidence of a plane electromagnetic wave with H-polarization:

$$H_z^{(3)} = r_{hh}\, e^{-ik_3(\vec{s}_{tr},\vec{r})}; \qquad (19)$$
$$E_y^{(3)} = r_{hh} \cos\theta_3\; e^{-ik_3(\vec{s}_{tr},\vec{r})};$$
$$E_z^{(3)} = r_{he}\, e^{-ik_3(\vec{s}_{tr},\vec{r})};$$
$$H_y^{(3)} = -r_{he}\frac{\cos\theta_3}{\eta_3}\, e^{-ik_3(\vec{s}_{tr},\vec{r})}.$$

The following notations are introduced in Eqs. (18) and (19): $k_3 = k_0\sqrt{\varepsilon_3\mu_3}$ is the wave number for a plane homogeneous wave in Region 3, $\vec{\mathbf{s}}_{tr} = \{-\cos\theta_3, \sin\theta_3\}$ is the unit vector that determines the direction of the transmitted wave propagation, $\eta_3 = \sqrt{\mu_3/\varepsilon_3}$ is the impedance of Region 3, and θ_3 is the angle of wave propagation into Region 3.

At the interfaces, the following boundary conditions are satisfied for the tangential components of the vectors:

$$\vec{\mathbf{E}}_\tau^{(1)}(y=0) = \vec{\mathbf{E}}_\tau^{(2)}(y=0); \qquad (20)$$
$$\vec{\mathbf{H}}_\tau^{(1)}(y=0) = \vec{\mathbf{H}}_\tau^{(1)}(y=0);$$
$$\vec{\mathbf{E}}_\tau^{(2)}(y=-h) = \vec{\mathbf{E}}_\tau^{(3)}(y=-h);$$
$$\vec{\mathbf{H}}_\tau^{(2)}(y=-h) = \vec{\mathbf{H}}_\tau^{(3)}(y=-h).$$

After substituting Eqs. (15) to (20) into the boundary conditions of Eq. (20), the solution to the problem is reduced to inhomogeneous systems of linear algebraic equations (SLAEs) for the cases of E- and H-polarizations of the incident wave:

$$\mathbf{B}_{H,E}\vec{\mathbf{R}}_{H,E} = \vec{\mathbf{A}}_{H,E}; \qquad (21)$$
$$\vec{\mathbf{R}}_E = \left[T_R^{(-)}, T_R^{(+)}, T_L^{(-)}, T_L^{(+)}, r_{ee}, r_{eh}, t_{ee}, t_{eh}\right]^T;$$
$$\vec{\mathbf{A}}_E = \left[1,0,0,\frac{\cos\theta}{\eta_1},0,0,0,0\right]^T;$$
$$\vec{\mathbf{R}}_H = \left[T_R^{(-)}, T_R^{(+)}, T_L^{(-)}, T_L^{(+)}, r_{hh}, r_{he}, t_{hh}, t_{he}\right]^T;$$
$$\vec{\mathbf{A}}_H = \left[0,1,-\eta_1\cos\theta,0,0,0,0,0\right]^T,$$

where

$$\varepsilon_2(\omega) = \varepsilon_{c2}\frac{1+2\alpha_2\varepsilon_{x2}(\omega)}{1-\alpha_2\varepsilon_{x2}(\omega)};$$
$$\chi_2(\omega) = \frac{\omega_0^2\beta_0\omega}{\omega_0^2 + 2i\,\delta_x\omega_0\omega - \omega^2};$$
$$\varepsilon_{x2} = \frac{\varepsilon_{s2}(\omega) - \varepsilon_{c2}}{\varepsilon_{s2}(\omega) + 2\varepsilon_{c2}};$$
$$\varepsilon_{s2}(\omega) = \varepsilon_\infty + \frac{(\varepsilon_{c2}-\varepsilon_\infty)\omega_p^2}{\omega_0^2 + 2i\,\delta_e\omega - \omega^2};$$
$$\omega_0 = \frac{1}{\sqrt{\varepsilon_{c2}\mu_{c2}}}\frac{1}{\sqrt{\frac{\sqrt{2}\pi}{8h}\left[1+\frac{h}{4l}\right](R+r)^3}};$$
$$\eta_2(\omega) = \sqrt{\varepsilon_2(\omega)/\mu_2};$$
$$\alpha_{R,L}(\omega) = \sqrt{1 - \frac{\varepsilon_1\mu_1\sin^2\theta}{\left(\sqrt{\varepsilon_2(\omega)\mu_2} \pm \chi_2(\omega)\right)^2}};$$
$$\eta_1 = \sqrt{\mu_1/\varepsilon_1};$$
$$k_{R,L}(\omega) = k_0\left(\sqrt{\varepsilon_2(\omega)\mu_2} \pm \chi_2(\omega)\right);$$
$$k_1 = k_0\sqrt{\varepsilon^{(1)}\mu^{(1)}};\quad k_3 = k_0\sqrt{\varepsilon^{(3)}\mu^{(3)}};$$
$$\eta_3 = \sqrt{\mu_3/\varepsilon_3};\quad \beta_{R,L}(\omega) = k_{R,L}(\omega)h\cos\theta_{R,L};$$
$$\beta_3 = k_3 h\cos\theta_3;$$
$$\varepsilon_{s2}(\omega) = \varepsilon_{s2} + \frac{\beta_{02}^2}{\omega_0^2-\omega^2};\quad \chi_2(\omega) = \frac{A_2 k_0\beta_{02}^2}{\omega_0^2-\omega^2}.$$

The explicit form of the matrix $\mathbf{B}_{H,E}$ is not given in the article because of its significant volume.

From the numerical solution to the SLAE of Eq. (22), the unknown elements of the matrices of the reflection and transmission coefficients expressed in Eqs. (8) to (10) are determined.

3. Numerical results

In numerical modeling by solving the SLAE of Eq. (22) for the case of the incidence of a plane electromagnetic wave with E-polarization, the frequency dependence of the moduli of the transmission and reflection coefficients of the main and cross-polarized field components were calculated.

As an example, a structure based on a set of strip C-shaped elements with a strip width of 2 cm was considered. All elements were randomly oriented and evenly placed at a distance of 10 cm. The thickness of the metamaterial layer was 10 cm. The container material had relative dielectric permeabilities of $\varepsilon_{c2} = 1{,}5$ and $\mu_{c2} = 1$ (expanded polystyrene). The element parameters were $R = 0{,}02$ m, $R - r = 0{,}02$ m, and $H = 0{,}1$ m. Regions 1 and 3 were vacuum with

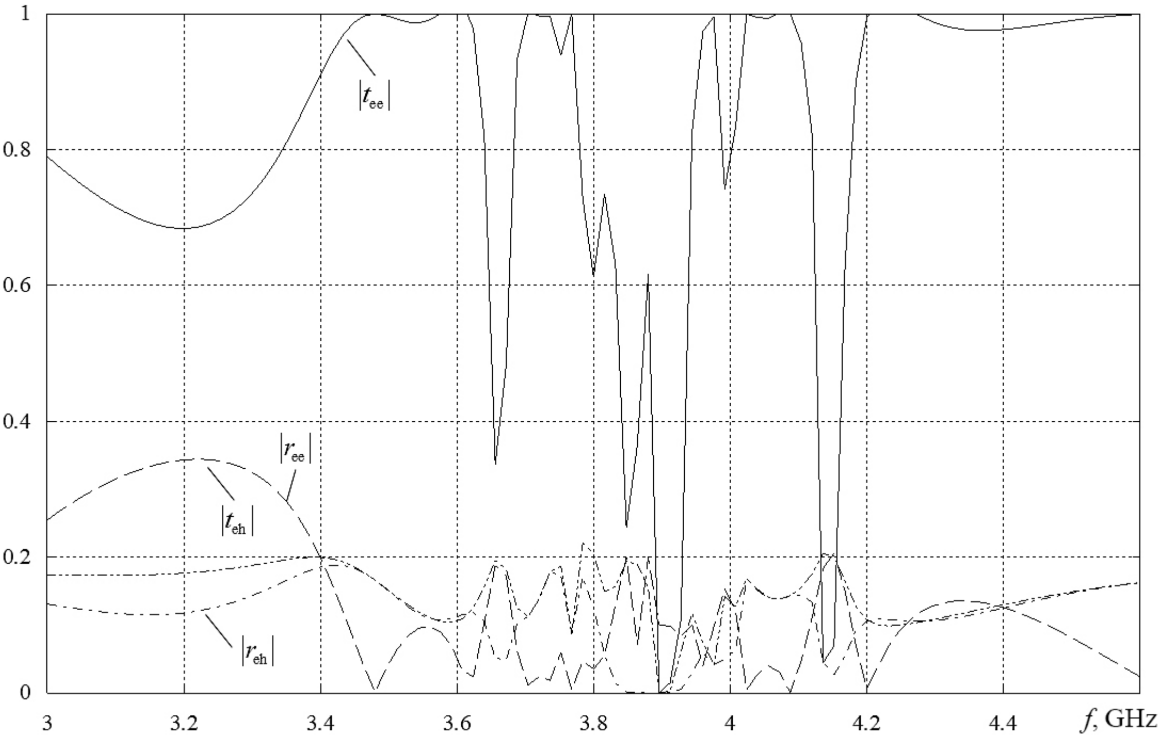

Fig. 4. Frequency dependences of the factors of transmission and reflection coefficients of the main and cross-polarized component components

Рис. 4. Частотные зависимости модулей коэффициентов прохождения и отражения основной и кросс-поляризованной компонент поля

$\varepsilon_{1,3} = \mu_{1,3} = 1$. The incident wave of the metastructure occurred along the normal $\theta = 0$.

Fig. 3 shows the frequency dependence of the moduli of the reflection coefficients of the main ($|r_{ee}|$ denoted by the dotted line) and cross-polarized ($|r_{eh}|$ denoted by the dash-dash-dotted line) components and the transmission coefficients of the main ($|t_{ee}|$ denoted by the solid line) and cross-polarized ($|t_{eh}|$ denoted by the dash-dotted line) components of a metamaterial based on C-shaped elements with specified geometric dimensions.

As shown in Fig. 3, the structure exhibits pronounced frequency-selective properties. In the frequency range of 3,6–4,2 GHz, several resonant minima of the modulus of the transmittance coefficient are noted. In the same frequency range, the moduli of the reflection coefficients of the main and cross-polarized field components and the modulus of the transmission coefficient of the cross-polarized component do not exceed 0,2. The deepest resonant minima are noted at frequencies of 3,9 and 4,17 GHz. Near these frequencies, the electromagnetic field is concentrated in a layer of CMM based on a set of C-shaped elements, and the structure acts as a frequency-selective concentrator of microwave energy. Notably, similar effects were observed in CMMs based on sets of thin-wire conductive single-start and multi-start spiral elements and strip gammadions with an arbitrary number of starts. Moreover, even with the normal incidence of a plane electromagnetic wave on the CMM layer, a rather strong cross-polarization of the field is registered both in the structures of the reflected and transmitted waves.

Furthermore, a metamaterial based on a uniform set of chaotically oriented C-shaped elements with a radius twice that of the previous case was considered. The element parameters were $R = 0,04$ m, $R - r = 0,02$ m, and $H = 0,1$ m.

Fig. 4 shows the frequency dependence of the moduli of the reflection coefficients of the main ($|r_{ee}|$ denoted by the dotted line) and cross-polarized ($|r_{eh}|$ denoted by the dash-dash-dotted line) components and the transmission coefficients of the main ($|t_{ee}|$ denoted by the solid line) and cross-polarized ($|t_{eh}|$ denoted by the dash-dotted line) components of ametamaterial based on C-shaped elements with specified geometric dimensions.

As shown in Fig. 4, in the frequency range under study, one resonant minimum is noted at a frequency of 4,3 GHz, at which the transmission coefficient of the main field component tends to zero. Near the same frequency, the moduli of the reflection coefficients of the main and cross-polarized field components and the modulus of the transmission coefficient

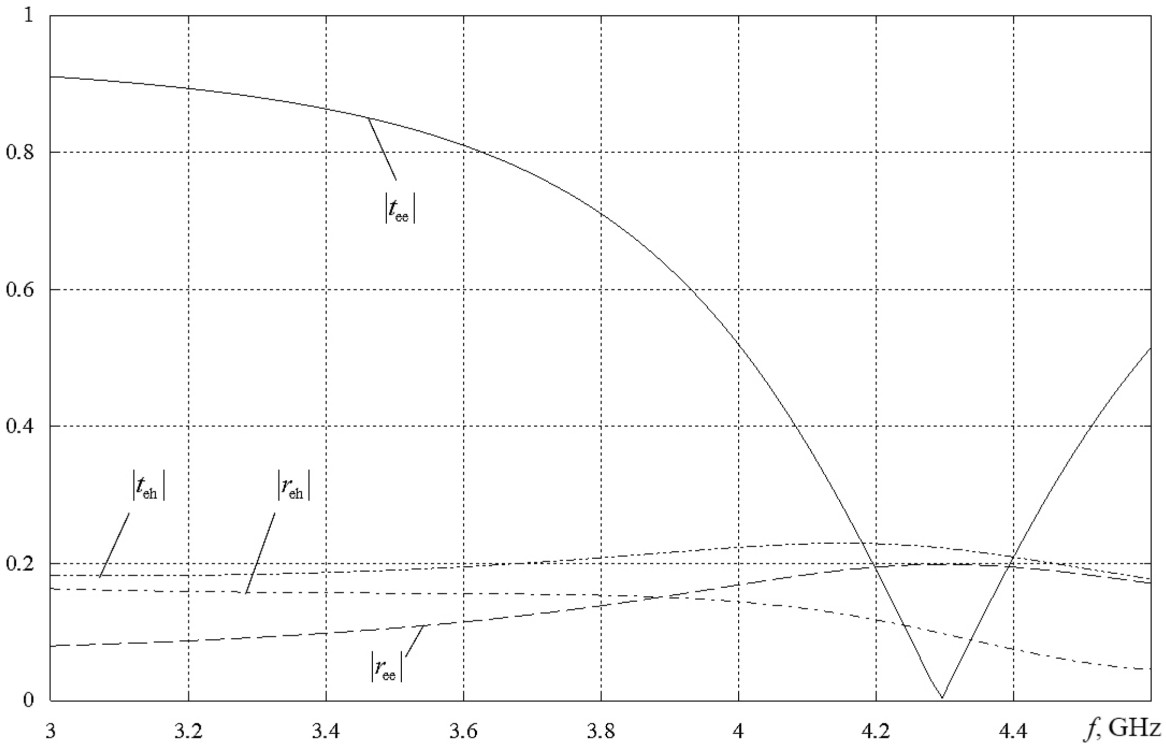

Fig. 5. Frequency dependences of the moduli of the transmission and reflection coefficients of the main and cross-polarized field components

Рис. 5. Частотные зависимости модулей коэффициентов прохождения и отражения основной и кросс-поляризованной компонент поля

of the cross-polarized component do not exceed 0,2, which corresponds to the mode of microwave energy concentration in the CMM layer. Notably, compared with the previous case, the resonant minimum near the frequency of 4,3 GHz is wide; therefore, the energy concentration occurs in the frequency range of 4,2–4,4 GHz.

As an example, a structure based on a set of strip C-shaped elements with a strip width of 2 cm was considered. All elements were randomly oriented and evenly placed at a distance of 20 cm. The metamaterial layer thickness was 10 cm. The container material had relative dielectric permeabilities of $\varepsilon_{c2} = 1{,}5$ and $\mu_{c2} = 1$ (expanded polystyrene). The element parameters were $R = 0{,}02$ m, $R - r = 0{,}02$ m, and $H = 0{,}1$ m. From the given values, in this metamaterial, the distance between adjacent chiral inclusions is twice that of the previous case considered.

Fig. 5 shows the frequency dependence of the moduli of the reflection coefficients of the main ($|r_{ee}|$ denoted by the dotted line) and cross-polarized ($|r_{eh}|$ denoted by the dash-dash-dotted line) components and the transmission coefficients of the main ($|t_{ee}|$ denoted by the solid line) and cross-polarized ($|t_{eh}|$ denoted by the dash-dotted line) components of a metamaterial based on C-shaped elements with specified geometric dimensions.

As shown in Fig. 5, the structure exhibits pronounced frequency-selective properties. In the frequency range of 3,45–4,15 GHz, a significant number of resonant minima of the modulus of the transmittance coefficient are noted. In the same frequency range, the moduli of the reflection coefficients of the main and cross-polarized field components and the modulus of the transmission coefficient of the cross-polarized component do not exceed 0,2. The deepest resonant minima are noted at frequencies of 3,78 and 3,9 GHz. Near these frequencies, the electromagnetic field is concentrated in a layer of CMM based on a set of C-shaped elements, and the structure acts as a frequency-selective concentrator of microwave energy.

Conclusion

This study presented an example of the construction of a particular mathematical model of a CMM based on a uniform set of C-shaped elements, which considers the basic properties of chirality, heterogeneity, and dispersion of dielectric permeability and chirality. As an example of the use of the developed model, the problem of the incidence of a plane electromagnetic wave with linear polarization on a planar layer of the metamaterial under study was solved. Notably, a CMM based on a set of C-shaped elements

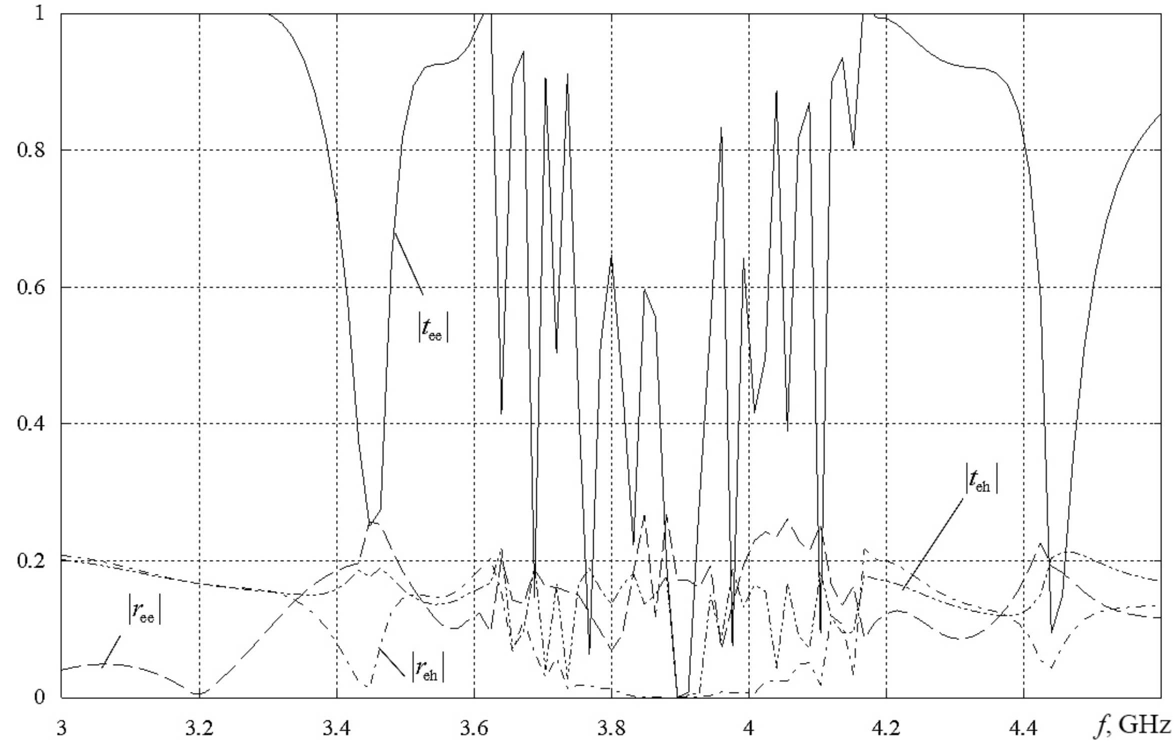

Fig. 6. Frequency dependences of the moduli of the transmission and reflection coefficients of the main and cross-polarized field components

Рис. 6. Частотные зависимости модулей коэффициентов прохождения и отражения основной и кросс-поляризованной компонент поля

has frequency-selective properties. This study proved that, near some discrete frequencies, the metastructure is opaque and nonreflective for incident microwave radiation with linear polarization. In these frequency ranges, a frequency-selective effect occurs in the metamaterial, which consists of the normally (radially) incident microwave field that is concentrated in the planar layer of the CMM. Previously, similar effects were observed in CMMs based on sets of thin-wire conductive single-start and multi-start spiral elements and strip gammadions with an arbitrary number of starts. This study also proved that the effect of frequency-selective concentration of microwave energy occurs more obviously in CMMs based on three-dimensional microelements than in CMMs based on flat two-dimensional chiral inclusions. A similar effect can be used to create frequency-selective concentrators (hubs) of microwave energy.

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Исследование кирального метаматериала СВЧ-диапазона на основе равномерной совокупности С-образных проводящих элементов

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Аннотация – В работе рассмотрен искусственный киральный метаматериал, созданный на основе однородного контейнера из вспененного диэлектрика, в котором равномерно размещены и произвольно ориентированы плоские проводящие микроэлементы S-образной формы. Для описания исследуемого метаматериала построена частная математическая модель, учитывающая киральность, дисперсию и гетерогенность структуры. Для учета гетерогенности использовалась модель Максвелла Гарнетта. Для учета дисперсии параметра киральности была использована модель Кондона, известная из теории оптически активных сред. Методом частичных областей была решена задача о падении плоской электромагнитной волны линейной поляризации на планарный слой, созданный на основе исследуемого кирального метаматериала. Решение задачи было сведено к неоднородной системе линейных алгебраических уравнений относительно неизвестных коэффициентов отражения и прохождения с учетом кросс-поляризации электромагнитного поля. Анализ численных результатов показал, что структура обладает ярко выраженными частотно селективными свойствами, в частности, как и в случае кирального метаматериала на основе трехмерных проводящих элементов, были определены дискретные частоты, на которых структура концентрирует падающее СВЧ-излучение внутри себя, в то время как на других частотах она является прозрачной для СВЧ-излучения. Киральный метаматериал на основе С-образных микроэлементов может быть использован для создания узкополосных частотно селективных концентраторов СВЧ-энергии планарного типа.

Ключевые слова – киральная среда; киральный метаматериал; метаматериал; метаструктура; С-элемент; пространственная дисперсия; частотная селективность; модель Максвелла Гарнетта; модель Кондона; СВЧ-энергия.

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