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EMF generation by magnetostatic waves in the YIG(111)−Pt structure in weak bias fields

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In a structure of an epitaxial film of yttrium iron garnet (YIG) with crystallographic orientation (111) $11.8\,\mu$m thick and 5 nm thick platinum (Pt) film deposited on its surface, the effect of EMF generation in a platinum film during the propagation of magnetostatic waves (MSW) in the structure was studied at values of the tangential constant magnetic field H less than the saturation field $H_s \sim 65$ Oe of the YIG film. The experiments were performed in a geometry where the field **H** was parallel to the crystallographic direction $[1\bar{2}1]$ and to the MSW antennas, and the distances from the input antenna to the output antenna and to the Pt film were ~ 5 and ~ 0.5 mm, respectively. In the structure under consideration, at $|H| < H_s$, a stripe domain structure (SDS) was formed, which in fields $|H| < H_1 \sim 5-7$ Oe acquired a branching character in the near-surface layer. In the range of fields $H_1 < |H| < H_2 \approx 40$ Oe, MSW propagation was observed in the frequency band $\Delta F_I \sim 300-550$ MHz, which was accompanied by EMF generation due to the inverse spin Hall effect. In the interval $H_2 < |H| \le H_s$, MSW propagation was observed in the frequency band $\Delta F_2 \approx 750-1750$ MHz, while the frequency interval in which the EMF signal was recorded turned out to be several times smaller due to the development of MSW parametric instability.

Keywords: magnetostatic surface waves, yttrium iron garnet, domain structure, platinum, inverse spin Hall effect.

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1. Introduction

Study of EMF generation during spin waves (SW) propagation in magnetic dielectric−metal structures is of interest for creation of energy-efficient element base on the principles of magnonics and spintronics [1–3]. Structures based on yttrium-iron garnet (YIG) and platinum (Pt) films are studied most widely, where both coherent and incoherent SW may efficiently inject spin current $\mathbf{I}_s$ through YIG/Pt interface. Spin current is detected with the help of inverse spin Hall effect (ISHE) [4], which results in Pt film in generation of electric current

$$\mathbf{I}_e \propto [\mathbf{n}\mathbf{I}_s], \quad (1)$$

where $\mathbf{n}$ — unit vector of spin moment in YIG [1–5]. Besides, from contacts to Pt, located along the direction perpendicular to $\mathbf{n}$, EMF $U = I_e R$ value is measured, where R — Pt resistance [1–5]. EMF generation in YIG−Pt structures by advancing SW was studied in both geometry of magnetostatic surface waves (MSSW), when wave vector $\mathbf{k}$ is perpendicular to direction of tangent field $\mathbf{H}$ ($\mathbf{k} \perp \mathbf{H}$) [6–14], and in geometry of backward volume magnetostatic waves (BVMSW), when $\mathbf{k} \parallel \mathbf{H}$ [13–16]. Besides, in papers [6–13] studies of EMF generation effect were conducted in magnetization fields H, exceeding the necessary one for magnetization of YIG film before saturation H_s. This paper reports an observation in geometry $\mathbf{k} \perp \mathbf{H}$ of EMF generation effect by propagating magnetostatic waves (MSW) in YIG−Pt structure at weak magnetization fields ($|H| \le H_s$), compliant with the availability of domain structure (DS) in the YIG film. Please note that DS effect at magnetoresistance due to spin Hall effect for YIG−Pt structures was considered in papers [17–19].

2. Experiment procedure

Experiments were carried out with YIG film grown epitaxially on substrate of gadolinium-gallium garnet with crystallographic orientation (111). The film had thickness $d \approx 11.8\,\mu$m, effective magnetization of saturation $4\pi M_{ef} = 4\pi M - H_u \sim 1640$ G, where H_u — field of uniaxial anisotropy; field of cubic anisotropy $H_c \sim -40$ Oe, and was characterized by noticeable thickness heterogeneity, which complicated determination of SW relaxation speed in the FMR spectrum. For measurements, a waveguide was cut from YIG film with dimensions 10×5 mm, the

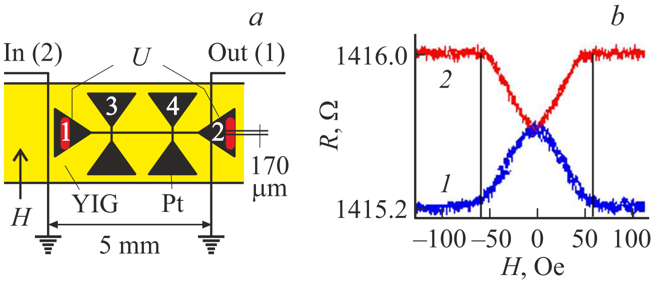

Figure 1. *a* — layout geometry; *b* — dependences of electric resistance *R* of the bar on the field value *H*, applied in the plane of the structure in direction $H \perp I$ (blue curve *1*) and $H \parallel I$ (curve *2*). Measurements were carried out at DC current value $I \sim 100\,\mu$A.

short side of which matched the crystallographic axis $[1\bar{2}1]$. Its surface was coated with platinum film with thickness of 5 nm by magnetron sputtering, which is used to form a Hall bar using technologies of photolithography and ion etching, and the bar geometry is schematically shown in Fig. 1, *a*. Longitudinal and transverse (in respect to the long axis of the waveguide) strips had width $170\,\mu$m, triangular contact sites were used to connect wire contacts using current-conducting glue.

To observe the effect of EMF generation by propagating MSW the YIG−Pt structure was placed in the layout of the delay line on MSW, which were excited and received by wire antennas with diameter $30\,\mu$m, the distance between which was 5 mm. Besides, the input antenna (*2*) was distant from Pt film by distance ≈ 0.5 mm, and output (*1*) one covered Pt, see Fig. 1, *a*. External magnetic field **H** was applied in parallel to antennas, which meets the condition of excitation MSSW in fields $|H| > H_s$ [20]. To study effect of field value H at propagation and dispersion of MSW in the structure, using a vector analyzer, frequency dependences of the module and phase of the transfer coefficient $S_{12}(f)$ from the input to the output of the layout were recorded with the level of incident power $P_{\text{in}} = -25$ dBm, which prevented impact of processes of parametric instability at measured characteristics. To measure EMF, input power was increased to level $P_{\text{in}} = 7$ dBm and was modulated by meander with frequency of 11.3 kHz, which made it possible, using a synchronous detector, to record from contacts *1* and *2* to platinum, frequency dependences of EMF $U(f)$.

3. Measurement results

Prior to experiments of EMF generation by propagating MSW, the structure was tested for presence of magnetoresistance effect $R(H)$ due to spin Hall effect. For this purpose, contacts *1* and *2* of Hall bar were connected to current source I, and voltage dependence $U(H)$ was taken from contacts *3* and *4*. In Fig. 1, *b* there are measurement results $R(H) = U(H)/I$ at DC current value $I \sim 100\,\mu$A and magnetization in the structure plane for $J \perp I$ (curve *1*) and $H \parallel I$ (curve *2*). You can see that dependences $R(H)$ have typical appearance [17] for YIG−Pt structures. Vertical lines in Fig. 1, *b* mark saturation fields $|H_s| \sim 65$ Oe.

To determine DS nature in the structure, optical polarization and magnetic-force microscopes (MFM) were used. In fields $|H| < H_s$ a block stripe domain structure (SDS) was formed. The platinum film did not provide noticeable effect at size of blocks, period Λ and nature of SDS. Besides, SDS behavior during variation of magnetization field in the considered structure in general was similar to the one observed earlier for YIG films [21–31]. For the studied structure, three intervals of fields could be identified, where nature and behavior of DS during variation of **H** noticeably differed. At $|H| < H_1 \sim 5{-}7$ Oe SDS in the near-surface layer would acquire „branching“ [21–24] („wavy“ [25,26]) nature with period $\Lambda \sim 7\,\mu$m and block size $150{-}200\,\mu$m. In the interval of fields $H_1 < |H| < H_2 \sim 40$ Oe „waviness“ of domains would disappear, blocks would increase to size $200{-}300\,\mu$m, while no noticeable change of Λ was observed, see inserts to Fig. 2, where brightness of light and dark tones illustrates angle of „output“ of magnetization vector **M** from YIG film plane. In interval $H_2 < |H| \leq H_s$ blocks were growing, with the noticeable growth of DS period, which at $|H| \sim H_s$ achieved values $\Lambda \sim 20\,\mu$m.

Fig. 3 shows frequency dependences $S_{12}(f)$ (thin grey and thick black lines comply with $P_{\text{in}} \sim -25$ and 7 dBm, accordingly) and $U(f)$ at $P_{\text{in}} \sim 7$ dBm, measured at different values of magnetization field (specified near curves in Oe, sign „minus“ complies with direction **H**, when maximum intensity of MSW „is pressed“ to surface of YIG film, bordering with platinum). At $H = -700$ Oe the width of frequency area of EMF observation was close to the registered width of observation strip MSSW (see Fig. 3) and contained maximum $U_{\max}$ near long-wave border of the strip of existence of MSSW $f_0 = \sqrt{H(H + 4\pi M)}$, as previously described in [13]. When the value H decreased, propagation of MSSW at $P_{\text{in}} \sim 7$ dBm occurred under the conditions of three-magnon decay processes development [20], which resulted in lower level of output signal of MSSW compared to linear mode of their propagation (at $P_{\text{in}} = -25$ dBm, see Fig. 3). And EMF generation was observed only in the field of frequency f_0, and Umax value reduced. However, in the range of variation H from -35 to -10 Oe in the frequency band ΔF_I 350−500 MHz, there is growth of transfer ratio $S_{12}(f)$ observed (see Fig. 2), and value of EMF signal increases to the level that is only twice inferior to the case of saturated YIG film at $H = -700$ Oe and exceeds values corresponding to propagation of MSW in the saturated film at $|H| \leq 300$ Oe (see Fig. 3, 4). Further decrease $|H|$ to zero causes reduced EMF signal to the noise level, and value $S_{12}(f)$ decreased to induction level (red lines in Fig. 3). When the sign of the magnetization field changes, the EMF sign changes as well, and the nature of $U_{\max}$ value variation with growth of $|H|$ qualitatively complies with the one described above (see Fig. 4 and insert to it), and quantitative difference is obviously related to nonreciprocal nature of propagation MSSW [20].

4. Discussion of results

Possibility of propagation of various MSW types in YIG films in small magnetization fields was shown more than 30 years ago for various domain structures [27–45]. In the studied structure at $H < 30$ Oe DS has stripe nature (see inserts to Fig. 2), and dispersion dependence built using phase-frequency characteristic (see insert to Fig. 3) certifies propagation in the frequency interval ΔF_I of MSW with direct dispersion. When MSW propagation direction changes to reverse one (when the input one is antenna (*1*)), level of $S_{21}(f)$ while preserving the direction of the field **H** turned out to be approximately 3 dB lower than for $S_{12}(f)$, which makes it possible to suggest surface nature of MSW propagating in this frequency range [20]. Besides, the maximum transfer coefficient S_{12} is only slightly inferior to the case of saturated film at $H = -700$ Oe and exceeds values S_{12} for values H, compliant with the area of three-magnon decays of MSSW. The reason for this is apparently higher threshold powers for development of these processes in DS, previously considered in [29]. In our measurements the variation of level P_{in} from 7 dBm to -25 dBm did not impact the type of dependence $S_{12}(f)$ in frequency interval ΔF_I in any way. We would also add that in this interval in the frequency dependence of the power $S_{22\text{norm}}(f)$ reflected from the input antenna (*1*) (normalized by the type of this dependence in absence of MSW in the considered frequency range — at $H = 3$ kOe) during change of input power from 7 to -10 dBm, no changes occur, in contrast to frequency interval ΔF_2 (see Fig. 4, *b*).

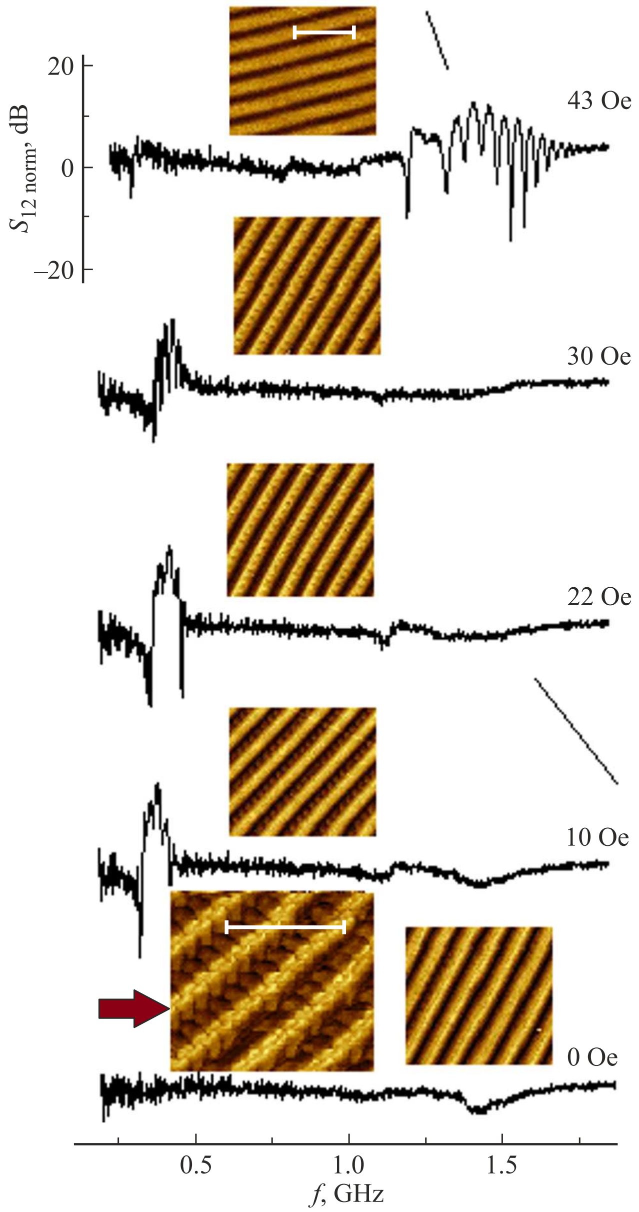

Figure 2. Dependences $S_{12\text{norm}}(f)$ and images of surface structure of DS, produced with the help of MFM at values H, specified in curves. The arrow indicates the view of the surface structure of film DS extracted from electromagnet. The scale in all images, except for the one indicated with the arrow, is the same. Length of scale mark 20 μm.

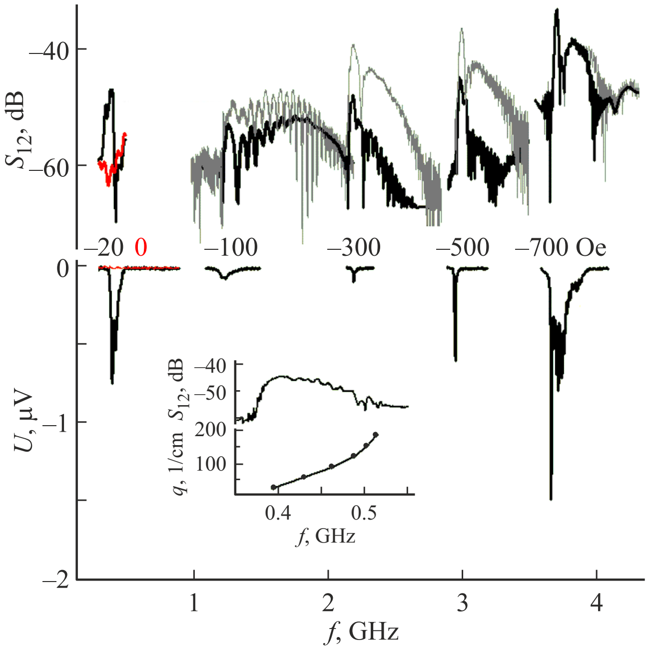

Figure 3. Frequency dependences of transfer coefficient module $S_{12}(f)$ (thin and thick lines comply with $P_{\text{in}} \sim -25$ and 7 dBm, accordingly) and EMF $U(f)$ for $P_{\text{in}} \sim 7$ dBm for various values H (specified in curves in Oe). The insert shows dependence $S_{12}(f)$ and dispersion dependence of MSW at $H = -20$ Oe.

We would like to emphasize that EMF generation found in the frequency interval ΔF_I is observed in the conditions, when there is a stripe domain structure present in the YIG film, when magnetization in the film volume has components directed along the normal line to the film surface, being oppositely directed in the neighboring domains, which is specific for YIG films (111) [42]. However, EMF generation according to ISHE mechanism

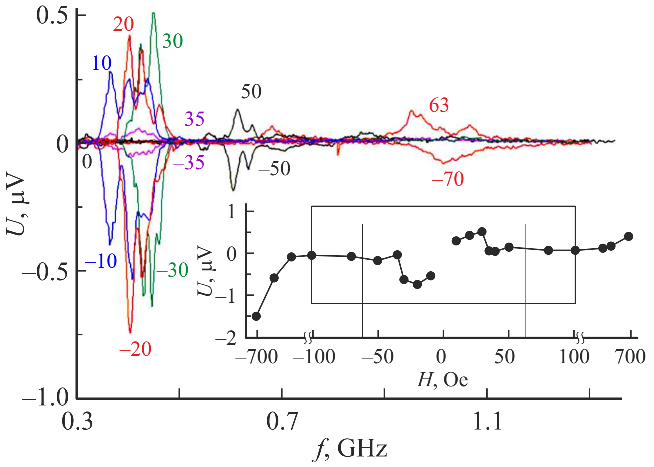

Figure 4. Dependences $U(f)$ for various values of the field H (shown in curves in Oe). The insert shows dependence $U_{max}(H)$. Vertical lines limit the interval of fields compliant with non-saturated state of YIG film.

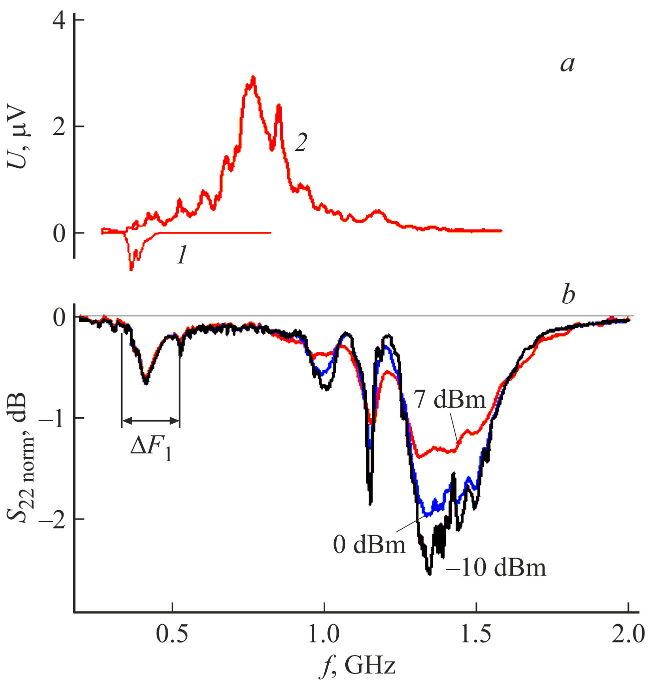

Figure 5. *a* — frequency dependences $U(f)$ during excitation of MSSW in the geometry of the experiment (1) and during change of direction of MSSW (2) propagation at $P_{in} = 7$ dBm; *b* — frequency dependence $S_{22norm}(f)$ for various levels of input power. $|H| = 20$ Oe.

suggests a magnetization component in the film surface being tangent thereto in the layer with thickness of not more than 1 nm [46]. Such orientation of magnetization may be observed, when there are „closing“ domains [20] in the near-surface film layer. At the same time, length of the platinum element is much more than width of domains, which makes it possible to suggest restriction of the measured EMF as a result of EMF „averaging“ effect in the areas of YIG film with the opposite direction of magnetization, which is apparently observed at $H = 0$ (see Fig. 3). Absence of this effect with growth of value H is probably related to complicated nature of the domain structure, which may result in quantitative differences of tangent magnetization component distribution in the neighboring domain.

Images of domain structures obtained by us using MFM (see inserts to Fig. 2) reflect the structure of the domain scattering fields in the near-surface layer [19]. You can see that features of smaller scale with complex appearance manifest on the background of the stripe structure. Such results may be related to availability of near-surface blind-end DS [20]. At the same time, in YIG films, whose field of uniaxial anisotropy H_a exceeds ~ 120 Oe, the near-surface layer may be heterogeneous by thickness [24]. Let us note that in the studied YIG film the estimated value H_a was ~ 100 Oe. We were not able to study the structure of the surface layer and show availability of the magnetization component tangent to the film surface, which is necessary to observe ISHE. Nevertheless, please note that change in the direction of field H causes change of the sign of the generated EMF (see Fig. 4), which complies with ISHE mechanism (*1*).

To conclude, we would like to add that the considered results were obtained for the case, when the input antenna *(2)* was distant from Pt film at distance of ~ 0.5 mm (see Fig. 1, *a*) and, accordingly, spin current pumping was carried out by the fields of the propagating MSW. In Fig. 5, *a* curve *2* represents results of EMF measurement in the described structure, but for the case of using as an exciting antenna (*1*), located above platinum (see Fig. 1, *a*) at $P_{in} = 7$ dBm, $|H| = 20$ Oe (direction of field $\mathbf{H}$ changed to the opposite one to ensure the location of MSW intensity maximum near the surface of YIG film bordering with platinum). It is seen that in this case the level of EMF signal and width of its observation stripe considerably exceed the results (curve *1* in Fig. 5, *a*), produced when used as an exciting antenna (*2*). Discussion of this effect is beyond this paper.

5. Conclusion

EMF generation was detected according to the mechanism of inverse spin Hall effect in MSW propagation in the structure of YIG film−platinum at values of magnetization field compliant with formation of the strip domain structure in the YIG film. The produced results demonstrate the ability to carry out microwave spin pumping in YIG−Pt structures at weak magnetization fields (or in absence of fields), which may be useful for development of spintronics devices and for study of the near-surface domain structure of magnetic films. The ability to detect spin current carried by spin waves in films with DS may also be useful for development of approaches to building reservoir computers based on spin waves in films with SDS [47].

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Conflict of interest

The authors declare that they have no conflict of interest.

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