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Investigation of the interference of magnetostatic surface waves using the inverse spin Hall effect

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The effect of EMF generation due to the inverse spin-Hall effect during the propagation of magnetostatic surface waves (MSSW) in the structure of yttrium iron garnet (YIG) — platinum based on a two-layer YIG film with different saturation magnetizations of the layers ($(4\pi M_1 > 4\pi M_2)$ has been experimentally studied. It was shown that the magnitude of the EMF resonantly increases at the frequencies of hybridization of the MSSW with the exchange modes of the structure. At the same time, at the frequencies of the MSSW of the layer with a higher magnetization, oscillations of the EMF are observed, caused by its hybridization with the exchange modes of both the layer with $4\pi M_1$ and the layer with lower magnetization, which indicates the influence of interlayer exchange on the efficiency of spin pumping in the structure under consideration. The influence of the interference of counterpropagating MSSWs on the generated EMF has been studied. It has been shown that the EMF value is sensitive to the phase difference between counterpropagating MSSWs and oscillates. In this case, the amplitude of the oscillations is determined by the ratio of the wavelength of the MSSW and the length of the platinum film.

Keywords: magnetostatic waves, yttrium iron garnet, platinum, interference, inverse spin Hall effect.

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1. Introduction

The effects of propagation and interference of spin waves (SW) in magnetic microstructures are promising for building energy-efficient information technologies based on them [1–4]. These effects are used to develop prototypes of logic devices [4,5], holographic memory [6], signal processors [7], as well as the ability to characterize magnetic particles [8] and a special kind of computing [9]. When carrying out experiments to excite spin waves and record the result of their interference, current microstrip antennas were generally used. At the same time, the desire to miniaturize devices encounters an obstacle in the form of limiting a number of device parameters due to an increase in the level of direct electromagnetic leakage between the antennas.

An alternative to a current receiving antenna may be a thin-film platinum element located on the surface of the spin wave conductor, on which an electric voltage of U, proportional to the amplitude of SW [10–12], will be generated due to the inverse spin Hall effect. Work [13] shows that when a platinum element is positioned in the interference field of backward volume magnetostatic waves, the effect is sensitive to the result of phase wave interference and, therefore, it is promising for use in phase sensitive spin logic devices. Features of EMF U generation in thin-film Pt/YIG structures based on yttrium-iron garnet films (YIG), caused by hybridization effects of propagating magnetostatic surface waves (MSSW) with volume exchange modes of the film, are investigated in [14]. It is shown that on spin wave resonances (SWR) frequencies, the EMF can increase several times compared to neighboring frequency regions. From this point of view a research of EMF generation in the structure of platinum — two-layer exchange film is interesting. The fact is that when MSSW are distributed in such films, the SWR spectrum is not only enriched, but also demonstrates a number of features in restructuring of the magnetization field — such as „deep" depth oscillation in AFC at SWR frequencies or the SWR frequency „repulsion" effect [15,16]. It is also interesting to consider the influence of these features on the generation of EMF when counter propagating of two MSSW.

The aim of the present work is to study the interference of magnetostatic surface waves in exchange-coupled films of YIG with the help of the inverse spin Hall effect.

2. Studied specimens and experimental procedure

The measurements were carried out using a two-layer yttrium-iron garnet film, grown on a substrate of a gadolinium-gallium garnet using a liquid-phase epi-

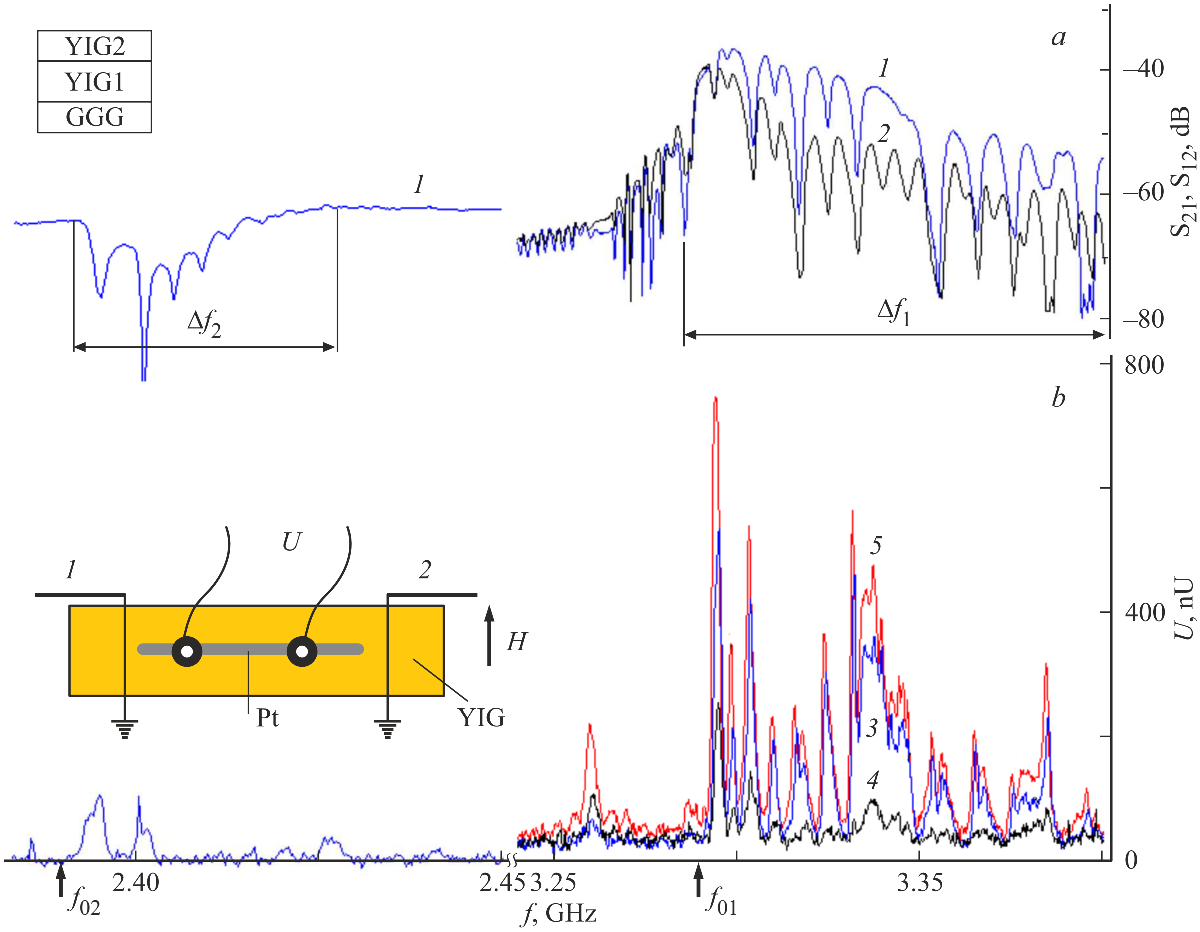

Figure 1. *a* – the dependences of $S_{21}(f)$ (curve *1*) and $S_{12}(f)$ (curve *2*), the inset shows the film structure; *b* — the frequency dependence of $U(f)$ for the cases of supply of microwave power to input 1, input 2 and both inputs simultaneously (curves it *3*, *4* and *5*, respectively). The grayscale line shows the platinum film sensor configuration $H = 572$ Oe.

taxy in two stages. Firstly, YIG film with composition $Y_3Fe_5O_{12}$ was deposited on the substrate, and then — the YIG film, doped with gallium and scandium composition $Y_3Fe_4Ga_{0.8}Sc_{0.2}O_{12}$ (see the inset in Fig. 1, *a*). The saturation and thickness of the first and second layers were $4\pi M_1 = 1750$ G, $d_1 = 8\,\mu$m and $4\pi M_2 = 640$ G, $d_2 = 6\,\mu$m, respectively. The waveguide was cut from the film with flat dimensions of 5×12 mm, on the surface of which the magnetron sputtering and photolithography process was used to form a sensor of platinum film with a thickness of 6 nm, the configuration of which is represented on the inset to Fig. 1, *b*. The width of the platinum strip was $500\,\mu$m.

The resulting structure was placed in the mock-up of the delay line, excitation (and receiving when feeding microwave power only on one antenna) of spin waves was carried out by wire antennas 1 and 2 (see inset in Fig. 1, *b*) with a diameter of $50\,\mu$m, the distance between antennas being 10.7 mm. The **H** magnetic field was applied in the plane of the structure parallel to the antennas, allowing the excitation of magnetostatic surface waves (MSSW) [17]. The Keysight M9374A network analyzer was used to monitor the frequency dependency of $S(f)$ transmission ratio module of a magnetostatic wave in the case of microwave power supply to one or the other antenna, and as a microwave signal generator when investigating interference effects. In the latter case, the microwave power from the output of the vector network analyzer was fed to the divider, from the outputs of which it was fed to the input antennas, with the antenna's feeding path 1 including a phase converter and an adjustable attenuator. Wire contacts were attached to the platinum strip by means of conductive glue. The distance between L contacts was 6 mm. The voltage between the contacts was measured using a selective nanovoltmeter SR830 DSP. To synchronize the selective voltmeter, microwave power modulation of 10.399 kHz was used.

In Fig. 1, *a*, the curve *1* represents the dependence $S_{21}(f)$ obtained with $H = 572$ Oe and using antenna 1 as the input. It can be seen that it contains two observation areas of SMSW: in the first layer Δf_1 and in the second layer Δf_2 with low frequency boundaries [17] $f_{01,2} = \gamma\sqrt{H(H + 4\pi M_{1,2})}$ and high frequency boundaries $f_{s1,2} = \gamma(H + 2\pi M_{1,2})$, $\gamma = 2.8$ MHz/Oe. Similarly to [15,16], Δf_1 area contains resonant loss growth areas of MSSW to propagate on the frequency of spin-wave resonance in both film layers [14]

$$f_{N1,2} = \sqrt{(f_H + f_{ex1,2}q_{N1,2}^2)(f_H + f_{m1,2} + f_{ex1,2}q_{N1,2}^2)}, \quad (1)$$

where $f_H = \gamma H$, $f_{m1,2} = \gamma 4\pi M_{1,2}$, $f_{ex1,2} = 2\gamma A_{1,2}/M_{1,2}$, $A_{1,2}$ — exchange hardness of layers, $q_{N1,2} = \pi N/d_{1,2}$, $N = 1, 2, \ldots$.

It should be noted that due to the non-reciprocal propagation of SMSW [17] at the selected field direction **H** the change of the direction of the SMSW wave vector to the opposite leads to an increase in loss of propagation — see curve *2* in Fig. 1, *a*, corresponding to the use of antenna 2 as an incoming one. It can be seen from the comparison of curves *1* and *2* that the change of the propagation direction of SMSW does not cause the SWR frequency change.

In Fig. 1, *b*, a frequency dependence of $U(f)$ for cases of microwave power supply of input 1 or input 2 (curves *3* and *4*, respectively) is represented. It can be seen that the value of EMF in Δf_1 is almost an order of magnitude higher than that of Δf_2. For this reason, we will only consider the frequency domain Δf_1. Note that the presence of layer *2* exchange-bonded to layer *1* leads to an increase in the number of SWR in frequency region Δf_1 (compared to the YIG film of the same thickness), which is useful when studying EMF generation, as noted above, increases near the frequencies of SWR generated in the platinum strip EMF [14]. Comparing *3* and *4* curves in Fig. 1, *b*, one can also see that the change of the propagation direction of MSSW (switching the input from antenna 1 to antenna 2) is accompanied by a decrease in the amount of guidance EMF.

When the magnetic field magnitude changed, the „deeps“ depth depending on $S_{21}(f)$ oscillated similarly [15,16], with changes in $U(f)$ dependency. Fig. 2 illustrates these changes when adjusting the value H from 572 to 594 Oe. In Fig. 2, *a*, which shows $H = 572$ Oe, the black arrow marks a resonance at 3404 MHz frequency (selected for observation); while the red arrow marks the corresponding peak of EMF. It can be seen that the depth of the „hole“ in $S_{21}(f)$ dependence is 2 dB, while $U = 296$ nV. With the increase of H to 579 Oe frequency and depth of the „deep“ change to 3434 MHz and 10 dB, respectively, while the value of U increases to 535 nV (Fig. 2, *b*). With a further increase of H the depth of the „deep“ increases to 40 dB, with U decreasing to 242 nV — see Fig. 2, *c–E*. Thus, it has been established that there is no direct correlation between the value of EMF signal in the given structure and the increase in the loss of MSSW at the frequencies of the resonance interaction with the exchange modes.

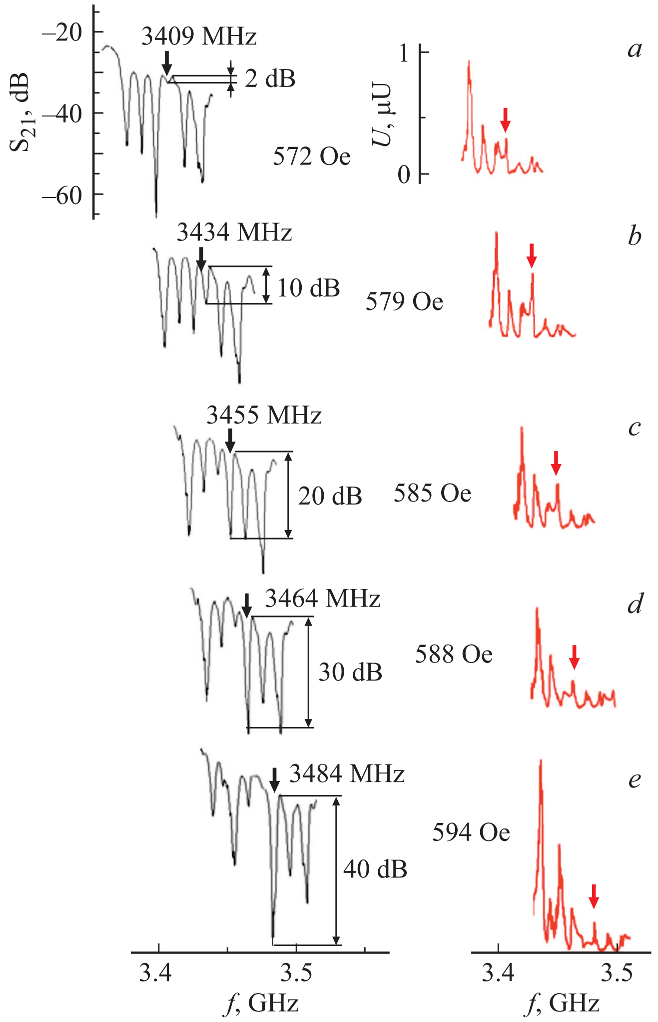

Figure 2. The dependency plots are $S_{21}(f)$ (black curves) and $U(f)$ (red curves) at $H = 572$, 579, 585, 588 and 594 Oe (*a, b, c, d, e*, respectively). The vertical scale range in all figures is the same.

For interference measurements, EMF levels were aligned by reducing the power input to antenna 1 using an attenuator. The relationship of $U(f)$ with the simultaneous supply of microwave power to antennas 1 and 2 is shown by curve *3* in Fig. 1, *b*. In Fig. 3, *a*, a part of this relationship is shown for an arbitrary value of $\Delta\phi$ phase difference between antennas, where several peaks are numbered. The dependences of the maximum magnitude of these peaks on the phase difference between antennas $\Delta\phi$ is presented in Fig. 3, *b*. The periodicity of these dependences with a period of 360° indicates that the change in the signal level is due to interference with the propagating MSSW. At the same time it is obvious that, as the frequency increases, accompanied by a decrease in the MSSW wavelength, the oscillation amplitude of peaks *1–3* decreases, while the maximum value of the peak marked with an asterisk is almost independent of $\Delta\phi$ (see Fig. 3, *b*). With the use of

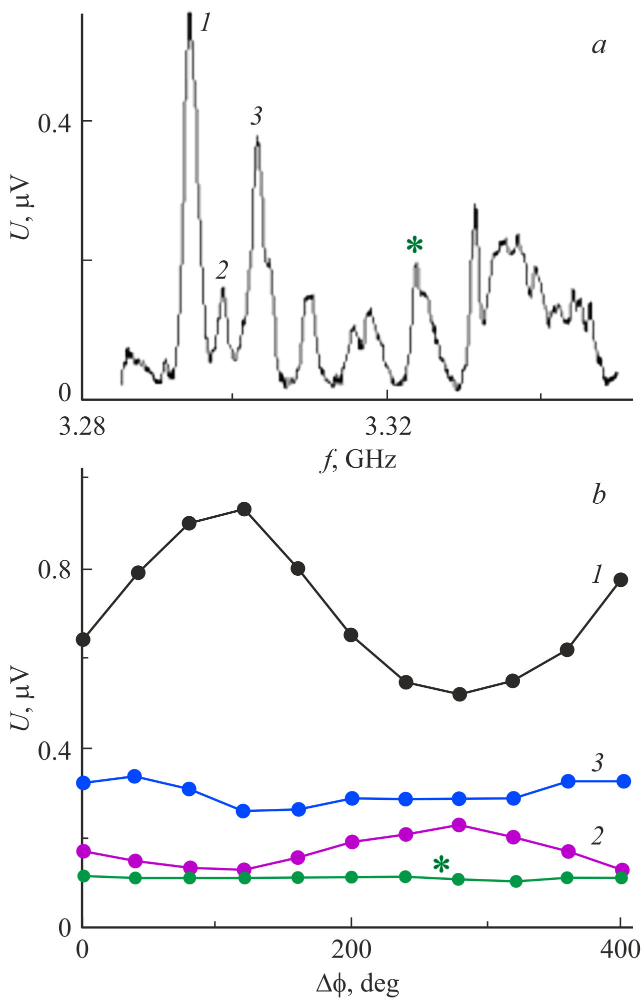

Figure 3. *a* — dependence area $U(f)$ with an arbitrary phase difference of $\Delta\phi$; *b* — dependence of the maximum values of the numbered phase shift peaks between the signals coming to the input antennas.

measured phase dependence the wavelengths of SMSW λ were determined similarly to [18] on peaks *1, 2, 3* and $*$ frequencies, marked in Fig. 3, *a*, which were 9, 5, 3.7 and 2.5 mm, respectively. Comparing these values with the length of the sensor $L = 6$ mm shows that for the oscillation amplitude of EMF, a change of $\Delta\phi$ significantly decreases at $L > \lambda$.

3. Conclusion

Experimental study of the EMF generation effect due to the inverse spin Hall effect at the propagation of magnetostatic surface waves in the structure of yttrium-iron garnet based on a two-layer exchange-bonded YIG film with different magnetization of layers saturation was carried out. It is shown that at the frequencies of the MSSW layer with greater magnetization, oscillations of EMF are observed, caused by hybridization with the exchange modes of both layers. The influence of interference of counterpropagating MSSW on generated EMF is investigated. It is shown that the value of EMF is sensitive to the phase difference of the opposite MSSW and oscillates, with the oscillation amplitude decreasing with the reduction of the length of interacting waves.

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Conflict of interest

The authors declare that they have no conflict of interest.

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