11

Nonreciprocity of microwave propagation in the[(CoFe)/Cu]/(glass) system

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The propagation of microwaves through the dielectric substrate/metal superlattice system [(CoFe)/Cu] has been investigated. The frequency dependences of transmission and reflection coefficients for the normal incidence of electromagnetic waves on the system in two opposite directions are measured. The effect of the substrate thickness on the magnitude of the microwave giant magnetoresistance effect during reflection and on nonreciprocity in the system is investigated. The influence of an external magnetic field on the nonreciprocity parameter is investigated. It has been established that under the conditions of nonreciprocity, the microwave giant magnetoresistance effect increases significantly when the wave is reflected.

Keywords: metal superlattices, microwave giant magnetoresistance effect, microwaves, transmission and reflection coefficients, nonreciprocity.

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Introduction

The reciprocity theorem is widely used when considering the propagation of light and microwaves [1]. In the paper [2] the conditions for the fulfillment of the reciprocity theorem for waves propagating in a material medium, including a magnetized one, are analyzed. The theorem is met, in particular, for a non-dissipative medium, in which the dielectric and magnetic susceptibility tensors are symmetric, but can vary in space. There are several types of nonreciprocity in wave propagation. Nonreciprocity can manifest itself in the amplitude, phase, and polarization of the waves. Phase nonreciprocity occurs when light interacts with a traveling ultrasonic wave [3]. The phase and amplitude nonreciprocities are calculated for light waves during acousto-optical interaction in gyrotropic cubic crystals, at that the gyrotropy parameter has a significant effect [4]. Nonreciprocity is associated with several interesting effects observed in the microwave range. In particular, nonreciprocity was observed in the excitation of spin waveguide modes by a microstrip antenna [5]. Reversing the direction of the magnetic field changes the direction of main excitation of spin waves. It is shown that the presence of interlayer interaction of the antiferromagnetic type in a nanostructure can significantly enhance the nonreciprocity in the propagation of spin waves [6]. Attempts were made to reduce the attenuation of spin waves, which is important for observing nonreciprocity [7,8]. It is known that nonreciprocal elements, such as a valve and a gyrator, have found a rather wide application in microwave technology [9–12].

Due to the giant magnetoresistance (GMR) effect the magnetic metal nanostructures [13–16] are used in sensors, hard drives, and microwave devices. The existence of the GMR effect in a wave reflected from a nanostructure was discovered in the ranges of centimeter and millimeter waves in the paper [17]. This effect, abbreviated as μGMR, when microwaves were used, was carefully studied for superlattices [18–20] and spin valves [21].

The superlattice/dielectric substrate composite system does not satisfy the conditions of the reciprocity theorem due to wave dissipation, and nonreciprocity can be observed in it. The study of such nonreciprocity is the main goal of the present work. At frequencies in the millimeter range, the dependences of the transmittance and reflectance of waves on frequency and external magnetic field are studied for two opposite directions of propagation. Experiments shown that the nonreciprocity in the amplitude of the reflection coefficient can vary depending on the magnetic field. Besides, there are grounds to expect that μGMR in the reflected wave can increase significantly if the wave first falls on the dielectric substrate, as compared to the case where the wave falls directly on the metal superlattice. The increase is achieved at frequencies where the substrate thickness is a multiple of a one forth of the wavelength, due to the appearance of standing waves in the substrate and due to the lower reflectance from the dielectric substrate. The material of this paper is presented in the following sequence. First, formulas for the transmittance and reflectance for the superlattice/dielectric substrate system are obtained and analyzed. This is followed by information on the samples used and measurement methods. Next, the results of

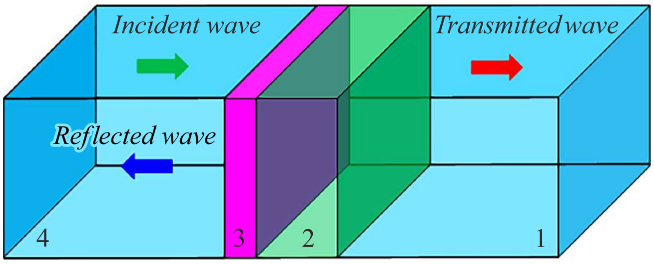

Figure 1. Layer numbering scheme in the problem of wave propagation in a layered system.

microwave measurements with the main attention to the effects of nonreciprocity are given. In the discussion, the results of microwave experiments and calculations are compared. The conclusion lists main results of the present paper.

1. Formulas for transmittance and reflectance and their analysis

The problem of propagation and reflection of waves from system of plane-parallel layers consisting of different media was considered in [22]. Note that in the system under consideration the numbering of the media, according to [22] is taken from right to left, while the incident wave propagates from left to right. The complex reflectances $\dot{R}$ and transmittances $\dot{T}$ for a system consisting of two half-spaces and $N-2$ layers are determined by the relations

$$\dot{R} = \frac{\dot{Z}_{\text{in}}^{(N-1)} - Z_N}{\dot{Z}_{\text{in}}^{(N-1)} + Z_N}, \tag{1}$$

$$\dot{T} = \frac{2Z_1}{Z_1 + \dot{Z}_2} \prod_{j=2}^{N-1} \left[\frac{\dot{Z}_{\text{in}}^{(j)} - \dot{Z}_j}{\dot{Z}_{\text{in}}^{(j)} + \dot{Z}_{j+1}} \exp(-i\dot{\varphi}_j) \right], \tag{2}$$

where

$$\dot{Z}_{\text{in}}^{(j)} = \dot{Z}_j \frac{\dot{Z}_{\text{in}}^{(j-1)} + i\dot{Z}_j \tan\dot{\varphi}_j}{\dot{Z}_j + i\dot{Z}_{\text{in}}^{(j-1)} \tan\dot{\varphi}_j} \tag{3}$$

— input impedance determined at the j-th interface (between mediums with numbers j and $(j+1)$, with $Z^{(1)}in$; $\dot{\varphi}_j = \dot{k}_j d_j$ — complex phase for layers with indices $j = 2, 3, \ldots, N-1$, d_j — thickness of the respective layers. A dot above the physical variable designation indicates that the given variable is complex.

Next, we consider the passage of electromagnetic waves through a system of two plane-parallel layers, i.e. at $N = 4$ (Fig. 1).

Let us assume that both half-spaces (media 1 and 4) have the same electrical and magnetic parameters, and, consequently, both impedances and wave numbers: $Z_4 = Z_1$, $k_4 = k_1$. Then the input impedances determined at the three boundaries of the system under consideration, according to expression (3), will have the form

$$Z_{\text{in}}^{(1)} = Z_1, \tag{4}$$

$$\dot{Z}_{\text{in}}^{(2)} = \dot{Z}_2 \frac{\dot{Z}_{\text{in}}^{(1)} + i\dot{Z}_2 \tan\dot{\varphi}_2}{\dot{Z}_2 + i\dot{Z}_{\text{in}}^{(1)} \tan\dot{\varphi}_2} = \dot{Z}_2 \frac{Z_1 + i\dot{Z}_2 \tan\dot{\varphi}_2}{\dot{Z}_2 + iZ_1 \tan\dot{\varphi}_2}, \tag{5}$$

$$\dot{Z}_{\text{in}}^{(3)} = \dot{Z}_3 \frac{\dot{Z}_{\text{in}}^{(2)} + i\dot{Z}_3 \tan\dot{\varphi}_3}{\dot{Z}_3 + i\dot{Z}_{\text{in}}^{(2)} \tan\dot{\varphi}_3}$$
$$= \dot{Z}_3 \frac{Z_1(\dot{Z}_2 - \dot{Z}_3 \tan\dot{\varphi}_2 \tan\dot{\varphi}_3) + i\dot{Z}_2(\dot{Z}_2 \tan\dot{\varphi}_2 + \dot{Z}_3 \tan\dot{\varphi}_3)}{\dot{Z}_2(\dot{Z}_3 - \dot{Z}_2 \tan\dot{\varphi}_2 \tan\dot{\varphi}_3) + iZ_1(\dot{Z}_3 \tan\dot{\varphi}_2 + \dot{Z}_2 \tan\dot{\varphi}_3)}. \tag{6}$$

Using relations (5), (6), we can obtain the following expression for the transmittance:

$$\dot{T} = \frac{2Z_1\dot{Z}_2\dot{Z}_3(1 + i\tan\dot{\varphi}_2)(1 + i\tan\dot{\varphi}_3)\exp[-i(\dot{\varphi}_2 + \dot{\varphi}_3)]}{Z_1\big(2\dot{Z}_2\dot{Z}_3 - (\dot{Z}_2^2 + \dot{Z}_3^2)\tan\dot{\varphi}_2 \tan\dot{\varphi}_3\big) + i\big(\dot{Z}_3(Z_1^2 + \dot{Z}_2^2)\tan\dot{\varphi}_2 + \dot{Z}_2(Z_1^2 + \dot{Z}_3^2)\tan\dot{\varphi}_3\big)}.$$

This formula can be rewritten as

$$\dot{T} = \frac{2Z_1\dot{Z}_2\dot{Z}_3}{\Delta}. \tag{7}$$

where

$$\Delta = Z_1\big(2\dot{Z}_2\dot{Z}_3 \cos\dot{\varphi}_2 \cos\dot{\varphi}_3 - (\dot{Z}_2^2 + \dot{Z}_3^2)\sin\dot{\varphi}_2 \sin\dot{\varphi}_3\big)$$
$$+ i\big(\dot{Z}_3(Z_1^2 + \dot{Z}_2^2)\sin\dot{\varphi}_2 \cos\dot{\varphi}_3 + \dot{Z}_2(Z_1^2 + \dot{Z}_3^2)\cos\dot{\varphi}_2 \sin\dot{\varphi}_3\big). \tag{8}$$

When deriving formulas (7) and (8), the following transformation for complex trigonometric functions was used:

$$(1 + i\tan\dot{\varphi}_2)(1 + i\tan\dot{\varphi}_3)\exp[-i(\dot{\varphi}_2 + \dot{\varphi}_3)] = \frac{1}{\cos\dot{\varphi}_2 \cos\dot{\varphi}_3}.$$

Substituting formula (6) into (1), we obtain the expression for the reflectance at $N = 4$:

$$\dot{R} = \frac{\dot{Z}_{\text{in}}^{(3)} - Z_1}{\dot{Z}_{\text{in}}^{(3)} + Z_1}. \tag{9}$$

Using relation (6), we transform formula (9) to the form

$$\dot{R} = \frac{Z_1(\dot{Z}_2^2 - \dot{Z}_3^2)\tan\dot{\varphi}_2 \tan\dot{\varphi}_3 + i\big(\dot{Z}_3(\dot{Z}_2^2 - Z_1^2)\tan\dot{\varphi}_2 + \dot{Z}_2(\dot{Z}_3^2 - Z_1^2)\tan\dot{\varphi}_3\big)}{Z_1\big(2\dot{Z}_2\dot{Z}_3 - (\dot{Z}_2^2 + \dot{Z}_3^2)\tan\dot{\varphi}_2 \tan\dot{\varphi}_3\big) + i\big(\dot{Z}_3(Z_1^2 + \dot{Z}_2^2)\tan\dot{\varphi}_2 + \dot{Z}_2(Z_1^2 + \dot{Z}_3^2)\tan\dot{\varphi}_3\big)}$$
$$= \frac{Z_1(\dot{Z}_2^2 - \dot{Z}_3^2)\sin\dot{\varphi}_2 \sin\dot{\varphi}_3}{\Delta}$$
$$+ \frac{i\big(\dot{Z}_3(\dot{Z}_2^2 - Z_1^2)\sin\dot{\varphi}_2 \cos\dot{\varphi}_3 + \dot{Z}_2(\dot{Z}_3^2 - Z_1^2)\cos\dot{\varphi}_2 \sin\dot{\varphi}_3\big)}{\Delta}. \tag{10}$$

In the particular case $|\dot{\varphi}_2| \neq 0$, $|\dot{\varphi}_3| = 0$, which corresponds to $d_3 = 0$, for the reflectance and transmittance we have

$$\dot{T} = \frac{2Z_1\dot{Z}_2}{2Z_1\dot{Z}_2 \cos\dot{\varphi}_2 + i(Z_1^2 + \dot{Z}_2^2)\sin\dot{\varphi}_2}, \tag{11}$$

$$\dot{R} = \frac{i(\dot{Z}_2^2 - Z_1^2)\sin\dot{\varphi}_2}{2Z_1\dot{Z}_2 \cos\dot{\varphi}_2 + i(Z_1^2 + \dot{Z}_2^2)\sin\dot{\varphi}_2}. \tag{12}$$

Obviously, formulas (11), (12) completely coincide with the known expressions for a single flat layer bordering on two identical half-spaces [9].

In the formulas above $Z_1 = Z_4 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ — are the impedances of media 1 and 4, $\dot{Z}_2 = \sqrt{\frac{\mu_0 \dot{\mu}_{\text{eff}_2}}{\varepsilon_0 \dot{\varepsilon}_2}}$ — impedance of medium 2, i.e., a metal nanostructure with permittivity $\dot{\varepsilon}_2 = \varepsilon_2' - i\varepsilon_2''$ and effective permeability $\dot{\mu}_{\text{eff}_2} = \mu_{\text{eff}_2}' - i\mu_{\text{eff}_2}''$. Note that here we mean the effective magnetic permeability of a transversely magnetized ferromagnetic medium when the magnetization field is directed perpendicular to the direction of wave propagation. In this case, the medium is gyrotropic, and its magnetic properties are described by the Polder tensor for magnetic permeability. As shown, for example, in [23], the expressions for impedance and wavenumber, which correspond to a plane electromagnetic wave propagating in such a medium, contain the components of the magnetic permeability tensor only in the form of a specific combination called the effective magnetic permeability. Medium 3 is a non-magnetic dielectric with magnetic permeability $\mu_3 = 1$ and permittivity $\dot{\varepsilon}_3 = \varepsilon_3' - i\varepsilon_3''$. Accordingly, the medium 3 impedance is $\dot{Z}_3 = \sqrt{\frac{\mu_0}{\varepsilon_0 \dot{\varepsilon}_3}}$.

The wavenumber in the medium 2 — is a complex value $\dot{k}_2 = k_2' - ik_2''$, it can be represented in the form [23]:

$$k_2' = \frac{\omega}{c}\sqrt{\frac{|\dot{\varepsilon}_2||\dot{\mu}_{\text{eff}_2}| + \varepsilon_2'\mu_{\text{eff}_2}' - \varepsilon_2''\mu_{\text{eff}_2}''}{2}},$$

$$k_2'' = \frac{\omega}{c}\sqrt{\frac{|\dot{\varepsilon}_2||\dot{\mu}_{\text{eff}_2}| - \varepsilon_2'\mu_{\text{eff}_2}' + \varepsilon_2''\mu_{\text{eff}_2}''}{2}}.$$

In medium 3, the real and imaginary parts of the wavenumber are determined by the formulas

$$k_3' = \frac{\omega}{c}\sqrt{\frac{|\dot{\varepsilon}_3| + \varepsilon_3'}{2}}, \quad k_3'' = \frac{\omega}{c}\sqrt{\frac{|\dot{\varepsilon}_3| - \varepsilon_3'}{2}},$$

and in media 1 and 4 the wavenumber — is a real value: $k_1 = k_4 = \frac{\omega}{c}$.

Let us consider how the expressions for the reflectance and transmittance (7) and (10) change if media 2 and 3 are interchanged, which is similar to reversing the direction of propagation of the incident wave. To do this, in formulas (7), (8), (10) you need to make the following replacements: $\dot{Z}_2 \leftrightarrow \dot{Z}_3$ and $\dot{\varphi}_2 \leftrightarrow\ dot\varphi_3$. It is easy to make sure that the expressions (7) and (8) will not change in this case. But the formula (10) with such replacements takes the form

$$\dot{R} = \frac{-Z_1(\dot{Z}_2^2 - \dot{Z}_3^2)\sin\dot{\varphi}_2\sin\dot{\varphi}_3}{\Delta} + \frac{i\left(\dot{Z}_3(\dot{Z}_2^2 - Z_1^2)\sin\dot{\varphi}_2\cos\dot{\varphi}_3 + \dot{Z}_2(\dot{Z}_3^2 - Z_1^2)\cos\dot{\varphi}_2\sin\dot{\varphi}_3\right)}{\Delta}, \tag{13}$$

i.e. the first term in the numerator changes sign, while the rest of the numerator, and the denominator of the expression remain unchanged.

Formulas (10) and (13) can be conventionally represented as complex numbers

$$\dot{z}_1 = \frac{a + ib}{v + iw}, \quad \dot{z}_2 = \frac{-a + ib}{v + iw}.$$

Using the well-known properties of complex numbers [24], the following relations can be written:

$$|\dot{z}_1| = |\dot{z}_2| = \sqrt{\frac{a^2 + b^2}{v^2 + w^2}};$$

$$\dot{z}_1 = \frac{(a + ib)(v - iw)}{v^2 + w^2} = \frac{av + bw}{v^2 + w^2} + i\,\frac{bv - aw}{v^2 + w^2},$$

$$\mathrm{Re}(\dot{z}_1) = \frac{av + bw}{v^2 + w^2}, \quad \mathrm{Im}(\dot{z}_1) = \frac{bv - aw}{v^2 + w^2};$$

$$\arg(\dot{z}_1) = \begin{cases} \mathrm{atan}\left(\dfrac{bv - aw}{av + bw}\right), & av + bw > 0, \\ \pi + \mathrm{atan}\left(\dfrac{bv - aw}{av + bw}\right), & av + bw < 0,\ bv - aw > 0, \\ -\pi + \mathrm{atan}\left(\dfrac{bv - aw}{av + bw}\right), & av + bw < 0,\ bv - aw > 0; \end{cases}$$

$$\dot{z}_2 = \frac{(-a + ib)(v - iw)}{v^2 + w^2} = \frac{-av + bw}{v^2 + w^2} + i\,\frac{bv + aw}{v^2 + w^2},$$

$$\mathrm{Re}(\dot{z}_2) = \frac{-av + bw}{v^2 + w^2}, \quad \mathrm{Im}(\dot{z}_2) = \frac{bv + aw}{v^2 + w^2};$$

$$\arg(\dot{z}_2) = \begin{cases} \mathrm{atan}\left(\dfrac{bv + aw}{-av + bw}\right), & -av + bw > 0, \\ \pi + \mathrm{atan}\left(\dfrac{bv + aw}{-av + bw}\right), & -av + bw < 0,\ bv + aw > 0, \\ -\pi + \mathrm{atan}\left(\dfrac{bv + aw}{-av + bw}\right), & -av + bw < 0,\ bv + aw > 0. \end{cases}$$

Therefore, returning to formulas (10) and (13), we can conclude that in a lossless system consisting of two layers, reversing propagation of the incident wave does not lead to change in the modulus of the complex reflectance $\dot{R}$, but leads to changes in its real and imaginary parts, and hence the argument, i.e., the system consisting of two plane-parallel layers has phase nonreciprocity. It is important to emphasize that the complex transmittance $\dot{T}$ remains the same when the direction of propagation of the incident wave is reversed, regardless of the presence or absence of losses in media 2 and 3.

We will consider two system configurations: (3—2) — alternation of layers, corresponding to the standard arrangement of media 4-3-2-1 when the wave falls from medium 4, as shown in Fig. 1; (2—3) — alternation of layers, corresponding to the location of the media 4-2-3-1 when

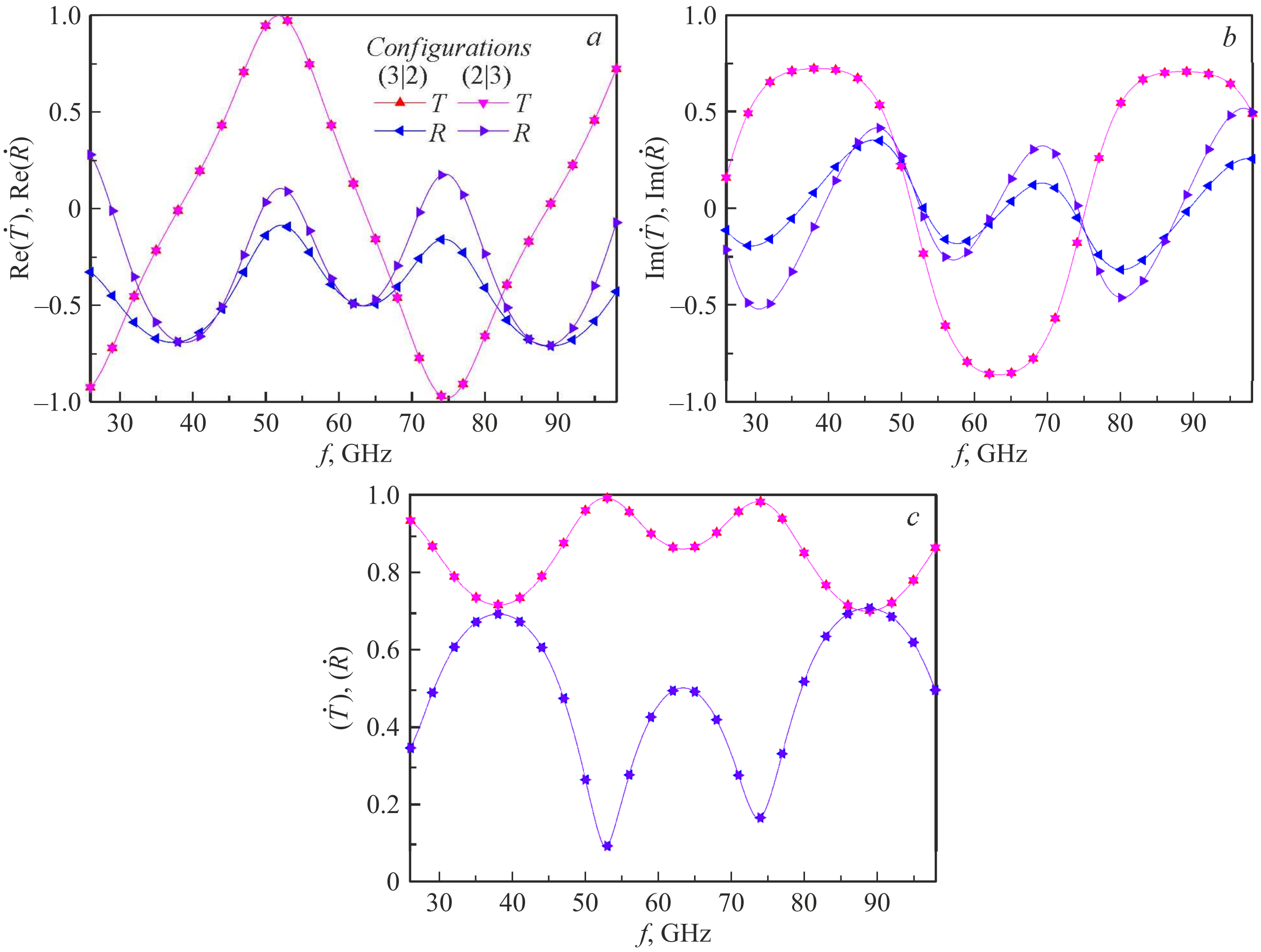

Figure 2. Frequency dependences of the transmittance and reflectance for system of two lossless dielectric layers: *a* — real parts of the coefficients; *b* — imaginary parts of coefficients; *c* — modules of coefficients.

the wave falls from the medium 4. The results of calculating the frequency dependences using formulas (7), (10), (13) for the system of two lossless dielectric layers are shown in Fig. 2. Media parameters: $\varepsilon_2' = 3$, $\sigma_2 = 0$, $d_2 = 2\,\mathrm{mm}$; $\varepsilon_3' = 6$, $\sigma_3 = 0$, $d_3 = 1\,\mathrm{mm}$, where σ_2, σ_3 are the conductivities of layers 2 and 3. In this paper we consider microwaves of sufficiently high frequencies — above 26 GHz, at which the magnetic permeability of medium 2 is close to the values $\mu_2' = 1$, $\mu_2'' = 0$ due to dispersion. Therefore, we do not consider the effect of magnetic permeability on the transmittance and reflectance. Medium 3 is considered to be a non-magnetic dielectric with $\mu_3' = 1$, $\mu_3'' = 0$. The results for the real parts of the coefficients are shown in Fig. 2, *a*, the imaginary parts in Fig. 2, *b*, the absolute values of the coefficients are in Fig. 2, *c*.

The frequency dependences of the coefficients in Fig. 2 have an oscillatory character due to the fulfillment of the conditions for quarter- and half-wave wafers, and the establishment of the standing wave mode. Comparing the calculation results, we can conclude that the real and imaginary parts of the transmittance do not change when the direction of propagation is reversed. The real and imaginary parts of the reflectance change when the direction of wave propagation changes, but in such a way that the modules of the coefficients do not change.

Consider now the system consisting of a dielectric layer with low losses and conductive layer. The following media parameters are selected. For conductive layer: $\varepsilon_2' = 3$, $\sigma_2 = 150\,\mathrm{S/m}$, $\mu_2' = 1$, $\mu_2'' = 0$, $d_2 = 2$,mm; for dielectric: $\varepsilon_3' = 6$, $\sigma_3 = 0.2\,\mathrm{S/m}$, $\mu_3' = 1$, $\mu_3'' = 0$, $d_3 = 1$ mm. This system does not satisfy the conditions for the fulfillment of the reciprocity theorem. The results of the calculation are shown in Fig. 3. As before, the frequency dependences of the real and imaginary parts of the system transmittance are identical, and the dependences of the reflectance change significantly when changing the direction of wave propagation. In this case, the moduli of the reflectance essentially depend on the direction of propagation. Thus, in the considered system, there are both phase and amplitude nonreciprocities in the reflected wave. In the following Sections of the article we will consider the case of the system consisting of dielectric substrate and thin metal

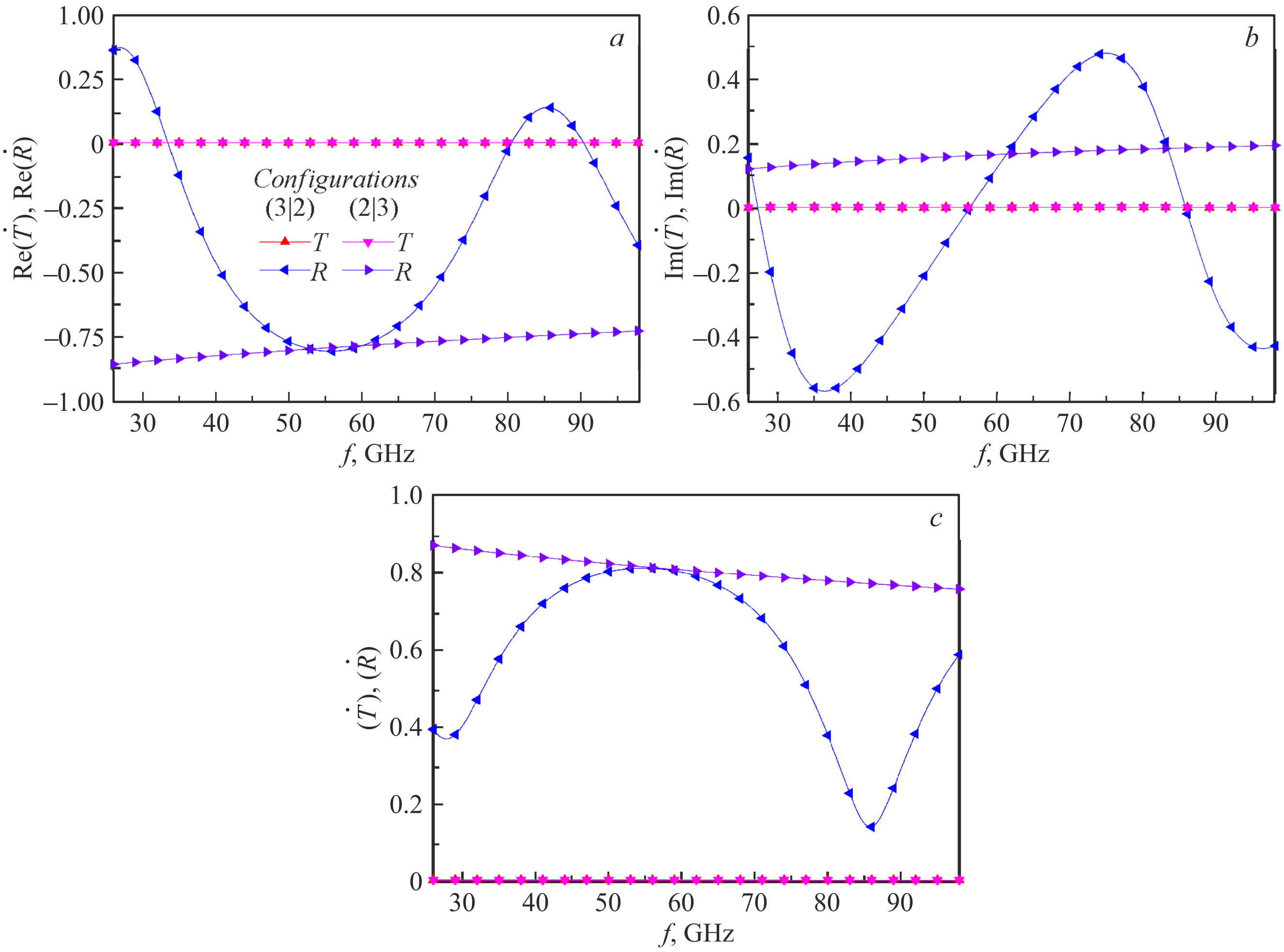

Figure 3. Frequency dependences of the transmittance and reflectance for system of dielectric layer with low losses and conductive layer with moderate conductivity: *a* — real parts of the coefficients; *b* — imaginary parts of coefficients; *c* — modules of coefficients.

layer with high conductivity, which corresponds to the experimental conditions.

2. Specimens and methods of study

The choice of objects under study is of critical importance in this paper. First, since the goal was to study the magnetic field effect on nonreciprocity, it is advisable to choose the object under study whose material constants change strongly in the magnetic field. Therefore, the superlattice of $Co_{90}Fe_{10}$/Cu system was chosen, in which the ferromagnetic layers are prepared from the alloy $Co_{90}Fe_{10}$, and the intermediate non-magnetic layer — spacer — from copper. The layer thicknesses are chosen from the condition of obtaining the maximum GMR. In particular, the thickness of the spacer Cu is 0.9 nm; it provides the antiparallel ordering of the magnetic moments of neighboring layers of $Co_{90}Fe_{10}$ superlattice and, consequently, the maximum GMR effect [20]. The number of layer pairs 6 was chosen in accordance with calculations of μGMR effect [25], where it was found that the largest μGMR in wave reflection is achieved at total superlattice metal thickness of 15–20 nm. The composition of the samples under study is expressed by the formula $Ta(3)/[Co_{90}Fe_{10}(1.5)/Cu(0.9)]_6/PyCr(5)/glass$, where the numbers in parentheses express the layer thickness in nanometers. The superlattice is deposited on the glass substrate with a buffer layer of permalloy–chromium alloy (PyCr), and covered with a protective layer of tantalum. The superlattice was obtained by magnetron sputtering on MPS-4000-C6 unit. The first sample was grown on Corning eagle XG glass substrate 0.5 mm thick with roughness Ra < 10 Å. The second sample is the same superlattice, but its substrate is glued together from 8 plates 0.5 mm thick. Such a total thickness of the substrate $d_s = 4$ mm was chosen from the consideration that the microwave measurement frequency range 26–38 GHz would include the frequency at which the thickness of this substrate would correspond to a multiple of one forth of the wavelength. The superlattice period and the state of the interfaces were studied by small-angle X-ray scattering. Superlattice magnetoresistance

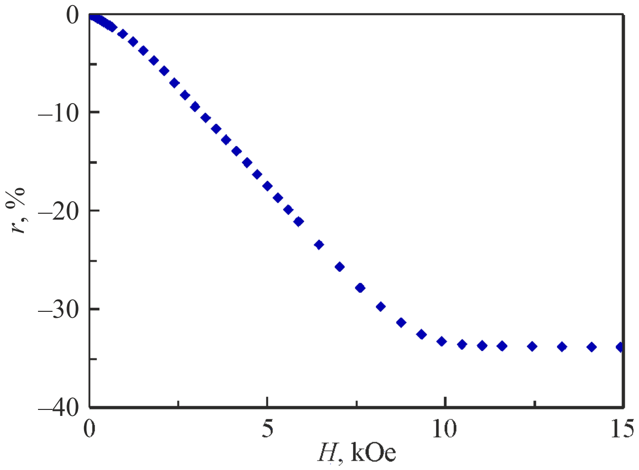

Figure 4. Magnetoresistance of superlattice Ta(3)/[$Co_{90}Fe_{10}$(1.5)/Cu(0.9)]$_6$/PyCr(5)/glass.

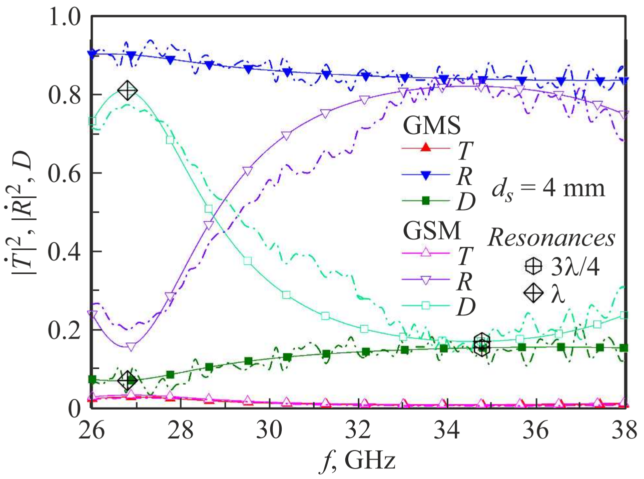

Figure 5. Frequency dependences of transmittance, reflectance and dissipation coefficients for sample with $d_s = 4$ mm. Dashed dependences — experiment, solid lines — calculation.

$r = [R(H) - R(0)]/R(0) \cdot 100\%$, where $R(H)$ — resistance in field H, $R(0)$ — resistance at $H = 0$ in fields up to 15 kOe is shown in Fig. 4.

Microwave measurements were performed in the frequency range 26–38 GHz using the method described in [19,20]. The samples were placed in the cross-section of a rectangular waveguide, completely overlapping it. A constant magnetic field was applied in the superlattice plane parallel to the narrow side of the waveguide, so that the vector of the constant magnetic field **H** was perpendicular to the vector of the alternating magnetic field of the wave $\mathbf{H}_\sim$. Using a scalar network analyzer, the frequency and field dependences of the modules of the transmittance $|\dot{T}(H)|$ and reflectance $|\dot{R}(H)|$ were measured, on the basis of which the dissipated power fraction or dissipation factor D were calculated.

3. Microwave measurements

The microwave transmittance and reflectance were measured as a function of frequency at a field $H = 0$ and as a function of the magnetic field at several fixed frequencies. The results of measuring the frequency dependence for sample with substrate $d_s = 4$ mm thick are shown in Fig. 5. The positions of the frequencies corresponding to the conditions $d_s = 3\lambda/4$ and λ are marked. In the experimental part of this paper we introduce the notation for the sequence of layers: 1) the designation GMS corresponds to the incidence of wave from generator first onto a metal superlattice, and then onto dielectric substrate; 2) the notation GSM corresponds to the incidence of the wave from the generator first onto the substrate and then onto the superlattice. The results in the case of GMS are as expected: the modulus of the reflectance is ~ 0.9, while the modulus of the transmittance is much smaller, as would be expected for system containing metal layer. The dissipation D in this case increases monotonically with frequency increasing. The results in the case of GSM are of greater interest. The frequency dependence of the reflectance is nonmonotonous; the frequency 27 GHz has a minimum corresponding to the condition $d_s = 3\lambda/4$. The dependence of dissipation in this case is also nonmonotonic, and its maximum is at frequency of 27 GHz. This maximum occurs as a result of the standing waves establishment in the wafer. Note that the frequency dependences of the transmittances in the cases of GMS and GSM are identical to each other, as expected.

The solid lines in Fig. 5 show the results of calculating the coefficients and dissipation using formulas (7), (10), (13). The calculation takes into account the total thickness of the superlattice metal $d = 22.4$ nm, the permittivity of the substrate $\varepsilon_s = 5$, and its thickness $d_s = 4$ mm. The best agreement between calculation and experiment was achieved with the following superlattice parameters, more precisely, effective material constants: $\varepsilon' = 37.5$, $\sigma = 2.07 \cdot 10^6$ S/m. Sufficiently good agreement between the calculation results and experimental data shows that the frequency dispersion of the material constants in this frequency range is small. There is a significant difference between the frequency dependences of the dissipation D for the GSM and GMS cases. A particularly large difference in dissipation, both in the experimental data and in the calculation, was recorded near the frequency $f = 27$ GHz, at which the condition $d_s = 3\lambda/4$ is satisfied. It can be assumed that this difference is associated with the establishment of the standing wave mode. The radical difference in the frequency dependences of the reflectance shows that in the system consisting of dielectric substrate $d_s = 4$ mm thick and metal superlattice with high conductivity, in the absence of magnetic field there is a significant nonreciprocity at microwave frequencies.

Let us consider the results of measurements in external magnetic field. They are made in fields up to 12 kOe. Remind that the magnetoresistance of the studied superlattice saturates in the field ~ 10.5 kOe. The results of measuring

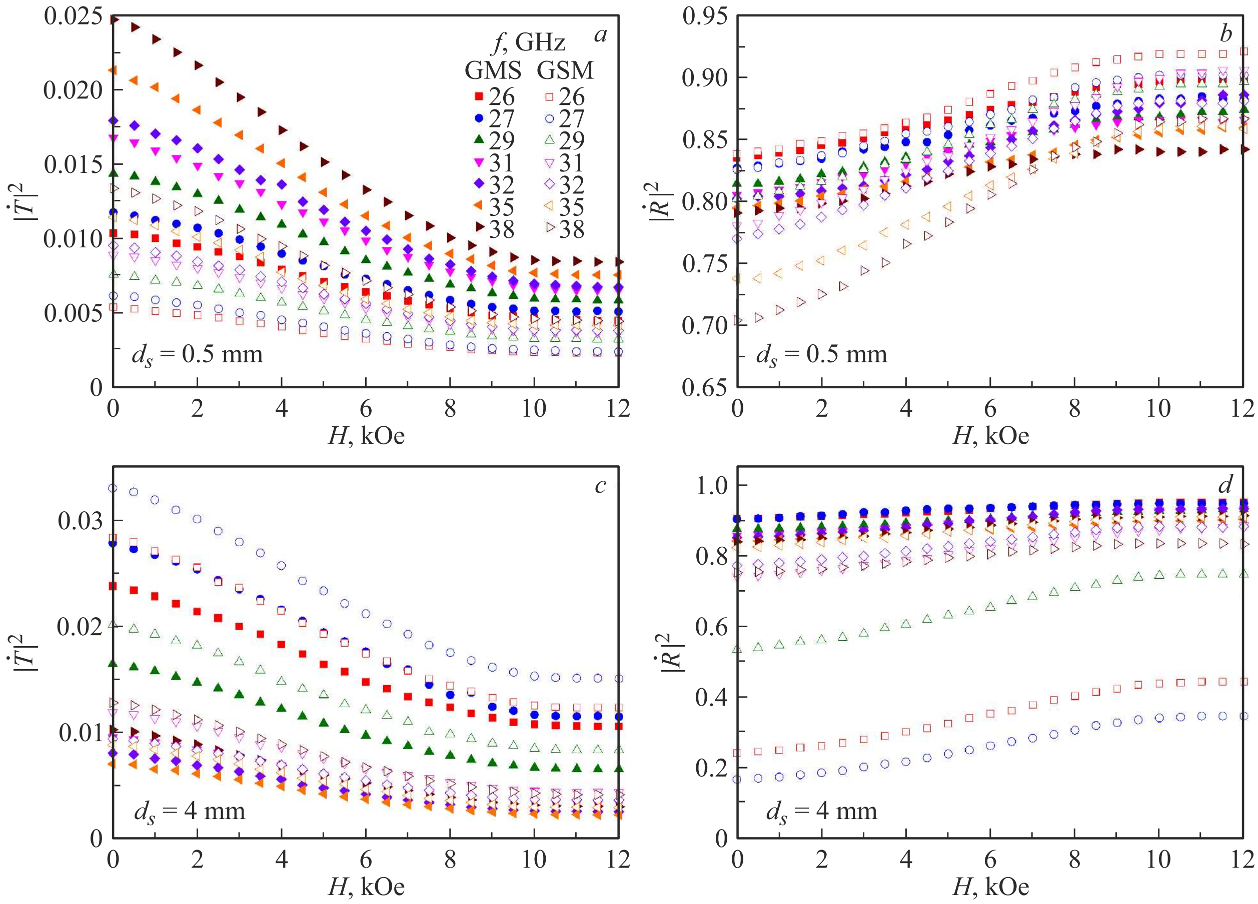

Figure 6. Transmittance and reflectance vs. magnetic field, measured at several frequencies, for samples with substrates 0.5 mm (a, c, e) and 4 mm (b, d, f): *a, b* — transmittance; *c, d* — reflectance.

the microwave transmittance and reflectance for two substrate thicknesses and two propagation directions are shown in Fig. 6. As expected, as the magnetic field increases, the transmittance decreases, since the conductivity increases. The nature of the field dependence of the transmittance is similar to the dependence of the relative magnetoresistance, as was previously indicated for the [(CoFe)/Cu] [14,16] and Fe/Cr [17–19] superlattices. The effect of the substrate thickness affects the reflectance in the comparison of the GMS and GSM options. In magnetic field the reflectance increases due to the μGMR effect. Comparison of Fig. 6, *b* and Fig. 6, *d* shows that in the GSM option at frequencies close to 27 GHz, the value of the reflectance is small, but it changes significantly when magnetic field is applied. The largest relative changes at $f = 27$ GHz reach +44%.

The fraction of microwave power dissipated in the superlattice/substrate system was calculated by the formula $D = 1-|\dot{R}|^2-|\dot{T}|^2$. Microwave power is spent for Joule losses in the superlattice metal and dielectric losses in the substrate. If there is a large difference in reflectance between the GMS and GSM cases, and the transmittance is small, $|\dot{T}| \ll 1$, then there must be a difference in microwave power dissipation between the GMS and GSM cases. Estimates shown that the dissipation is large in the GSM option for substrate 4 mm thick. At the frequency 27 GHz, corresponding to the condition $d_s = 3\lambda/4$, the fraction of the dissipated power reaches 80%. For substrate 0.5 mm thick, the fraction of the dissipated power does not exceed 26%. This difference is explained by the establishment of the standing waves mode in the substrate at $f = 27$ GHz at thickness of 4 mm; as a result, the reflection decreases, the amplitude of the microwave fields in the substrate increases, and therefore the dissipation increases. Note that the application of the magnetic field in all cases leads to decrease in dissipation, which is natural, since the effective conductivity of the superlattice increases due to the μGMR effect and, therefore, the Joule losses decrease.

4. Results and discussion

In Section 4 we compare the experimental data with the calculation results. The transmittance and reflectance were calculated using the formulas (7), (10), (13) for the options of the propagation direction GMS and GSM and two values of the substrate thickness 0.5 and 4 mm.

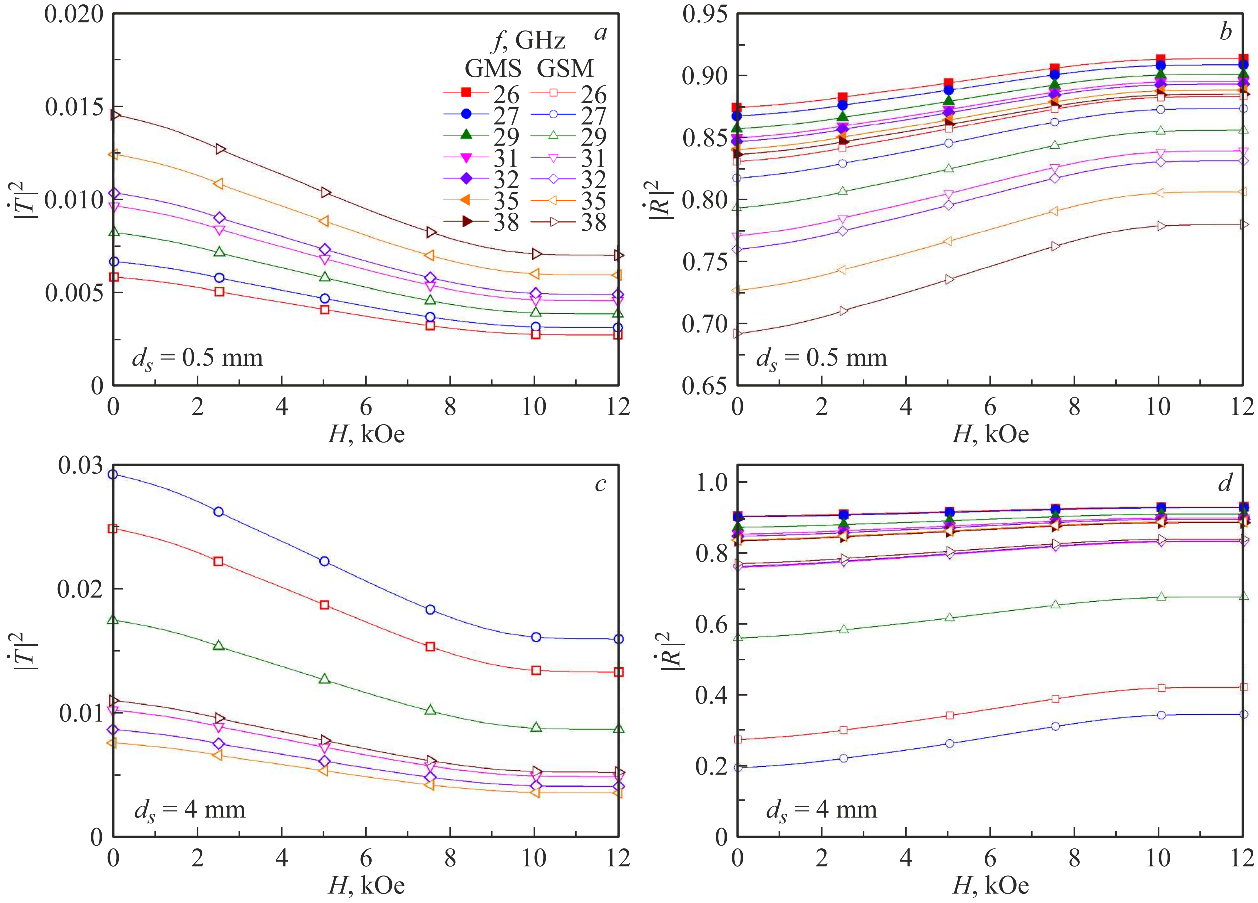

Figure 7. Transmittance and reflectance vs. magnetic field, calculated for the superlattice/substrate system: *a, c* — transmittance; *b, d* — reflectance. The calculations were performed for substrates with thickness of 0.5 mm (*a, b*) and 4 mm (*c, d*).

The calculation results are presented in Fig. 7. All the main features of the dependences obtained experimentally and shown in Fig. 6 are reproduced in the calculations. The type of $\dot{T}(H)$ and $\dot{R}(H)$ dependences, the presence of saturation in strong fields, and the magnitude of the saturation field are reproduced. In many cases, there is an approximate correspondence between the numerical values of the coefficients.

In the calculation for substrate 0.5 mm thick, the values of the transmittance were lower than in the experiment. The differences in the dependences of the reflectance for systems with substrates of different thicknesses, obtained in the calculation, are in full agreement with the experiment. Thus, for a substrate 0.5 mm thick in the GMS option the wave frequency has only a very small effect on the numerical values of the reflectance. For this substrate thickness the maximum value of the reflectance in the GSM option is 0.87, and the minimum value is 0.68. Approximately the same maximum and minimum values of 0.92 and 0.71 were recorded in the experiment.

The features of the reflectance for a substrate 4 mm thick were well reproduced in the calculation. In particular, the minimum and maximum values of the reflectance at frequency of 27 GHz are 0.19 and 0.37 in the experiment and 0.2 and 0.37 in the calculation. Thus, the performed experiments and calculations confirm the above assumptions about the role of the substrate thickness in the reflection of microwaves. The calculations also confirmed the conclusion about nonreciprocity in the superlattice/substrate system, made on the basis of the experiments performed.

To quantify the degree of nonreciprocity, one can introduce the nonreciprocity parameter by analogy with [5,6]. The system, in which waves propagate and reflect, is represented as a quadripole, for which the coefficients $\dot{S}_{ij}$ of the scattering matrix $\dot{\mathbf{S}}$ [26,27] are introduced. The parameters $\dot{S}_{11}$ and $\dot{S}_{21}$ — are the coefficients $\dot{R}$ and $\dot{T}$ for GMS configuration, and parameters $\dot{S}_{22}$ and $\dot{S}_{12}$ — coefficients $\dot{R}$ and $\dot{T}$ for GSM configuration. Then the nonreciprocity parameter β is defined [5,6], as

$$\beta = \frac{|\dot{S}_{21}||\dot{S}_{11}|^{-1}}{|\dot{S}_{21}||\dot{S}_{11}|^{-1} + |\dot{S}_{12}||\dot{S}_{22}|^{-1}}. \quad (14)$$

The dependences of the nonreciprocity parameter on the magnetic field for the superlattice/substrate system are shown in Fig. 8 for two thicknesses: $d_s = 0.5$ and 4 mm. In all cases, as the magnetic field increases, the parameter β increases, i. e., it approaches the value $\beta = 0.5$, which

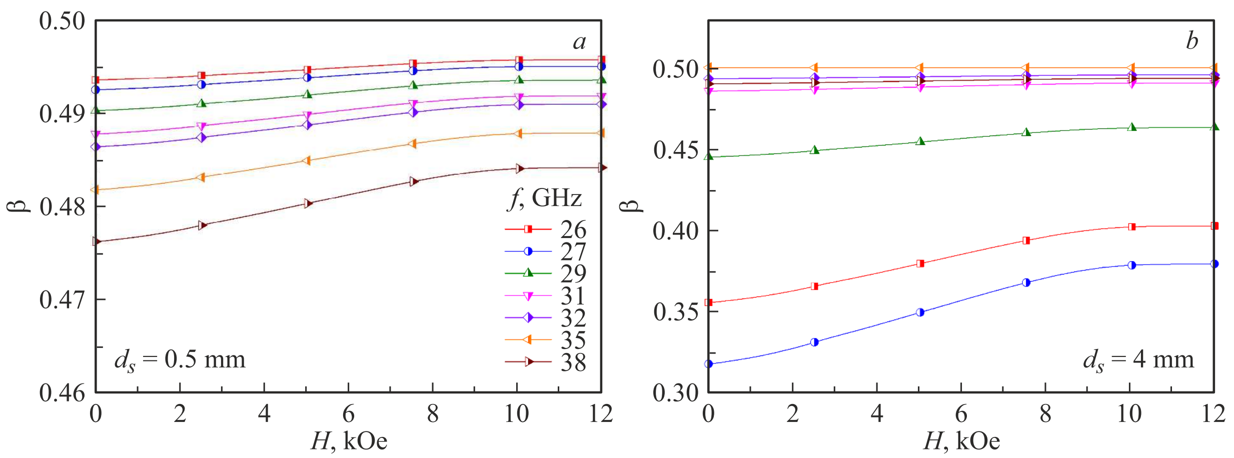

Figure 8. Nonreciprocity coefficient vs. magnetic field for substrates 0.5 (a) and 4 mm (b) thick.

corresponds to a completely reciprocal system. For a system with $d_s = 0.5$ mm the values of the parameter β vary from 0.47 to 0.49, i.e. very close to 0.5. Significantly greater differences from the reciprocity condition are observed for $d_s = 4$ mm. In this case, for frequencies 26 and 27 GHz, near the condition $d_s = 3\lambda/4$, the nonreciprocity parameter changes from 0.32 to 0.4.

Conclusion

The transmission and reflection of microwaves from dielectric substrate/metal superlattice [(CoFe)/Cu] system was studied. The frequency dependences of the transmittance and reflectance are measured for normal incidence of waves in two opposite directions, as well as the dependences of these coefficients on the magnetic field. There is a radical difference in the frequency dependences of the reflectance measured without magnetic field when the waves fall in opposite directions. It was established that in system consisting of dielectric substrate with thickness that is multiple of the thickness of a quarter-wave wafer, the metal superlattice with high conductivity, in the absence of magnetic field, there is a significant nonreciprocity. The fraction of the microwave power dissipated in the superlattice/substrate system is very different for the cases where the wave first falls on the substrate compared to the case where the wave first falls on the metal superlattice. In particular, for the substrate 4 mm thick at frequency of 27 GHz, the fraction of the dissipated power reaches 80%. For substrate 0.5 mm thick, the fraction of the dissipated power does not exceed 26%. The application of the magnetic field in all cases leads to decrease in dissipation, which is natural, since the conductivity of the superlattice increases due to the μGMR effect and, therefore, the Joule losses decrease.

Experiments shown that the nonreciprocity in the amplitude of the reflection coefficient can vary depending on the magnetic field. It was found that the microwave giant magnetoresistive effect in the reflected wave increases significantly if the wave first falls on the dielectric substrate, compared with the case of the wave falling directly on the metal superlattice. The increase is achieved at frequencies where the substrate thickness is a multiple of a one forth of the wavelength, due to the appearance of standing waves in the substrate and due to the lower reflectance from the dielectric substrate.

The experimental results were compared with calculations. The calculation reproduces the features of the field and frequency dependences of the reflectance. In particular, for substrate 4 mm thick the minimum and maximum values of the reflectance at frequency of 27 GHz are 0.19 at $H = 0$ and 0.37 at $H = 10.5$ kOe in the experiment and, respectively, 0.2 and 0.37 in the calculation. The performed experiments and calculations confirm the assumptions about the role of the substrate thickness in the reflection of microwaves. The calculations also confirmed the conclusion about nonreciprocity in the system (superlattice/substrate), made on the basis of the experiments performed. To quantify the degree of nonreciprocity, the nonreciprocity parameter was introduced. With the magnetic field increasing, the parameter of nonreciprocity increases, i.e., it approaches the value 0.5, which corresponds to completely reciprocal system.

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Conflict of interest

The authors declare that they have no conflict of interest.

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