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Spin wave propagation in a tangentially magnetized $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$ film

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The propagation of surface and backward volume magnetostatic waves in a saturated ferrite garnet film of the composition $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$ is investigated. Comparison of the experimentally obtained dispersion dependences with the results of numerical modeling allows us to conclude that the saturation magnetization is non-uniformly distributed across the film thickness. It is shown that in the low-frequency region of the spectrum, the losses due to propagation of surface magnetostatic waves are comparable with a similar parameter in a yttrium iron garnet film obtained using liquid-phase epitaxy. In the range of magnetization field values $0 < H < 400$ Oe, the possibility of observing spin-wave excitations of the domain structure is shown.

Keywords: garnet film of composition $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$, surface and backward volume magnetostatic waves, spin-wave excitations of the domain structure.

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1. Introduction

Epitaxial films of ferrite garnets are actively studied in connection with the possibility of a variety of practical applications. For the development of devices using spin wave (SW) excitation and propagation, films of iron-yttrium garnet (YIG) $Y_3Fe_5O_{12}$, ferromagnetic resonance line width (FMR) are widely recognized as the best ΔH which can be $0.2-0.5$ Oe, which ensures low losses of SW propagation [1,2]. In addition, when polarized optical radiation passes through the YIG films, the polarization plane rotates by an angle of φ (the Faraday effect), which makes it possible to rely on the use of these films in spin-wave magneto-optical electronics devices. The value of the specific rotation parameter $\phi = \varphi/t$, where t is the length of the light propagation path, is 0.1 deg/μm at a wavelength of 633 nm. It turned out to be possible to increase the value of ϕ by replacing yttrium ions with bismuth ions in the crystal lattice. The parameter ϕ increases to 7.8 deg/μm for the compound $Y_{3-x}Bi_xFe_5O_{12}$ ($x = 0.8-3$) [3], however, ΔH increases to $25-30$ Oe [4], which is sufficient to use such a material as a waveguide SW is unacceptable. In order to improve the combination of magnetic and optical properties of ferrite-garnet films, various rare earth elements in various combinations and proportions are included in their crystal lattice, and various substrates and technologies for producing films are used [5–14]. It follows from the literature available to us that the best results are achieved when yttrium ions are replaced in the crystal lattice by a combination of bismuth and lutetium ions $(LuBi)_3Fe_5O_{12}$. In this case, the value of ϕ can be 2 deg/μm, and ΔH does not exceed $0.4-5$ Oe [10–18]. The minimum values from this range are comparable to the value of this parameter for YIG. Indeed, the propagation of magnetostatic waves in films $(LuBi)_3Fe_5O_{12}$ is described in a number of papers [15–21]. It should be noted that these studies were conducted when the films were magnetized to saturation. At the same time, it is known that the domain structure exists in an abnormally wide (compared with films of YIG) range values of the bias field of $0 < H < 400$ Oe in a film, for example, with the composition of $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$ [22]. The possibility of observing propagating spin-wave excitations in this range of fields was not considered.

We study in this paper the propagation of magnetostatic waves (MSW) in a tangentially magnetized film with the composition $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$. The possibility of propagation of spin-wave excitations in a domain structure observed in the range of magnitudes of the bias field of $0 < H < 400$ Oe is shown.

2. Examined samples and experimental procedure

The studied sample was a waveguide with planar dimensions of 9×5 mm, cut from a film with the composition $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$ obtained by liquid-phase epitaxy on a substrate of gadolinium-gallium garnet of crystallographic orientation (111) with a thickness of $t = 10\,\mu$m. The waveguide was installed in a delay line mockup (hereinafter

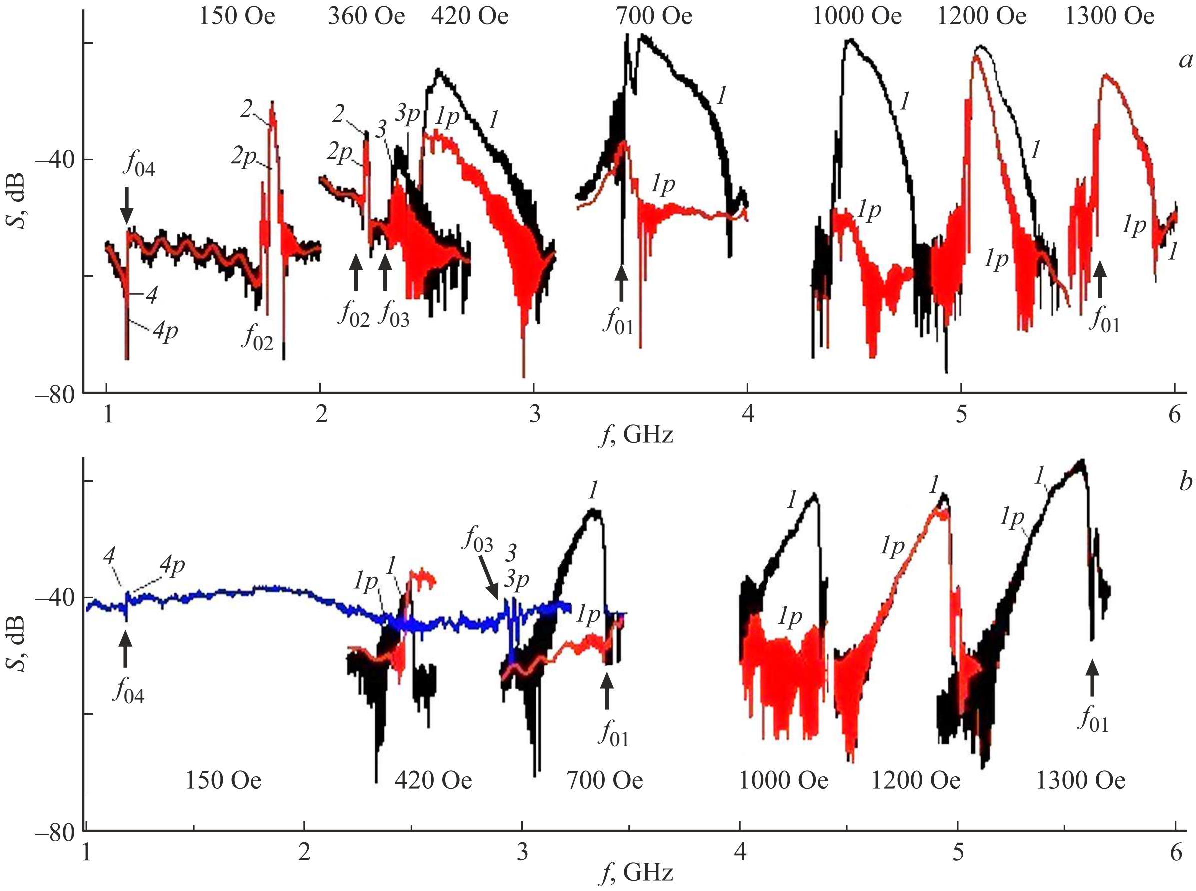

Figure 1. Dependencies $S(f)$ corresponding to excited MSSW (a) and BVMSW (b) for the values H indicated next to the curves.

referred to as the mockup) with $40\,\mu$m wide microstrip antennas with a distance of 4 mm between them, which was placed between the poles of the electromagnet. To study magnetostatic surface waves (MSSW) and backward volume magnetostatic waves (BVMSW), the bias field **H** was directed perpendicular and parallel to the long axis of the waveguide, respectively. Using a vector network analyzer, the frequency dependences of the module $S(f)$ and the phase $S^{ph}(f)$ of the transmission coefficient of the layout were recorded; the amount of power supplied to the antenna P_{in} could vary within $-30-7$ dBm. The phase frequency response $S^{ph}(f)$ was used to construct the dispersion dependencies of MSW $q'(f)$, where q' is the real part of the wavenumber q. The frequency dependence of the imaginary part of the wavenumber $q''(f)$, which characterizes the spatial decrement of SW, was determined in the layout of the delay line at MSSW with a variable distance between the antennas in the same way as described in Ref. [23].

3. Measurement results

Figure 1,a show the dependencies $S(f)$ corresponding to the excitation of MSSW at values of H indicated next to the curves. The curves obtained at $H > 400$ Oe, corresponding to the saturated state of the film, are labeled *1* and *1p* for P_{in}, equal to -20 and 7 dBm, respectively. Let's designate the MSSW observation bandwidth in YIG film as SWE1 (spin-wave excitation 1). When H is reduced to values less than the saturation field of $H_s \approx 400$ Oe, the band SWE 1 is divided into two signal transmission regions — low-frequency (curves *2, 2p*) and high-frequency (*3, 3p*), which can be identified with the observation of in-phase (SWE 2) and out-of-phase (SWE 3) magnetization oscillations in the domains, respectively [24]. SWE 2 is observed when H decreases to 0, whereas SWE 3 is recorded in the narrow range $300 < H < H_s$. In addition, a narrow band of signal registration caused by domain boundary displacement waves SWE 4 occurs at $H = 340$ Oe and is observed when H decreases to 0, [25] — see curves *4, 4p* for $H = 150$ Oe. The low-frequency boundaries of the observation areas $f_0(H)$ are shown by arrows in Figure 1,a ($f_{01}-f_{04}$ for SWE regions 1–SWE 4). The dependences of the frequencies $f_{01}-f_{04}$ on H are shown in Figure 2,a (curves *1s–4s*). It should be noted that the type of these dependencies obtained in case of reduction of H from $H > H_s$ to 0 remains the same in case of increase of H from 0 to $H > H_s$.

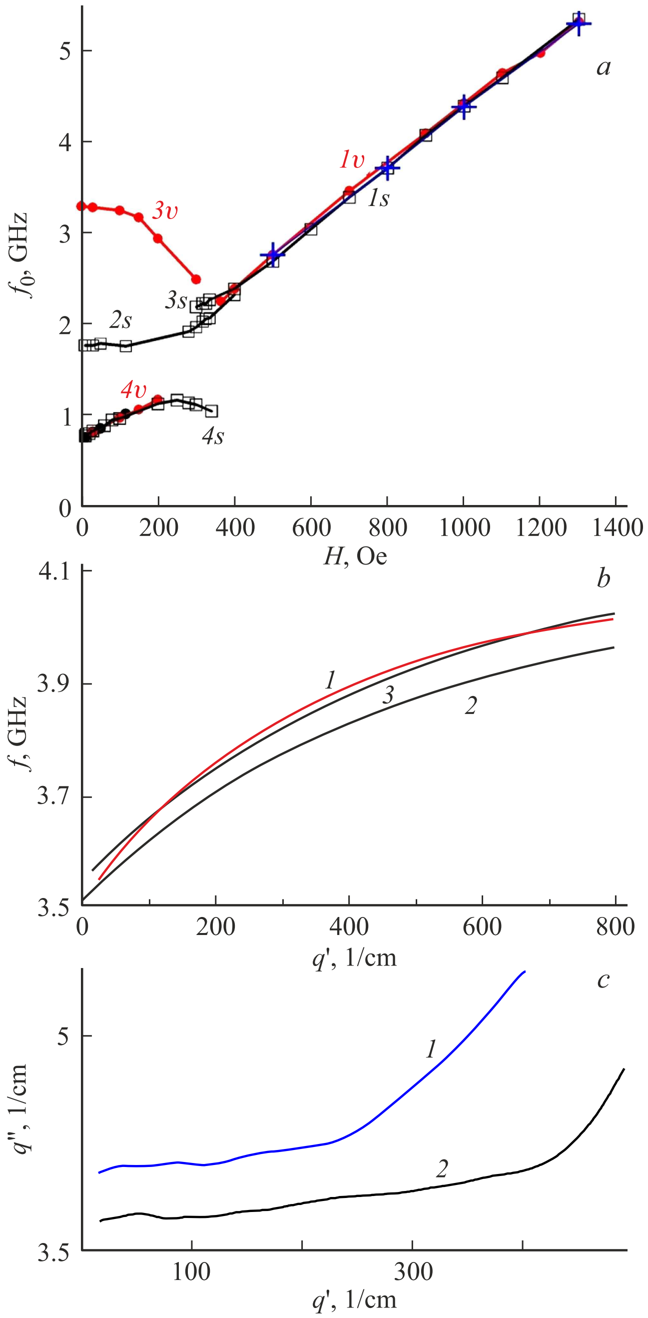

Figure 2. Frequency dependencies $f_{01}-f_{04}$ of the value H for MSSW (curves *1s–4s*) and BVMSW (curves *1v, 3v, 4v*), as well as the function $f_0 = \gamma\sqrt{H(H+4\pi M)}$ (crosses) (*a*); variance dependences MSSW obtained from experiment (curve *1*) and calculated for homogeneous (curve *2*) and heterogeneous (curve *3*) distributions $4\pi M$ by film thickness (*b*); dependencies $q''(q')$ for the studied film (curve *1*) and the film YIG (curve *2*) (*c*).

Figures 1, *b* and 2, *a* show, respectively, the dependencies $S(f)$ and $f_0(H)$, corresponding to the excitation of BVMSW. Figure 2, *a* shows that the dependences $f_{01}(H)$ for MSSW (curve *1s*) and BVMSW (curve *1v*) match in the range of saturating fields of $400 < H < 1300$ Oe. There are differences from the case of MSSW with $H < H_s$. So, the region SWE 3 occurs only when H decreases from 400 Oe to 320 Oe and then is observed to $H = 0$. No equivalent of the low-frequency (in-phase oscillations) region SWE 2 of the MSSW signal transmission is observed in the case of BVMSW. The SWE 4 signal caused by domain boundary displacement waves is recorded at $0 < H < 200$ Oe (curves *4, 4p* in Figure 1, *b*). In case of increase of H from 0 to $H > H_s$, the type of dependencies $f_0(H)$, represented in Figure 2, *a* by curves *1v, 3v, 4v*, is maintained, similarly to the case of MSSW.

Figure 3 shows the results of a study of the restructuring of the domain structure in the studied sample with a decrease of H from 1.4 kOe to 0. The image of the domain structure was obtained using a digital camera coupled with a polarization microscope. Domain registration became possible at values of H less than the saturation field $H_s \approx 380$ Oe. A strip domain structure of (DS) was observed with a period of 3.5–4 μm (Figure 3, *a, c*), which increased to about 6 μm (Figure 3, *b, d*) with the decrease of H to 0 with the width ratio of „of dark“ and „light“ domains close to unity. This dependence was maintained with the direction **H** both along the short (Figure 3, *a, b*) and along the long (Figure 3, *c, d*) sides of the waveguide. The arrows in Figure 3, *a–d* show the directions of propagation SW in geometry of MSSW (Figure 3, *a, b*) and BVMSW (Figure 3, *c, d*).

We would like to underline that registration of the DS and measurements of the dependence $S(f)$ were performed after the film was magnetized to saturation, followed by a decrease of H to 0. At the same time, it was discovered that both the appearance of the DS and the dynamics of its change during the rearrangement of H and the possibility of observing spin-wave excitations at $H < H_s$, significantly depend on the magnetic history of the sample. For example, let the film be magnetized to saturation in the direction of $\mathbf{H}_1$ along the short side of the waveguide (Figure 4, *a*). When this waveguide is placed in conditions where it will be magnetized in the other direction $\mathbf{H}_2$ (under experimental conditions $\mathbf{H}_1 \perp \mathbf{H}_2$), the increase of $\mathbf{H}_2$ from 0 to values close to the saturation field do not lead to a reorientation of the domains in the new direction of magnetization $\mathbf{H}_1$ (Figure 4, *b–f*). In turn, the dependencies of $f_0(H)$ do not differ for $H > H_s$ from those described above. Similar behavior of DS is also observed in the case when the waveguide is pre-magnetized in the direction of the long side, and the behavior of DS is studied with an increase from 0 of the field **H** directed along the short side of the waveguide. In our opinion, such a feature can be interpreted as a kind of „memory“ film of the orientation of magnetization in the saturation state. A detailed study of the dynamics of the domain structure in this film is beyond the scope of this paper.

4. Discussion of the results

Let us first consider the issue of an important parameter of magnetic films — saturation magnetization $4\pi M$.

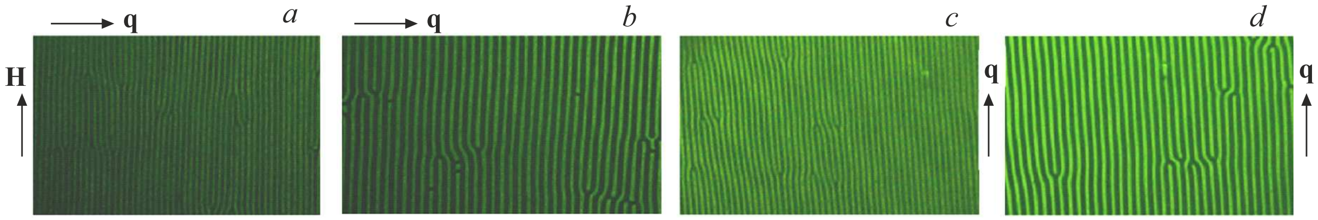

Figure 3. Images of domain structures in the studied film during magnetization along the short (a, b) and long (c, d) sides of the waveguide. $H = 380$ (a, c), $H = 0$ (b, d).

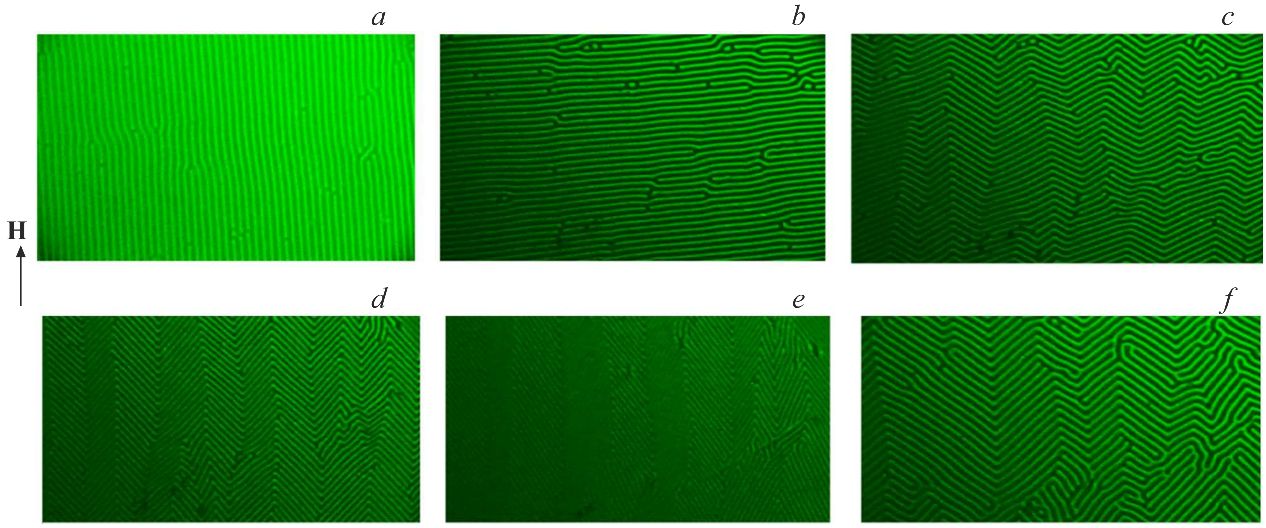

Figure 4. Images of domain structures in the studied film at $H = 0$ after pre-magnetization to saturation along the short side of the waveguide (a), when placed in a magnet for magnetization along the long side of the waveguide at $H = 0$ (b), $H = 60$ Oe (c), $H = 300$ Oe (d), $H = 350$ (e), when the decrease of H to 0 (f).

The blue crosses in Figure 2, *a* show the results of calculating the frequencies f_0 relative to the magnetized film for several values H, obtained using the well-known expression $f_0 = \gamma\sqrt{H(H + 4\pi M)}$, where $\gamma = 2.8$ MHz/Oe at $4\pi M = 1460$ G [26]. There is a good match with the measurement results (curves *1s, 1v*). At the same time, the calculation of the ispersion of $q'(f)$, performed at $t = 10\,\mu$m, $4\pi M = 1460$ G using the well-known expression [26] $f^2 = f_0^2 + \frac{f_m^2}{4}\left(1 - e^{-2qt}\right)$, where $f_m = \gamma 4\pi M$ (curve *2* in Figure 2, *b*), demonstrates a noticeable difference from the dependence obtained from the measurement results (curve *1* in Figure 2, *b*).

We calculated the dispersion relation similarly to Ref. [27], assuming that the value of the parameter $4\pi M$ may be variable in film thickness and varies linearly from $4\pi M_{bot}$ at the boundary of the film — substrate to $4\pi M_{surf}$ on the film surface. The values of $4\pi M_{bot}$ and $4\pi M_{surf}$ ranged from 1435–1490 G and 1510–1585 G, respectively. The best fit of the experimental curve was obtained at $4\pi M_{bot} = 1480$ G, $4\pi M_{surf} = 1520$ G (cf. curves *3* and *1* in Figure 2, *b*). The reason for the small differences in the course of the curves, as well as the increase in the parameter $4\pi M$ compared to the value determined from the measurement results f_0 $4\pi M = 1460$ G, are apparently related to the fact that the distribution law $4\pi M$ has a more complex film thickness. It should be noted that the assumption about the heterogeneity of this parameter in terms of the thickness of the film, which is identical in composition to the one under study, was expressed in Ref. [22].

Curves *1p–4p* on Figure 1, *a, b* show the type of dependencies $S(f)$ at the level of $P_{in} = 7$ dBm. It can be seen that nonlinear processes can develop in the film as the value of H decreases to ~ 1200 Oe, limiting the signal transmission level. It should be noted that this level in the area of $H < H_s$ in the case of MSSW, for example, turns out to be insufficient for SWE 2 — the type of dependence $S(f)$ does not change.

Figure 2, *c* shows the dependencies of spatial decrement MSSW from the real part of the wave vector $q''(q')$, measured in the test sample (curve *1*) and in a 15.6 μm thick YIG film at $H = 720$ Oe (curve *2*). Determined from the measurement results, for example, at $q'' = 200\,\text{cm}^{-1}$, the values of the parameter $\Delta H = q''/\gamma$ [28] were 0.4 Oe and 0.95 Oe for YIG and the studied film, respectively. It should be noted that the value obtained from the measurement results for the YIG film is in good agreement with the interval of 0.29−0.36 Oe indicated in the datasheet of the film.

5. Conclusions

The propagation of magnetostatic surface and backward volume waves in the range of 0.5−6 GHz in a tangentially magnetized ferrite-garnet film $Lu_{2.1}Bi_{0.9}Fe_5O_{12}$ has been studied In the range of magnitudes of the bias field of $H = 0-1.3$ kOe. The propagation of spin-wave excitations in the domain structure is studied in the range of $0 < H < 400$ Oe, corresponding to the unsaturated state of the film. The features of the behavior of the domain structure during the restructuring of the direction of the bias field are found, which are proposed to be interpreted as „memory“ of the orientation in the saturation state of the domain structure.

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Conflict of interest

The authors declare that they have no conflict of interest.

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