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Spin-wave diagnostics of epitaxial ferrite-dielectric structures

V. V. Tikhonov✉, *V. A. Gubanov*

Saratov State University, Russia
E-mail: ✉tvlad4@yandex.ru, vladmeen@gmail.com
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Abstract. *Purpose* of this study is to elucidate the mechanism of transformation of electromagnetic and exchange spin waves (ESW) in a thin transition layer of epitaxial ferrite–dielectric structures, as well as to investigate the possibilities of using short-wave ESW to diagnose magnetic inhomogeneities of epitaxial yttrium-iron garnet (YIG) films. *Methods*. In this paper, we study the hybridization processes of electromagnetic and exchange spin waves that occur in the transition layer of the YIG film. The features of the dispersion of coupled waves in the vicinity of phase synchronism frequencies under normal and tangential magnetization of the YIG film are investigated. *Results*. It is shown that within of the thickness transition layer, the dispersion of the excited ESW experiences significant distortions, which manifests itself in frequency shifts of the spin-wave resonance. Based on this, a method for calculating the distribution of spontaneous magnetization over the thickness of the YIG film was proposed, which was used to simulate the processes of excitation of spin-wave resonances. *Conclusion*. The proposed technique of spin-wave diagnostics of YIG films can be effectively used for non-destructive testing of all types of epitaxial ferrite-dielectric structures, which may be in demand in the field of production and in the field of their practical application.

Keywords: exchange spin waves, electromagnetic waves, epitaxial YIG films, magnetic inhomogeneity of YIG films, measurement technique.

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Introduction

The current stage of development of micro- and nanoelectronics is characterized by the wide application of quantum phenomena in solids. This was the basis for the rapid development of fundamental and applied research in the field of micro- and nanomagnetism. In terms of practical application, the studies of spin-wave excitations in magnetically ordered ferrite media are of the greatest interest. On the basis of these studies, new scientific directions have been formed, such as spin-wave electronics [1], spintronics [2] and magnonics [3–5]. The further development of these directions was associated with the practical development of ultrashort exchange spin waves with lengths of the order of 100 nm and less [6]. The existence of spin waves was predicted in 1930 in the famous work of Bloch [7]. However, their practical development began relatively recently. This became possible thanks to the creation of high-quality epitaxial films of iron-trium garnet (YIG) grown on non-magnetic substrates of gadolinium-gallium garnet (GGG) [8–10]. YIG films turned out to be the most favorable medium for the propagation of spin waves. However, according to some indicators, they required further improvement. The most acute problem of YIG films was multilayering, which inevitably arose in the process of epitaxial growth. A transition (diffusion) layer, which was characterized by reduced magnetization, was always formed on the inner surface of the film bordering the GGG substrate. This was equally true for films grown by liquid-phase epitaxy [9] and by ion-beam sputtering [10]. Complete elimination of the transition layer is not possible. You can only reduce its thickness by adjusting the growth mode. However, this required means of controlling the distribution of magnetization over the thickness of the films. This problem was solved by the method of layer-by-layer etching and spectral analysis of the elemental composition of the film [9]. However, this gave only a qualitative idea of the magnetic properties of the layers. In addition, the film itself was completely destroyed at the same time. At the same time, it was known that the magnetic inhomogeneity of the GIG films promotes the excitation of exchange spin waves traveling in the transverse direction of the film [11, 12]. In the case of pulsed excitation, they could be observed in the form of a series of delayed echo pulses, which carry information about the magnetic properties of the propagation medium. By the delay of the echo pulses, it was possible to calculate the magnetization distribution over the thickness of the film [13, 14]. However, this technique was suitable only for sufficiently thick YIG films, in which the delay of the echo pulses significantly exceeded the duration of the probing microwave pulse. In this paper, we propose a technique for spin-wave diagnostics of the magnetic structure of the YIG film without any restrictions on the thickness of the film. The proposed technique is based on the measurement of spin-wave resonance frequencies and mathematical processing of measurement results.

1. Measurement methodology

As a test sample, a film of YIG was used, with respect to which it was only known that it was grown by liquid-phase epitaxy on a YYG substrate with a surface orientation (111). The experimental sample of the film had dimensions of 2×2 mm. The measurement task was to determine a set of film parameters necessary for modeling the processes of excitation of spin-wave resonances.

The measurements were carried out in a continuous excitation mode. The resonances were excited by a quasi-homogeneous microwave magnetic field, which was created by a microstrip converter shorted at the end. The width of the converter was 3 mm. The film sample was installed near the shorted end of the converter. The S11 parameters of the microwave signal reflected from the converter input were measured. The measurements were carried out using a vector meter of

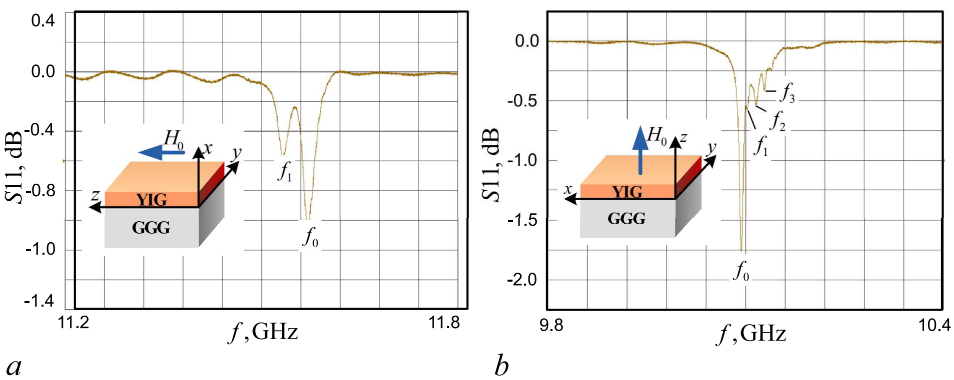

Fig. 1. The amplitude-frequency characteristic of the reflected signal of the experimental design of the YIG film: *a* — with tangential magnetization (magnetizing field $H_0 = 3972$ Oe, resonant frequencies $f_0 = 11.572$ GHz, $f_1 = 11.532$ GHz); *b* — with normal magnetization (magnetizing field $H_0 = 5501$ Oe, resonant frequencies $f_0 = 10.089$ GHz, $f_1 = 10.095$ GHz, $f_2 = 10.103$ GHz, $f_3 = 10.116$ GHz). The inserts show the magnetization geometry of the film sample

electrical circuits with tangential and normal magnetization of the film. The measurement results are shown in Fig. 1.

In both cases, peaks of absorption of the microwave signal were observed in the spectrum of the reflected signal. However, the nature of these peaks differed significantly. During tangential magnetization of the film, two resonant peaks were observed, as shown in Fig. 1, *a*. During normal magnetization, a series of peaks was observed, the amplitudes of which monotonically decreased with increasing excitation frequency (see Fig. 1, *b*). Peak frequencies were measured using vector meter markers. With the growth of the magnetizing field, the peaks monotonically shifted towards higher frequencies. At the same time, the frequency intervals between the peaks also monotonously increased.

2. Calculation method

To calculate the parameters of the YIG film, the linearized equation Landau – Lifshitz was solved

$$\frac{\partial\vec{m}}{\partial t} + \gamma H_0\left(\vec{m}\times\vec{z}\right) + \gamma M\left(\vec{z}\times\vec{h}\right) + \eta\vec{M}\left(\vec{z}\times\nabla^2\vec{m}\right) = 0 \tag{1}$$

and Maxwell 's system of equations

$$\begin{cases} \nabla\times\vec{e} = -\dfrac{1}{c}\dfrac{\partial}{\partial t}\left(\vec{h}+4\pi\vec{m}\right), \\ \nabla\times\vec{h} = \dfrac{\varepsilon}{c}\dfrac{\partial\vec{e}}{\partial t}, \\ \nabla\cdot\vec{e} = 0, \\ \nabla\cdot\left(\vec{h}+4\pi\vec{m}\right) = 0, \end{cases} \tag{2}$$

where $\vec{H}_0 \parallel \vec{M} \parallel \vec{z}$ — the constant components of the magnetizing field and the intrinsic magnetization of the YIG film, $\vec{m}$, $\vec{h}$, $\vec{e} \sim \exp\left(i\omega t\right)$ — variable components of magnetization, magnetic and electric fields. The calculations used the inhomogeneous exchange constant $\eta \approx (\gamma J_0/\mu_B)\, a^2 \simeq \gamma\alpha M = 7.64\times10^{-2}$ см^{2}c^{-1}, n J_0 — the exchange integral, μ_B — Boron magneton, a — the crystal lattice constant of the YIG film, which with an accuracy of 0.08% coincided with the lattice constant of the substrate YYYY. Crystallographic anisotropy and dissipative losses in the YIG film were not taken into account.

The solution was sought in the form of flat monochromatic waves of precession of magnetization $\vec{m} \sim \exp\left[i\left(\omega t - \vec{k}\cdot\vec{r}\right)\right]$, where $\vec{k}$ — wave vector, $\vec{r}$ — radius vector, $\omega = 2\pi f$ — circular frequency, f — excitation frequency. With this in mind, the equation Landau –Lifshitz(1) was reduced to the form

$$i\omega\vec{m} + \left(\omega_H + \eta k^2\right)\left(\vec{m}\times\vec{z}\right) = \gamma M\left(\vec{h}\times\vec{z}\right), \tag{3}$$

which in coordinate form had the form

$$\begin{cases} i\omega m_x + \left(\omega_H + \eta k^2\right) m_y = \gamma M h_y, \\ i\omega m_y - \left(\omega_H + \eta k^2\right) m_x = -\gamma M h_x, \\ m_z = 0, \end{cases} \tag{4}$$

where $\omega_H = \gamma H_i$, H_i — the inner field of the YIG film. Expressions for electromagnetic fields were obtained from Maxwell's equations (2)

$$\vec{e} = 4\pi \frac{k_0 \left(\vec{k} \times \vec{m}\right)}{k^2 - \varepsilon k_0^2}, \quad \vec{h} = 4\pi \frac{\varepsilon k_0^2 \vec{m} - \vec{k}\left(\vec{k} \cdot \vec{m}\right)}{k^2 - \varepsilon k_0^2}, \tag{5}$$

which in coordinate form, taking into account $m_z = 0$, had the form

$$\begin{cases} e_x = \dfrac{-4\pi k_0 k_z}{k^2 - \varepsilon k_0^2} m_y, \\ e_y = \dfrac{4\pi k_0 k_z}{k^2 - \varepsilon k_0^2} m_x, \\ e_z = \dfrac{4\pi k_0}{k^2 - \varepsilon k_0^2}\left(k_x m_y - k_y m_x\right), \end{cases} \qquad \begin{cases} h_x = \dfrac{-4\pi}{k^2 - \varepsilon k_0^2}\left[\left(k_x^2 - \varepsilon k_0^2\right) m_x + k_x k_y m_y\right], \\ h_y = \dfrac{-4\pi}{k^2 - \varepsilon k_0^2}\left[\left(k_y^2 - \varepsilon k_0^2\right) m_y + k_x k_y m_x\right], \\ h_z = \dfrac{-4\pi k_z}{k^2 - \varepsilon k_0^2}\left(k_x m_x + k_y m_y\right), \end{cases} \tag{6}$$

where $k_0 = \omega/c$ — the wave number of the electromagnetic wave, $c \simeq 3 \cdot 10^{10}$ см/с — the speed of light in a vacuum.

Substituting the expressions h_x, h_y into the right part of equations (4) from (6), the coupling equations of the transverse components of the magnetization precession vector were obtained

$$m_y = \frac{\omega_M k_x k_y + i\omega\left(k^2 - \varepsilon k_0^2\right)}{\omega_M\left(\varepsilon k_0^2 - k_y^2\right) - \left(\omega_H + \eta k^2\right)\left(k^2 - \varepsilon k_0^2\right)} m_x, \tag{7}$$

$$m_x = \frac{\omega_M k_x k_y - i\omega\left(k^2 - \varepsilon k_0^2\right)}{\omega_M\left(\varepsilon k_0^2 - k_x^2\right) - \left(\omega_H + \eta k^2\right)\left(k^2 - \varepsilon k_0^2\right)} m_y. \tag{8}$$

Multiplying equations (7) and (8), it was not difficult to obtain an expression of the law of dispersion of spin waves

$$\omega^2 = \left(\omega_H + \eta k^2\right)^2 \left\{\left[1 + \frac{\omega_M}{\omega_H + \eta k^2} \frac{k_x^2 - \varepsilon k_0^2}{k^2 - \varepsilon k_0^2}\right]\left[1 + \frac{\omega_M}{\omega_H + \eta k^2} \frac{k_y^2 - \varepsilon k_0^2}{k^2 - \varepsilon k_0^2}\right] - \left(\frac{\omega_M}{\omega_H + \eta k^2} \frac{k_x k_y}{k^2 - \varepsilon k_0^2}\right)^2\right\}. \tag{9}$$

By dividing equation (7) by (8), an expression was obtained for determining the ellipticity parameter of the magnetization precession

$$\left(\frac{m_y}{m_x}\right)^2 = \frac{\omega_M k_x k_y + i\omega\left(k^2 - \varepsilon k_0^2\right)}{\omega_M k_x k_y - i\omega\left(k^2 - \varepsilon k_0^2\right)} \cdot \frac{\left(\omega_H + \eta k^2\right)\left(k^2 - \varepsilon k_0^2\right) + \omega_M\left(k_x^2 - \varepsilon k_0^2\right)}{\left(\omega_H + \eta k^2\right)\left(k^2 - \varepsilon k_0^2\right) + \omega_M\left(k_y^2 - \varepsilon k_0^2\right)}. \tag{10}$$

Expressions (9), (10) were obtained in the most general form, but in the case of an infinite ferrite, they could be simplified somewhat by choosing the position of the coordinate axes so that the wave vector $\vec{k}$ completely lies in the plane (x, z). Then by substituting $k_y = 0$, the expression of the law of variance (9) was reduced to the form

$$\omega = \left(\omega_H + \eta k^2\right)\theta, \tag{11}$$

and the expression (10) — to the form

$$m_y = \pm i m_x \theta, \tag{12}$$

where $\theta = \sqrt{\left[1 + \frac{\omega_M}{\omega_H + \eta k^2} \frac{k_x^2 - \varepsilon k_0^2}{k^2 - \varepsilon k_0^2}\right]\left[1 - \frac{\omega_M}{\omega_H + \eta k^2} \frac{\varepsilon k_0^2}{k^2 - \varepsilon k_0^2}\right]}$ — the ellipticity parameter of the magnetization precession. In the case of excitation of precession by a homogeneous microwave field, at $k_0 = 0$, the expression of the ellipticity parameter was greatly simplified

$$\theta = \sqrt{1 + \frac{\omega_M}{\omega_H + \eta k^2} \frac{{k_x}^2}{k^2}}. \tag{13}$$

Using the ellipticity parameter, it was possible to reduce the task to finding only one component of the precession vector, for example m_x.

Bexpressions (11)–(13) were used to calculate the parameters of the YIG film. At the same time, it was assumed that within the thickness of the transition layer of the film, the YIG ($Fe_3Y_5O_{12}$) magnetic ions Fe^{3+}, Y^{5+} were partially replaced by non-magnetic ions Gd^{3+}, Ga^{5+} of the YYYY substrate ($Gd_3Ga_5O_{12}$) [15]. According to the theory of diffusion in solids [16], the distribution of the concentration of substituting ions was adequately described by the Gauss function $N \sim \exp\left[-(r_i/\sigma\,)^2\right]$, where σ is the phenomenological parameter of the distribution, r_i is the coordinate in the transverse direction of the YIG film . With this in mind , the distribution of magnetization over the thickness of the film could be represented as

$$M = M_0\left[1 - \exp\left(-{r_i}^2/\sigma^{\,2}\right)\right], \tag{14}$$

n M_0 — homogeneous magnetization of the film outside the transition layer. The magnetization distribution function (14) was used to calculate the wave characteristics of the precession wave at tangential $(r_i = x)$ and at normal $(r_i = z)$ magnetization of the film. The waves traveling in the transverse direction of the film of the YIG were considered.

In the case of tangential magnetization of the film, the dispersion equation (11) was reduced to the form

$$\omega = \left(\omega_H + \eta {k_x}^2\right)\sqrt{1 + \frac{\omega_M}{\omega_H + \eta {k_x}^2}}, \tag{15}$$

from which it was not difficult to obtain an expression for the wave number

$$k_x = \mathrm{Re}\left[\sqrt{\frac{1}{\eta}\left(\sqrt{\frac{{\omega_M}^2}{4} + \omega^2} - \frac{\omega_M}{2} - \omega_H\right)}\right], \tag{16}$$

where $\omega = 2\pi f$, $\omega_H = \gamma H_0$, $\omega_M = 4\pi\gamma M_0\left[1 - \exp\left(-x^2/\sigma^{\,2}\right)\right]$. Expression (16) was used to record the condition of excitation of the precession wave. With tangential magnetization of the film, this condition coincided with the condition of synchronism (matching) with an external homogeneous microwave field and had the form

$$k_x\left(f, H_0, M_0, \sigma, x\right) = 0. \tag{17}$$

From condition (17) it was not difficult to obtain the coordinate dependence of the excitation frequency

$$f\left(H_0, M_0, \sigma, x\right) = \frac{\gamma}{2\pi}\sqrt{H_0\left\{H_0 + 4\pi M_0\left[1 - \exp\left(-{r_i}^2/\sigma^{\,2}\right)\right]\right\}} \tag{18}$$

and the frequency dependence of the coordinate of the excitation plane of the precession wave

$$x_0\left(f, H_0, M_0, \sigma\right) = \sigma\sqrt{\ln\left[\frac{4\pi M_0 H_0}{{H_0}^2 + 4\pi M_0 H_0 - \left(2\pi f/\gamma\,\right)^2}\right]}. \tag{19}$$

By substituting in (18) the limit values of the coordinates $x_{\min} = 0$ and $x_{\max} = \infty$, expressions of the boundary frequencies of the excitation band were obtained

$$f_{\min} = \frac{\gamma H_0}{2\pi}, \tag{20}$$

$$f_{\max} = \frac{\gamma}{2\pi}\sqrt{H_0\left(H_0 + 4\pi M_0\right)}. \tag{21}$$

From expression (21) it was not difficult to obtain a formula for calculating the homogeneous magnetization of the film outside the transition layer

$$M_0 = \frac{\left(2\pi f_{\max}/\gamma\,\right)^2 - {H_0}^2}{4\pi H_0}. \tag{22}$$

Substitution in (22) of the experimental values of the field $H_0 = 3972$ E and resonant frequency $f_{\max} = f_0 = 13.536$ GHz the parameter value was received $M_0 \simeq 151$ Гс.

To calculate the parameter of the magnetization distribution σ, the phase condition of excitation of spin-wave resonances $\varphi = n\pi$ was used, where φ is— the onset of the phase of the precession wave at the path length $l = x_0 - 0$. For the first SVR mode , this condition had the form

$$\varphi\left(f, H_0, M_0, \sigma\right) = \int\limits_0^{x_0(f,H_0,M_0,\sigma)} k_x\left(f, H_0, M_0, \sigma, x\right)dx = \pi. \tag{23}$$

When substituting in (23) the magnetizing field $H_0 = 3972$ E, resonant frequency $f_1 = 13.49$ GHz and the parameter $M_0 \simeq 151$ Gs was the equation $\varphi\left(\sigma\right) = \pi$, which was solved by numerical methods. As a result, the value of the parameter $\sigma \simeq 6.48 \times 10^{-6}$ sm.

In the case of normal magnetization of the film, the dispersion equation (11) was reduced to the form

$$\omega = \omega_H + \eta k_z^2, \tag{24}$$

from which the expression for the wave number followed

$$k_z = \mathrm{Re}\left(\sqrt{\frac{\omega - \omega_H}{\eta}}\right), \tag{25}$$

where $\omega_H = \gamma H_0 - 4\pi\gamma M_0\left[1 - \exp\left(-z^2/\sigma^2\right)\right]$. Here and in the future, the parameters M_0 и σ, obtained in calculations for the case of tangential magnetization of the film were used. As in the previous case, from the condition of excitation of the precession wave $k_z(f, H_0, M_0, \sigma, z) = 0$ the frequency expressions were obtained

$$f(H_0, M_0, \sigma, z) = \frac{\gamma}{2\pi}\left\{H_0 - 4\pi M_0\left[1 - \exp\left(-\frac{z^2}{\sigma^2}\right)\right]\right\} \tag{26}$$

and coordinates of the plane of excitation of the precession wave

$$z_0(f, H_0, M_0, \sigma) = \sigma\sqrt{\ln\left[\frac{4\pi\gamma M_0}{2\pi f - \gamma(H_0 - 4\pi M_0)}\right]}. \tag{27}$$

By substituting in (26) the limit values of the coordinates $z_{\min} = 0$ and $z_{\max} = \infty$, expressions of the boundary frequencies of the excitation band were obtained

$$f_{\min} = \frac{\gamma}{2\pi}(H_0 - 4\pi M_0), \quad f_{\max} = \frac{\gamma H_0}{2\pi}. \tag{28}$$

To calculate the thickness of the YIG film h , the phase condition of excitation of spin-wave resonances was used in the form of

$$\int_{z_0(f,H_0,M_0,\sigma)}^{h} k_z(f_n, H_0, M_0, \sigma, z)dz = n\pi. \tag{29}$$

By substituting in (29) the experimental values of $H_0 = 5501$ E, $f_3 = 10.128$ GHz and calculated values $M_0 \simeq 151$ Gs, $\sigma \simeq 6.48 \times 10^{-6}$ sm the equation $\varphi(h, n) = n\pi$ was obtained, which was solved by numerical methods. As a result, the desired value of the film thickness $h \simeq 2.15$ microns was obtained.

3. Discussion

The found values of the parameters M_0, σ, and h were used to simulate the processes of excitation of spin-wave resonances in the selected sample of the YIG film. In Fig. 2 a calculated

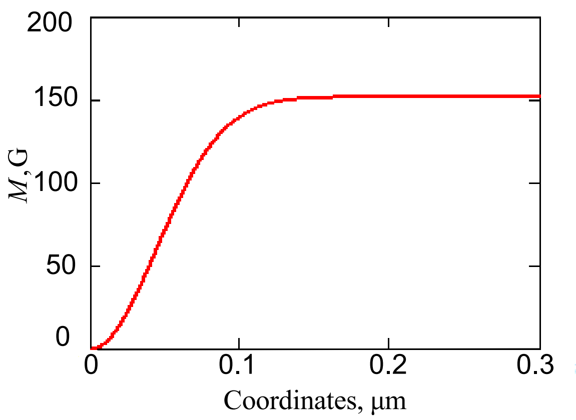

Fig. 2. . The distribution of spontaneous magnetization over the thickness of the experimental YIG film sample

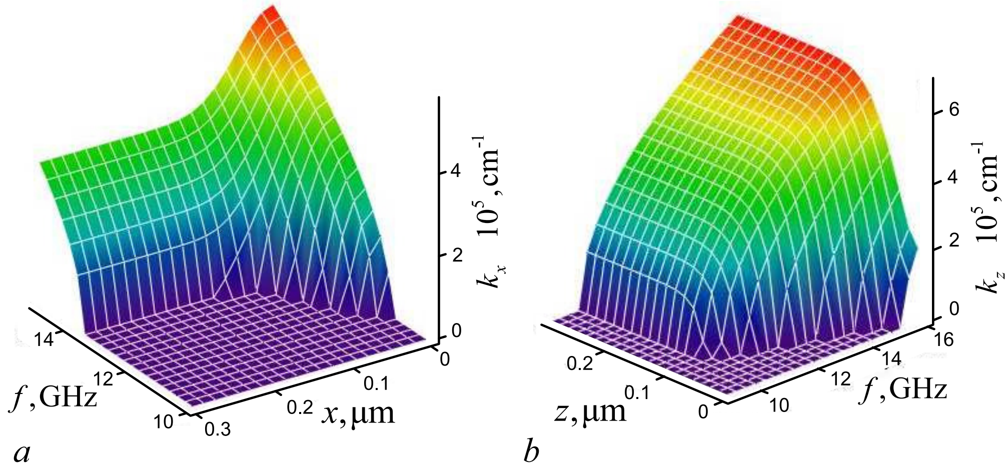

Fig. 3. The dispersion of the precession wave at tangential (a) and at normal (b) magnetization of the experimental YIG film

graph of the distribution of spontaneous magnetization over the thickness of the experimental sample of the YIG film is presented.

It can be seen that within the thickness of the transition layer, the magnetization of the film monotonically increased according to the law of normal distribution from zero to $M_0 = 151$ Gs. Using the 3σ principle, it was not difficult to calculate the thickness of the transition layer $\delta \simeq 0.19$ microns.

In Fig. 3 3D graphs of the laws of dispersion of the OSV at the tangent $k_x(f,x)$ are presented (Fig. 3, a) and the normal magnetization of the YIG film $k_z(f,z)$ (fig. 3, b).

It can be seen that within the thickness of the transition layer, the dispersion of the OSV experiences strong distortions, and the nature of these distortions significantly depended on the orientation of the magnetizing field. During tangential magnetization, a shift of the dispersion surface to the region of lower frequencies occurred. During normal magnetization, a shift of the dispersion surface deep into the JIG film is occurred. According to the condition of matching with an external homogeneous microwave field, the origin of the precession wave occurred at the intersection of the dispersion surfaces $k_x(f,x)$ and $k_z(f,z)$ with the plane $k_x = 0$ and $k_z = 0$. Using expressions (19) and (27), it was not difficult to calculate the frequency dependence of the

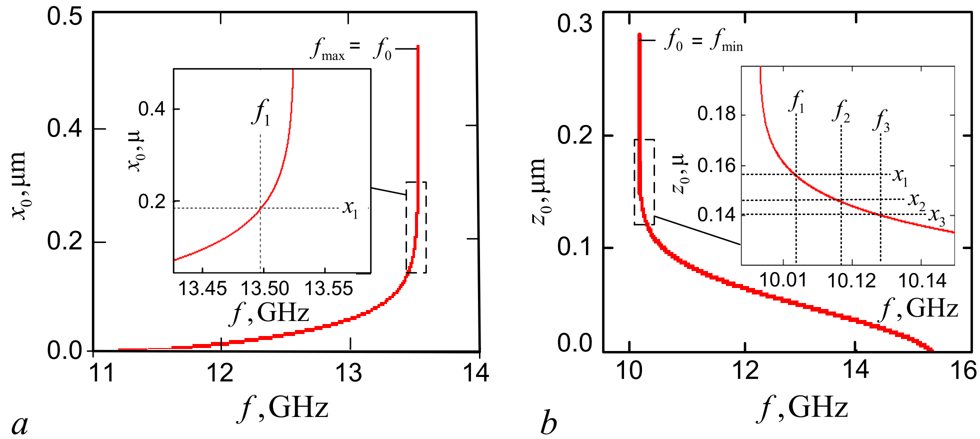

Fig. 4. Coordinates of the excitation plane of the precession wave at tangential (a) and at normal (b) magnetization of the YIG film

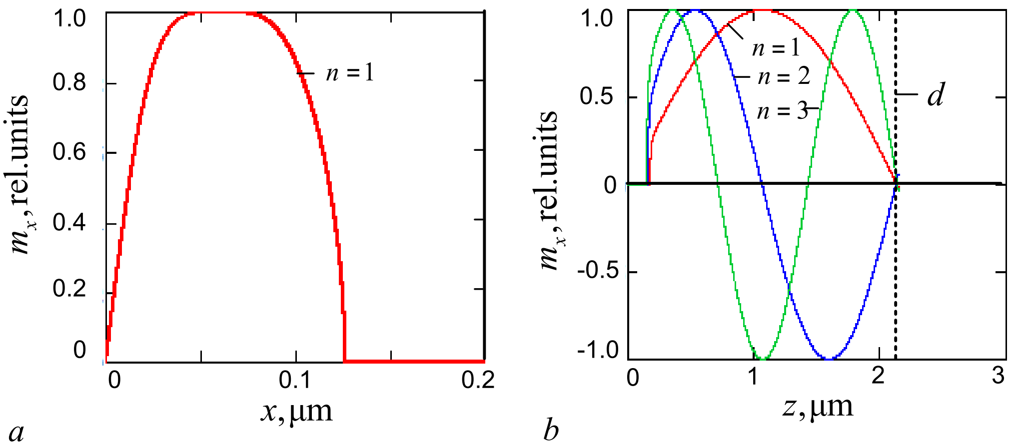

Fig. 5. Plots of spin-wave resonances in an experimental sample of a YIG film under tangential magnetization (a) and under normal magnetization (b). $n = 1, 2, 3$ — the numbers of resonant modes (color online)

coordinates of the excitation of the precession wave at the tangent $x_0(f)$ (Fig. 4, a) and the normal magnetization of the JIG film $z_0(f)$ (fig. 4, b).

From the comparison of the graphs in Fig. 2 and fig. 4, a, b it follows that the frequencies f_0 of the most intense peaks in Fig. 1, a, b correspond to the excitation frequencies of the homogeneous precession of magnetization in the homogeneous part of the film of the YIG. It follows from this (see Fig. 3, a) that when the film is tangentially magnetized, the frequency $f_1 < f_0$ corresponds to the excitation frequency of the first mode of an inhomogeneous spin-wave resonance excited within the thickness of the transition layer. Resonant modes of a higher order were not observed in our experiments. Similarly, in the case of normal magnetization of the frequency film $f_1, f_2, f_3, ... > f_0$ also correspond to the frequencies of inhomogeneous resonances, but, unlike from the previous one, excited mainly in the homogeneous part of the YIG film.

In Fig. 5 plots of inhomogeneous spin-wave resonances at tangential magnetization are presented $m_x \sim \sin\left[k_x\left(f_1, x\right) x\right]$ (fig. 5, a) and with normal magnetization of the YIG film $m_x \sim \sin\left[k_z\left(f_n, z\right) z\right]$ (fig. 5, b).

It can be seen that the inhomogeneity of the magnetization in the transition layer significantly distorts the sinusoidal nature of the oscillations. This was most clearly manifested when the film was tangentially magnetized. Under normal magnetization of the film, distortions were manifested only near the excitation coordinate of the exchange spin wave.

Conclusion

Based on the conducted studies, it was shown that the transition (diffusion) layer, which inevitably occurs on the inner surface of the epitaxial YIG film, plays an important role in the excitation of short-wave exchange spin waves. The inhomogeneity of magnetization in the transition layer provides a condition for hybridization and energy conversion of electromagnetic and exchange spin waves. The excited spin waves are very sensitive to the magnetic properties of the propagation medium, which is manifested in the frequency shift of spin-wave resonances. Based on this, a method was proposed for measuring the magnetization distribution over the thickness of epitaxial YIG films. The proposed technique was based on measuring the frequencies of spin-wave resonances and mathematical processing of measurement results. It was found that the thin transition layer has its own resonant properties, which are manifested during tangential magnetization of the YIG film. The technique of spin-wave diagnostics can be effectively used for non-destructive testing of all types of ferrite film structures, which will undoubtedly be in demand in the production of multilayer ferrite films and in their practical application.

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