

Nonlinear cavity-magnonics system based on a superthin yttrium-iron-garnet film

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The paper presents the results of an experimental study of the system consisting of a microstrip half-wave resonator (MSHWR) and superthin yttrium-iron-garnet (YIG) film at higher power levels. It has been shown that in the linear mode the superthin YIG film located in the alternating current antinode of the MSHWR fundamental oscillation operates as a gyromagnetic resonator (GMR) at the ferromagnetic resonance (FMR) frequency. The latter is determined by the external static magnetic field orientation transverse to the distribution of the MSHWR standing wave alternating current. The study has established that, if MSHWR is replaced with a microstrip transmission line operating in the traveling wave mode, then the superthin YIG film does not act as GMR at the same static magnetic field orientation with respect to the microstrip conductor. In the nonlinear mode, the „MSHWR-superthin YIG film“ system is a multifunctional nonlinear device with power thresholds lower than in the case of micron-thick YIG films.

Keywords: cavity magnonics, superthin YIG films, nonlinear ferromagnetic resonance.

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Cavity magnonics is at present one of the rapidly developing areas of the magnetic phenomena physics devoted to studying the interaction of spin waves or their quanta (magnons) with spatially confined electromagnetic fields created by various-type resonators [1–5]. Such interaction may give rise to effects that are not observed in each individual subsystem (the magnon or photon one), as well as in a non-resonant photon subsystem [6]. Most cavity-magnonics studies were performed with dielectric ferrites in the form of spheres [1,2] and thin yttrium-iron-garnet (YIG) films [3–9] having record low Gilbert attenuation parameter $\alpha = 10^{-5} - 10^{-3}$ and high spin density $4.0 \cdot 10^{27} \text{ m}^{-3}$.

It is well known that in thin (micron-thick) YIG films there may propagate magnetostatic spin waves (MSWs) excited typically by using an asymmetric microstrip transmission line (AMTL) [10]. The MSW excitation in a wide range of wavenumber k depends on the ratio between the YIG film thickness d and AMTL conductor width w . If $w \sim d$, the MSW excitation is most broadband [11]. If $w \gg d$, the range of excited MSW wave numbers is considerably narrower and close to frequency $f_{\perp} = \sqrt{f_H(f_H + f_M)}$ (where $f_H = \gamma H_0$, γ is the gyromagnetic ratio, $f_M = 4\pi\gamma M_0$, $4\pi M_0$ is the saturation magnetization) that is the ferromagnetic resonance (FMR) frequency in the case of transverse pumping [12]. Near this frequency, wave numbers of backward bulk MSWs (BBMSWs) and surface MSW are minimal.

Study [6] has shown that, if an AMTL-based microstrip half-wave resonator (MSHWR) with $w = 5 \cdot 10^{-4} \text{ m}$ operating in the standing electromagnetic wave mode is loaded onto the YIG film with $d = 4 \cdot 10^{-5} \text{ m}$ ($w \gg d$) and fed

with external static magnetic field H_0 applied so that its direction is orthogonal to the alternating current distribution along MSHWR (transverse electromagnetic pumping), then the BBMSW excitation efficiency in such a resonator system increases by $\sim 30 \text{ dB}$ compared to the case of using a similar-width microstrip conductor in AMTL operating in the traveling wave mode. In addition, studies [6,13] have shown that the MSHWR–YIG film system at high microwave signal powers is a nonlinear multifunctional device which is not the case with conventional AMTL loaded onto the YIG film. This resonator system operates simultaneously as an amplifier of the signal-to-noise ratio in the BBMSW excitation band, as a power limiter at the frequencies of the system resonance maxima, and as a nonlinear phase shifter at the frequencies between those two frequency ranges.

This paper shows that, in the case of planar cavity-magnonics systems with $w \gg d$ operating at the static magnetic field H_0 orientation transverse to the microstrip conductor, a decrease in the YIG film thickness to sub-micron values (superthin YIG film) leads to excitation of only a uniform magnetization vector precession at the FMR frequency and only if MSHWR is used as an exciter. In the nonlinear FMR mode, the MSHWR-superthin YIG film system also exhibits nonlinear multifunctional properties, like the case of thicker YIG films (micron thickness), but at significantly lower threshold powers. The latter circumstance is important for creating nonlinear ferrite devices for 5G communication systems [14].

The Fig. 1 inset presents a schematic image of MSHWR in the central part of which there is a YIG film $d = 10^{-7} \text{ m}$

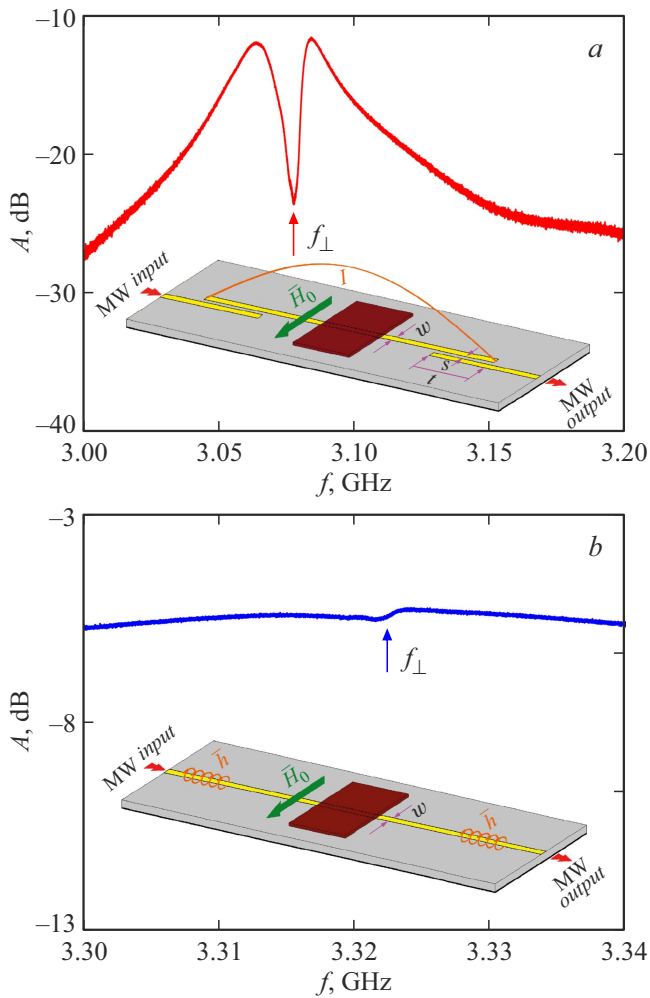


Figure 1. Amplitude-frequency characteristics of two systems (*a* — MSHWR –superthin YIG film, *b* — AMTL –superthin YIG film); the characteristics were measured at the field H_0 orientation transverse to the microstrip conductor. The measurements were performed in linear mode at input power $P_{in} = -30$ dBm. The internal magnetic field was $H_{int} = H_0 + H_A = 42.176$ (*a*) and 47.667 kA/m (*b*). The insets give schematic images of the systems under study.

thick, $3 \cdot 10^{-3}$ m wide (the width determines the degree of the film- MSHWR overlap) and 10^{-2} m long. The YIG film thickness was measured with optical profilometer Talysurf CCI 2000 and met the YIG film certified parameters. The YIG film grown by liquid-phase epitaxy on a gadolinium-gallium garnet substrate is characterized by the near-surface effective magnetization $4\pi M_{eff} \cong 0.175$ T and certified FMR line width $2\Delta H \cong 87.535$ A/m at the frequencies of ~ 3 GHz. MSHWR is a planar resonator of the transmission type. It is fabricated based on AMTL consisting of a one-side-metallized dielectric substrate $5 \cdot 10^{-4}$ m thick on the other side of which there is a $w = 5 \cdot 10^{-4}$ m wide and $18.1 \cdot 10^{-3}$ m long microstrip conductor (resonator) open at both ends. To couple it to the generator and load, two $5 \cdot 10^{-4}$ m-wide microstrip conductors open at one end

are used. These conductors are located at the distance of $6 \cdot 10^{-4}$ m from the resonator. Its overlap with MSHWR is $5 \cdot 10^{-3}$ m. The main MSHWR oscillation mode is characterized by resonant frequency $f_0 = 3072$ MHz, loaded Q-factor $Q_H = 106$ and resonance-frequency attenuation $A_0 = -7.8$ dB. External static magnetic field H_0 is applied in the plane of the planar system under study and directed perpendicular to the distribution of the MSHWR standing wave alternating current (the case of transverse electromagnetic pumping). Actually, the YIG film is located in the antinode of the MSHWR fundamental mode alternating current, which, as shown below, provides efficient excitation of the magnetization vector uniform precession at FMR frequency f_{\perp} . Note that, to provide efficient excitation of spin-wave resonances in MSW resonators, the latter are also located in the alternating current antinode created not by MSHWR but by an AMTL segment short-circuited at one end to the ground [15].

Fig. 1, *a* shows the amplitude-frequency characteristic of the MSHWR–superthin YIG film system measured in the mode of coincidence between MSHWR natural frequency f_0 and FMR frequency $f_{\perp} = 3078$ MHz ($f_{\perp} \cong f_0$) of the gyromagnetic resonator constructed based on the superthin YIG film. The figure shows that the system resonance curve exhibits a pronounced dip whose frequency matches frequency f_{\perp} at $H_0 = 38.038$ kA/m and anisotropy magnetic field $H_A = 4.138$ kA/m. The level of attenuation at the dip frequency is -23.6 dB. On both sides of the dip, two maxima $f_{01} = 3064$ MHz and $f_{02} = 3084$ MHz are formed, whose attenuation levels are approximately the same ($A_{01} = -11.9$ dB and $A_{02} = -11.6$ dB). The dip frequency bandwidth Δf measured at the level of 3 dB with respect to the maximum attenuation level at frequency f_{\perp} is 4.2 MHz; this is that the FMR linewidth $2\Delta H \cong 119.366$ A/m corresponds to. Note that a similar situation associated with the formation of two maxima in the amplitude-frequency response of the planar resonator system was observed earlier in [6] for the case of a thicker YIG film ($d = 4 \cdot 10^{-5}$ m). However, in [6] the dip between the two maxima was much wider due to the BBMSW excitation in the YIG film.

The inset to Fig. 1, *b* shows a schematic image of AMTL loaded onto a YIG film with similar parameters. In this system, the static magnetic field H_0 direction is also orthogonal to the microstrip conductor but coincides with the direction of turns of the alternating magnetic field created by the traveling electromagnetic wave around the microstrip conductor (the case of longitudinal electromagnetic pumping). In this experiment, magnetic field H_0 is of a higher intensity ($H_0 = 43.529$ kA/m) than in the previous case at the same anisotropy field ($H_A = 4.138$ kA/m). Amplitude-frequency characteristic presented in Fig. 1 shows that excitation of a uniform magnetization vector precession at FMR frequency $f_{\perp} = 3322$ MHz is not observed, contrary to the case of MSHWR with the FMR excitation efficiency of ~ 15 dB. Thus, when field H_0 is oriented orthogonally to the microstrip conductor, FMR is detected at frequency f_{\perp} only

if MSHWR is used and is not observed at this frequency when AMTL is used as a non-resonator-type exciter.

Fig. 2 presents for comparison an amplitude-field characteristic of AMTL loaded onto a similar superthin YIG film. In this case, field H_0 is directed along the microstrip conductor and orthogonally to the turns of alternating magnetic field around the conductor (the case of transverse electromagnetic pumping, see the inset to Fig. 2). The results presented in Fig. 2 show that in the case of transverse pumping at frequency $f = 2900$ MHz a pronounced dip is observed in the amplitude-field characteristic at magnetic field $H_0 = 35.396$ kA/m. In this case, the frequency at which the amplitude-field characteristic was measured coincides exactly with FMR frequency f_{\perp} if $H_A = 2.944$ kA/m. The measured dependence of the transmission coefficient modulus on the external static magnetic field makes it possible to directly determine the FMR linewidth which is $2\Delta H \cong 87.535$ A/m. This FMR linewidth measured using AMTL coincides with its certified value. At the same time, though the FMR linewidth obtained using MSHWR is less accurate, it confirms that the presence of a dip in the amplitude-frequency characteristic of the resonator system is caused just by the FMR excitation.

Fig. 3, *a* demonstrates frequency dependences of the large-signal/small-signal ratio $LSSR = A_{lg} - A_{sm}$ (where A_{lg} is the attenuation coefficient in the large-signal mode (in decibels), A_{sm} is the attenuation coefficient in the small-signal mode) and nonlinear phase shift $NPS = \varphi_{lg} - \varphi_{sm}$ (where φ_{lg} is the phase shift in the large-signal mode, φ_{sm} is the phase shift in the small-signal mode). The obtained dependences clearly demonstrate the maximum LSSR increase by 8.1 dB at frequency $f_1 = 3077.5$ MHz ($f_1 \cong f_{\perp}$), maximum LSSR decrease by -3.5 dB at frequency $f_2 = 3083.9$ MHz ($f_2 \cong f_{02}$), and maximum non-

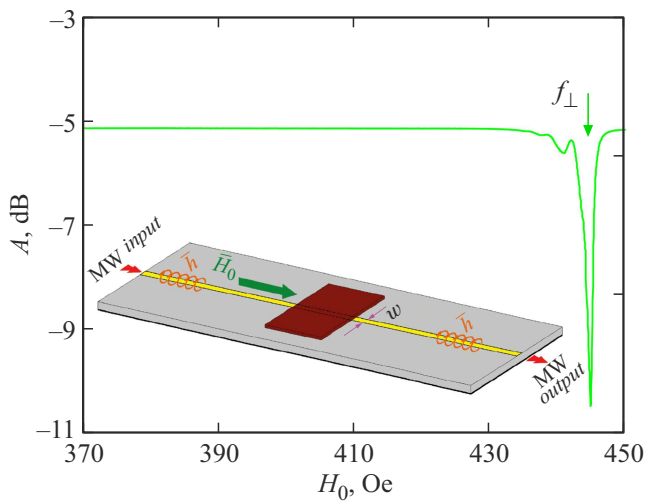


Figure 2. Amplitude-field characteristic of the AMTL-superthin YIG film system measured at the field H_0 orientation along the the microstrip conductor. The measurements were performed at frequency $f = 2900$ MHz and input power $P_{in} = -30$ dBm. The inset gives a schematic image of the system under study.

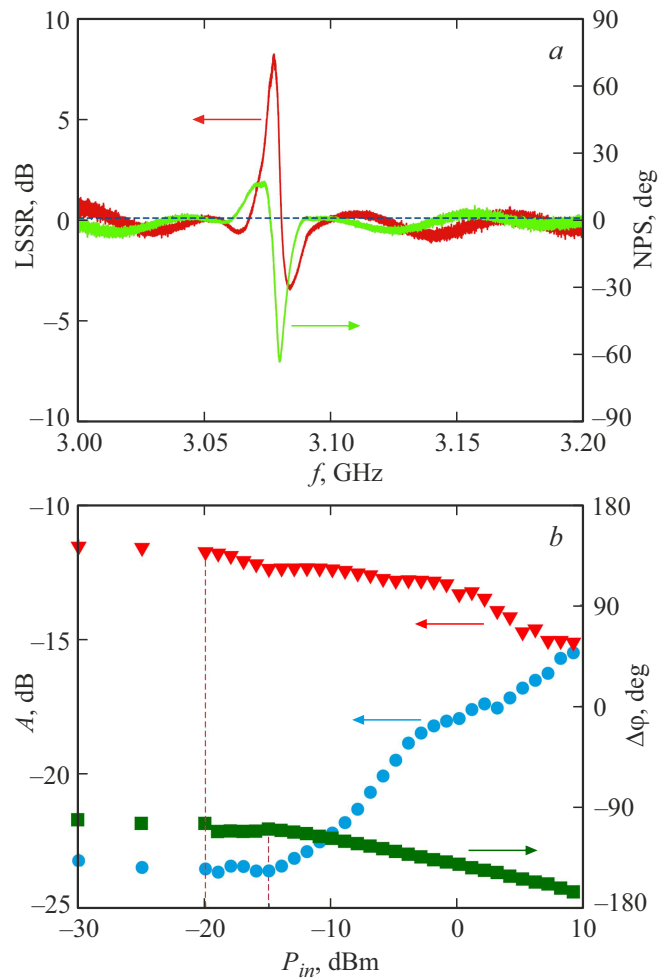


Figure 3. Nonlinear characteristic of the MSHWR superthin YIG film system measured at the field H_0 orientation along the the microstrip conductor. *a* — frequency dependences of the large-signal/small-signal ratio LSSR and nonlinear phase shift NPS obtained at the large-signal power $+9$ dBm and small-signal power -30 dBm; *b* — dependences of attenuation coefficient A (circles and triangles) and phase shift $\Delta\varphi$ (squares) on input power P_{in} measured at frequencies $f_1 = 3077.5$ MHz (circles), $f_2 = 3079.9$ MHz (squares) and $f_3 = 3083.93$ MHz (triangles). Results presented in both panels of the figure have been obtained for $H_{int} = 42.176$ kA/m.

linear phase shift of 64 deg at frequency $f_3 = 3079.9$ MHz. Note that, though the maximum values of LSSR and NPS obtained on MSHWR loaded onto a superthin YIG film operating in the FMR mode are inferior to similar values obtained on MSHWR loaded onto a thicker YIG film operating in the BBMSW excitation mode (the difference is ~ 7 dB and ~ 30 deg, respectively) [6,13], these LSSR and NPS values are unattainable in the AMTL superthin YIG film system at the similar field H_0 orientation. Those values may be increased by using higher-Q exciters of the resonator type.

Fig. 3, *b* shows power characteristics of the resonator system under study measured at three characteristic frequencies: f_1 , f_2 and f_3 . The presented results demonstrate

that nonlinear operating modes of the resonator system (nonlinear suppression of small signals, nonlinear limitation of large signals, and nonlinear phase shift variation) begin at threshold input powers ranging from -20 dBm to -15 dBm. Note that the above-mentioned nonlinear operating modes of the resonator system at those frequencies were not observed in experiments conducted earlier with similar MSHWR loaded onto a YIG film $4 \cdot 10^{-5}$ m thick [16]. This is because in the YIG film several tens of micrometers thick there were efficiently excited only long-wave BBMSW close to FMR frequency f_{\perp} for which nonlinear three-wave parametric decay processes were prohibited. Nonlinear four-wave BBMSW decay processes in the YIG film of the above thickness did not develop, since the maximum input powers of the resonator system ($P_{in} \sim +20$ dBm) used in the experiment were, apparently, below the nonlinear threshold of four-wave interactions. A decrease in the threshold of nonlinear four-wave interactions in nanometer-thick YIG films with respect to that in micron-thick YIG films was noted in [14] where superthin YIG films with AMTL in the „delay line“ configuration at $w \sim d$ were used to create a planar-design power limiter. Paper [14] shows that for MSWs excited in a superthin YIG film $d = 0.97 \cdot 10^{-7}$ m thick the threshold power levels at frequencies of ~ 4 GHz range from -20 dBm to -10 dBm. Thus, threshold power levels at FMR frequency f_{\perp} are consistent with similar values given in [14].

The obtained results are of interest in view of developing planar nonlinear devices based on the principles of cavity magnonics.

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Conflict of interests

The author declares that he has no conflict of interests.

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