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MAGNON-PLASMON POLARITONS IN THE LAYERED STRUCTURE METAL–FERRITE WITH A PERIODIC STRIPE-LIKE STRUCTURE OF DOMAINS

The theory of magnon-plasmon polaritons in the layered structure metal–ferrite–air is presented. It is assumed that the ferrite has an easy-axis anisotropy, and, in the absence of a magnetization field, it is in an unsaturated state with a periodic stripe-like domain structure. A dispersion dependence for magnon-plasmon polaritons and corresponding microwave field distributions in a waveguide structure based on $BaFe_{12}O_{19}$*-type hexaferrite are found. Effects associated with the hybridization of surface plasmon polaritons and domain resonances in the ferrite layer are analyzed. General characteristics of magnon-plasmon-polariton millimeter-wave resonators are discussed.*

Keywords: magnon-plasmon polariton, ferrite, periodic stripe-like domain structure.

1. Introduction

Surface electromagnetic waves (SEWs) were described for the first time by Sommerfeld in 1899 [1] and by Zenneck in 1907 [2]. The theoretical analysis of those waves, in which the Leontovich impedance boundary condition at the metal conductor surface was applied, can be found in books [3–5].

Waves of this type did not invoke much interest for a long time. However, several scientific groups sometimes returned to the consideration of this issue [6–8]. In the works by G.A. Melkov *et al.* written since 2000, it was proposed to use SEW resonators for measuring the surface impedances of high-temperature superconductors and for studying the Josephson junction arrays [9–13].

A new powerful wave of interest in SEWs arose owing to the formation of such a research direction as plasmonics [14–16]. SEWs at a flat conductive surface, which is a wave of the electric type (E-wave) that is inseparably coupled with the plasmon, i.e. free electron oscillations near the conductor surface, became the main subject of researches. Just the waves of this type were coined surface plasmon polaritons (SPPs). The attention was drawn to the fact that such waves occur in both optical and microwave spectral intervals [17]. In this connection, the interest in SPPs in the microwave range was renewed.

As a rule, when considering SPPs at the metal-insulator interface, the electric permittivity of a metal is assumed to acquire real values in the visible spectral range and imaginary values in the microwave one. In the general case, the electric permittivity of a metal is complex, so that the Drude model [18] should be used for a more accurate description. On the other hand, the dielectric permittivity of insulators at very high frequencies and far from all resonances tends to unity [17]. In the spectral interval of electron and vibrational transitions in atoms and molecules (the visible and infrared spectral ranges), the real part of the dielectric permittivity increases. At lower frequencies, the dielectric permittivity grows owing to mechanisms that result in the medium polarization. In the microwave range, the dielectric permittivity is different for polar and non-polar insulators and rapidly grows within the frequency interval corresponding to the reciprocal relaxation time of dipole moments in polar insulators. In this interval, the polar insulators strongly absorb radiation. At frequencies close to zero, the dielectric permittivity reaches a maximum. All of the aforesaid affects the frequency dependence of the dielectric permittivity and, as a consequence, the dispersion of SPPs.

On the other hand, when considering SPPs, the magnetic properties of the media are neglected in most cases, and their magnetic permeability is assumed to equal $\mu = 1$. This is valid for the visible and infrared spectral ranges, because magnetic excitations in magnetically ordered materials are usually concentrated in the microwave and subterahertz ranges. Nevertheless, when analyzing the propagation of microwave SPPs, the attention should also be paid to the cases where an insulator with the positive dielectric permittivity has the magnetic permeability that is different from unity and has a resonance frequency dependence. Therefore, the study of surface-type waves in the metal–ferrite structure is a challenging task. In this structure, a hybrid oscillation is possible with the participation of free electrons in the metal, magnetic moments in the ferrite, and an electromagnetic wave at the metal-ferrite interface, the latter is the magnon-plasmon polariton (MPP).

There are many works, in which SPPs were considered at the insulator–metal [17, 19], insulator–high-temperature superconductor [9], and magnetized semiconductor–insulator [20] interfaces. In this work, we focus attention on MPPs in a system of metal covered with a ferrite layer that has a periodic stripe-like domain structure (PSDS). The aim of the work consisted in studying the dispersion dependence of MPPs at a finite thickness of a ferrite layer, in calculating the distribution of electromagnetic fields, and in analyzing the limiting case of semiinfinite ferrite analytically.

2. Magnon-Plasmon Polariton in the Structure Metal–Ferrite Layer with the PSDS

Let us consider a structure consisting of a layer of uniaxial ferrite with the PSDS located on the surface of a semiinfinite metal (see Fig. 1). In the absence of a magnetization field, the magnetic moments in neighbor layer domains are directed in antiparallel to the easy magnetization axis (the x-axis). This structure with domains of two types has two oscillation eigenmodes [21]. When studying waves with the wavelength much longer than the period of the domain structure, the tensor of magnetic permeability averaged over this period can be used [22]:

$$\hat{\mu}_f = \mu_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mu_{22} & 0 \\ 0 & 0 & \mu_{33} \end{pmatrix}, \qquad (1)$$

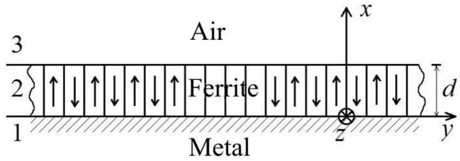

Fig. 1. Structure metal–ferrite with the PSDS

where

$\mu_{22} = (\omega^2 - \omega_2^2)/(\omega^2 - \omega_a^2)$,

$\mu_{33} = (\omega^2 - (\omega_a + \omega_M)^2)/(\omega^2 - \omega_2^2)$,

$\omega_2^2 = \omega_a(\omega_a + \omega_M)$, $\omega_a = \gamma H_a$, $\omega_M = \gamma M_s$. H_a is the uniaxial anisotropy field, and M_s the saturation magnetization of ferrite. Losses in the ferrite can be taken into account by making the substitution $\omega_a \to \omega_a + i\alpha\omega$, where α is the Gilbert relaxation parameter. A typical example of such a uniaxial ferrite is barium hexaferrite $BaFe_{12}O_{19}$ (BF) [22]. The corresponding value of the uniaxial anisotropy field is 1400 kA/m, the saturation magnetization is 380 kA/m, and the Gilbert relaxation parameter $\alpha = 0.001$ [23]. In this work, all theoretical dependences were obtained using the indicated BF parameters.

We will consider electromagnetic waves propagating along the z-axis and assume that the fields do not depend on the coordinate y and can be presented in the form $e^{i(\omega t - k_z z)}$.

The relative electric permittivity of a metal is determined from the Drude model [18],

$$\varepsilon_m = 1 - \frac{\omega_p^2}{\omega^2 - i\Gamma\omega}, \qquad (2)$$

where ω_p is the plasma frequency (the frequency of free electron oscillations in the metal), and Γ is the frequency of electron collisions.

Only E-waves will be considered, because it is the longitudinal component of the electric vector of an electromagnetic wave that is required for the formation of a plasmon. In this case, the electromagnetic wave has the following non-zero components: E_x, E_z, and H_y.

Let us apply the Hertz-vector formalism. From the Helmholtz equation, the solution for the electric Hertz vector looks like

$$\mathbf{\Gamma}_z^e = \psi(x) e^{-ik_z z} \mathbf{e}_z. \qquad (3)$$

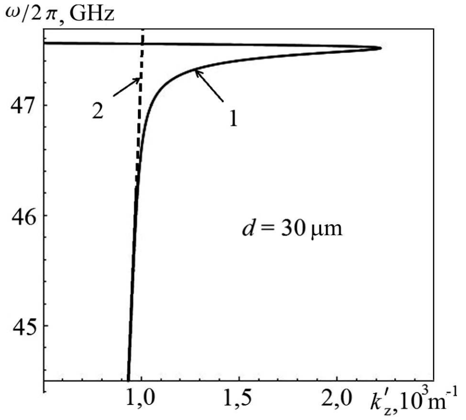

Fig. 2. Dispersion dependence for magnon-plasmon polaritons in the microwave range: (*1*) solution of the dispersion equation, (*2*) dispersion dependence for characteristic electromagnetic waves in vacuum

Membrane functions in the metal (1), ferrite (2), and air (3) are as follows:

$$\psi_1(x) = A_1 e^{\tau_1 x} + A_2 e^{-\tau_1 x},$$
$$\psi_2(x) = B_1 e^{\tau_2 x} + B_2 e^{-\tau_2 x},$$
$$\psi_3(x) = C_1 e^{\tau_3 x} + C_2 e^{-\tau_3 x}.$$

Satisfying the boundary conditions at infinity, $\psi_1(-\infty) \to 0$ and $\psi_3(\infty) \to 0$, we obtain that the constants A_2 and C_1 equal zero ($A_2 = C_1 = 0$). The wave numbers in the metal, ferrite, and air are determined as $k_1^2 = (\omega^2/c^2)\varepsilon_m$, $k_2^2 = (\omega^2/c^2)\varepsilon_f\mu_{22}$, and $k_3^2 = \omega^2/c^2$, respectively, where $c = 1/\sqrt{\varepsilon_0\mu_0}$ is the light speed in vacuum. The transverse wave numbers are determined from the equalities

$$\tau_1 = \sqrt{k_z^2 - (\omega^2/c^2)\varepsilon_m},$$
$$\tau_2 = \sqrt{k_z^2 - (\omega^2/c^2)\varepsilon_f\mu_{22}}, \tag{4}$$
$$\tau_3 = \sqrt{k_z^2 - (\omega^2/c^2)}.$$

With regard for the relation between the strength vectors of the electric and magnetic fields and the Hertz electric vector,

$$\mathbf{E} = \mathrm{grad}\ \mathrm{div}\boldsymbol{\Gamma}^e + k^2\boldsymbol{\Gamma}_z^e \quad \mathbf{H} = i\omega\varepsilon_0\varepsilon_f \mathrm{rot}\boldsymbol{\Gamma}_z^e,$$

the following expressions for the field components in ferrite are obtained:

$$E_x = -ik_z\tau_2(B_1e^{\tau_2 x} - B_2e^{-\tau_2 x})e^{-ik_z z},$$
$$E_z = -\tau_2^2(B_1e^{\tau_2 x} + B_2e^{-\tau_2 x})e^{-ik_z z}, \tag{5}$$
$$H_y = -i\omega\varepsilon_0\varepsilon_f\tau_2(B_1e^{\tau_2 x} - B_2e^{-\tau_2 x})e^{-ik_z z}.$$

The expressions for the fields in the metal and air are similar, with the substitutions $\tau_2 \to -\tau_1$, $B_2 \to A_1$, and $B_1 = 0$ in the case of the metal and $\tau_2 \to \tau_3$, $B_2 \to C_2$, and $B_1 = 0$ in the case of air.

Using the boundary conditions for the tangential components of the electric field strength vectors and the normal components of the electric induction vectors at the ferrite–metal interface, we obtain the following characteristic equation that couples the parameters τ_1, τ_2, τ_3, and k_z:

$$\sinh(\tau_2 d)(\tau_1\tau_3\varepsilon_f^2 + \varepsilon_m\tau_2^2) +$$
$$+ \cosh(\tau_2 d)(\tau_1\tau_2\varepsilon_f + \varepsilon_m\varepsilon_f\tau_2\tau_3) = 0. \tag{6}$$

Substituting Eqs. (4) into Eq. (6), we obtain a dispersion equation that makes it possible to find a dispersion dependence for MPPs. The numerical solution of this equation obtained for the structure Cu-BF with the SPDS, with a ferrite layer thickness of 30 μm, and in a frequency interval close to the domain resonance frequency $\omega_a/(2\pi) = 47.6$ GHz is shown in Fig. 2. This is a frequency interval, where the dispersion of MPPs has an anomalous character resulting from the hybridization of three excitations. Magnetic losses in the ferrite are taken into account in the framework of the Gilbert model, dielectric losses are characterized by the complex dielectric constant $\varepsilon_f = 16(1-0.01i)$, and the electric permittivity of the metal is determined by the Drude model with the parameters $\omega_p = 1.38 \times 10^{16}$ s^{-1} and $\Gamma = 2.9 \times 10^{13}$ s^{-1} as for copper.

If $d = 0$, Eq. (6) is reduced to the equation $\tau_1 + \tau_3\varepsilon_m = 0$. Then, using Eqs. (4), we obtain an expression for the longitudinal wave number, which coincides with the known expression [18]:

$$k_z^2 = \frac{\omega^2}{c^2}\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m + \varepsilon_d}, \tag{7}$$

provided that $\varepsilon_d = 1$, which is true for air.

In the other limiting case, $d \to \infty$, Eq. (6) is reduced to the equation $\varepsilon_m\tau_2 + \varepsilon_f\tau_1 = 0$. Carrying out a substitution similar to the previous case, the analytic expression for the longitudinal wave number is as follows:

$$k_z^2 = \frac{\omega^2}{c^2}\frac{\varepsilon_m\varepsilon_f(\varepsilon_m\mu_{22} - \varepsilon_f)}{\varepsilon_m^2 - \varepsilon_f^2}. \tag{8}$$

It is worth noting that, in the dispersion equations (6) and (8), one should take into account that $\omega \neq \omega_a$.

There is a varying magnetization m_y at the frequency $\omega = \omega_a$, despite that the varying magnetic field is absent.

In order to analyze the main parameters of MPPs, it is enough to use the results obtained in the framework of the infinite-ferrite model. The corresponding real and imaginary parts of the longitudinal wavenumber in the microwave and optical spectral ranges are shown in Fig. 3. As one can see, in the microwave range, there emerges an additional branch associated with MPPs. The horizontal asymptote in Fig. 3, *a* in the microwave interval exactly coincides with the frequency ω_a, if the losses in ferrite are not taken into account. In the same approximation, $k'_z = 0$ at the frequency ω_2. In the optical range, the components of the magnetic permeability tensor can be put equal to unity; therefore, the obtained upper frequency limit in the dispersion dependence shown in Fig. 3, *b* reproduces the known result [18]

$$\omega_{sp} = \frac{\omega_p}{\sqrt{\varepsilon_d + 1}} \tag{9}$$

at $\varepsilon_f = \varepsilon_d$. In this case, there are two frequency sections, where the imaginary part of the longitudinal wavenumber is much larger than the real one, so that the waves do not propagate.

It is also worth giving attention to the phase velocity of MPPs in the microwave range. Its frequency dependence is shown in Fig. 4. In particular, at frequencies slightly below ω_a, the phase velocity of MPP is substantially lower than that in the structure metal–non-magnetic insulator (with the same dielectric permittivity). This means that the MPP becomes a slow wave. The result obtained is analogous to the properties of SPPs in the optical range in a vicinity of the frequency ω_{sp}, but, here, it takes place in the microwave spectral interval. Such a slowing down of the MPPs provides an opportunity to miniaturize resonance structures on their basis.

In the frequency interval where $k''_z \gg k'_z$ (Fig. 3, *a*), the wave does not propagate along the medium interface, which is evidenced by the asymptotic growth of the phase velocity in the microwave range. In this section, the imaginary parts τ_1 and τ_2 are much larger than the real ones, and, hence, the separating interface between the metal and the ferrite with the PSDS loses its guide properties.

3. Penetration Depth of the MPP Field into the Metal and the Ferrite with the SPDS in the Microwave Range

Expressions for the transverse wavenumbers in the infinite-ferrite model look like

$$\tau_1 = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m^2(\varepsilon_f\mu_{22} - \varepsilon_m)}{\varepsilon_m^2 - \varepsilon_f^2}}, \tag{10}$$

$$\tau_2 = -\frac{\varepsilon_f}{\varepsilon_m}\frac{\omega}{c}\sqrt{\frac{\varepsilon_m^2(\varepsilon_f\mu_{22} - \varepsilon_m)}{\varepsilon_m^2 - \varepsilon_f^2}}. \tag{11}$$

Unlike the optical range, where the electric permittivity of a metal is determined by its real part, the imaginary part ε_m dominates in the microwave range. Therefore, the transverse wavenumbers are complex-valued here. In this connection, the MPP fields in the ferrite oscillate with an amplitude that exponentially decays with the distance from the metal. The

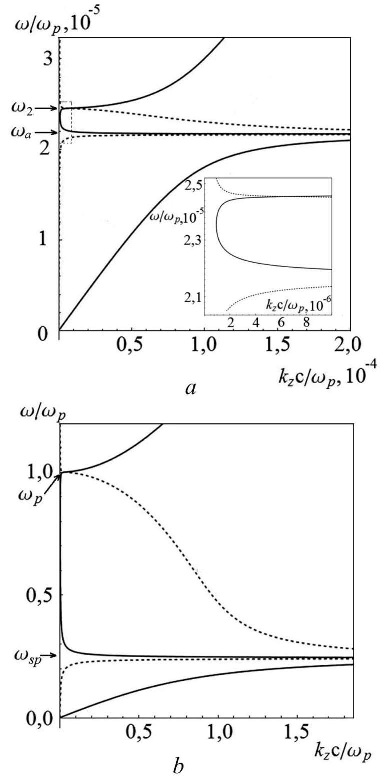

Fig. 3. Dispersion dependence for MPPs in the Cu-BF structure in the microwave (*a*) and optical (*b*) ranges. Solid and dashed curves describe the real (k'_z) and imaginary (k''_z) parts, respectively, of the normalized wave number. The calculation parameters $\omega_a/2\pi = 47.6$ GHz and $\omega_2/2\pi = 53.9$ GHz

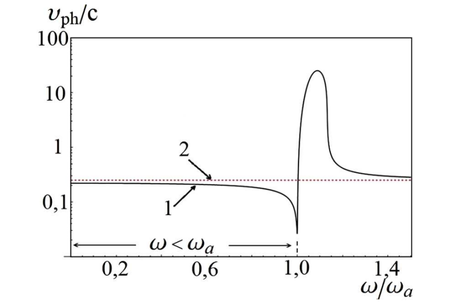

Fig. 4. Phase velocity of polaritons in the microwave range: MPPs in the structure metal–ferrite with the PSDS (*1*), plasmon-polaritons in the structure metal–non-magnetic insulator (*2*). The dielectric permittivities of ferrite and the non-magnetic insulator are identical and equal to $16(1 - 0.01i)$

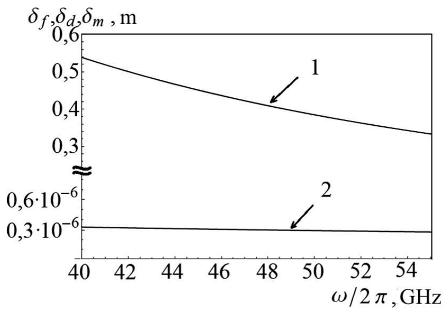

Fig. 5. Penetration depths of MPP field into the media: δ_f and δ_d in the structures metal–ferrite and metal–non-magnetic insulator (*1*), δ_m in the structures metal–ferrite and metal–non-magnetic insulator (*2*)

penetration depth of the MPP field into the ferrite is determined by the real part of the transverse wavenumber, $\delta_f = 1/\,\mathrm{Re}\ \tau_2$. In the microwave range, $|\varepsilon_f \mu_{22}| \ll |\varepsilon_m|$, so that the influence of the magnetic ferrite origin on the penetration depth of the MPP field into the ferrite and the metal was found to be insignificant. For example, for the Cu-BF structure, $\delta_f = \delta_d = 0.45$ m near the frequency ω_a. At the same time, $\delta_m = 0,3$ μm (see Fig. 5).

4. Resonators

An MPP-based resonator can be constructed from segments of a waveguide structure similarly to a resonator described in work [19]. The new resonator is a rectangular metal plate covered with a ferrite layer. To excite this resonator, it can be mounted in a rectangular waveguide section. Since the main wave type H_{10} has the electric field component directed normally to the wider waveguide wall, the resonator should be so arranged that the E_x and E_z projections of the electric field are different from zero. The size confinement of the structure metal–ferrite with the PSDS in the plane results in the quantization of the wave vector $\mathbf{k}_z$,

$$k_z^2 = \left(\frac{\delta_1 \pi}{a}\right)^2 + \left(\frac{\delta_2 \pi}{b}\right)^2, \qquad (12)$$

where a and b are the resonator sizes. In practice, the typical values of the indices δ_1 and δ_2 are not integer numbers, but numbers close to them. It happens because the wave field partially extends beyond the resonator.

5. Conclusions

A theory has been developed which describes magnon-plasmon polaritons (MPPs) in a layered system metal–ferrite with a periodic stripe-like domain structure. It is found that, in the absence of a magnetization field, the MPP dispersion dependence contains an additional branch in the microwave spectral interval, whose upper limiting frequency coincides with the domain resonance frequency.

The penetration depth of the microwave MPP electromagnetic field into the ferrite is calculated. The result is found to weakly depend on the magnetic properties of the ferrite.

It is demonstrated that the phase velocity of MPPs at frequencies below the domain resonance is lower than the phase velocity of surface plasmon polaritons at the metal–nonmagnetic insulator interface.

It is shown that the MPP is a slow wave in a vicinity of the domain resonance frequency. The MPP properties in this frequency interval make it possible to create millimeter-wave resonators of a new type.

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МАГНОН-ПЛАЗМОН-ПОЛЯРИТОНИ
В ШАРУВАТІЙ СИСТЕМІ МЕТАЛ–ФЕРИТ
ЗІ СМУГОВОЮ ПЕРІОДИЧНОЮ
ДОМЕННОЮ СТРУКТУРОЮ

Р е з ю м е

Представлена теорія магнон-плазмон-поляритонів у шаруватій структурі метал–ферит–повітря. Припускається, що ферит має анізотропію типу "легка вісь" та знаходиться в ненасиченому стані зі смуговою періодичною доменною структурою за відсутності поля підмагнічування. Знайдені дисперсійні залежності для магнон-плазмон-поляритонів та відповідні розподіли полів у хвилеводній структурі з гексаферитами типу $BaFe_{12}O_{19}$. Проаналізовані ефекти, пов'язані з гібридизацією поверхневих плазмон-поляритонів та доменних резонансів у феритовому шарі. Обговорені загальні характеристики магнон-плазмон-поляритонних резонаторів міліметрового діапазону.