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Excitation of exchange spin waves in a two-layer ferrite-ferrite structure

© V.V. Tikhonov, V.A. Gubanov, I.O. Filchenkov, A.V. Sadovnikov

Saratov National Research State University, Saratov, Russia
E-mail: tvlad4@yandex.ru

Received December 30, 2022
Revised February 6, 2023
Accepted February 8, 2023

The possibility of intense radiation of short-wave exchange spin waves excited in a thin transition layer at the internal boundary of a bilayer ferrite-ferrite structure is shown. Modelling of radiation processes has been exemplified by a tangentially magnetized bilayer film of ferric-yttrium garnet. It was found that the radiation of exchange spin waves has one-way character. The waves were radiated into the layer with decreased magnetization. Their group velocities were an order of magnitude lower than sound velocity in iron-yttrium garnet. Obtained results may be useful for creation of miniature controllable delay line on exchange spin waves.

Keywords: spin waves, ferrite, iron yttrium garnet, delay line.

DOI: 10.21883/TPL.2023.04.55879.19473

The introduction of short-wave (shorter than 100 nm) exchange spin waves (ESWs) into practical use is one of the goals of the current stage of development of magnonics [1]. The issues of excitation, reception, and control over the dispersion of travelling ESWs are crucial in this regard. Various approaches to ESW excitation have been proposed, and the method relying on the transformation of electromagnetic waves in nonuniform internal fields of ferrite turned out to be the most efficient. The field nonuniformity could be induced by demagnetization fields in bulk ferrite samples [2] or by the nonuniformity of magnetic properties of ferrite films [3].

It was demonstrated in [4] that a layered structure is an „intrinsic“ property of epitaxial yttrium iron garnet (YIG) films. A thin transition layer with reduced magnetization always forms on the inner surface of an YIG film adjacent to a nonmagnetic gadolinium gallium garnet substrate. It has been demonstrated recently [5,6] that the effects of transformation of electromagnetic and exchange spin waves are observed within this transition layer. Exchange waves were radiated into the bulk of an YIG film and reflected from its opposite surface. In the pulse mode, they could be observed as a regular series of delayed ESW echo pulses. The measured delay times of echo pulses provided an opportunity to calculate both the ESW propagation velocities and the YIG film magnetization profile. However, these effects were observed only in the case of normal film magnetization.

No pulse effects of ESW radiation were detected in a tangentially magnetized YIG film. Excited ESWs were localized within the transition layer. They were observed only as absorption peaks at the frequencies of spin-wave resonance excitation [7]. The measured spin-wave resonance frequencies could be used to calculate the wave characteristics of excited ESWs and the film magnetization profile, but it turned out to be impossible to set a long delay for a microwave signal.

In the present study, the possibility of producing a long ESW delay in the case of tangential film magnetization is examined. The effects of ESW excitation in a thin transition layer at the internal boundary of a bilayer ferrite-ferrite structure were studied for the purpose.

A bilayer YIG film with different layer magnetizations ($M_0 = 140\,\mathrm{G}$ and $M_1 = 300\,\mathrm{G}$) was taken as an example. The distribution of magnetization in the transition layer at the interface between contacting layers was characterized by distribution function $M(x) = M_0 + \delta M\left[1 - \exp(-x^2/\sigma^2)\right]$, where $\delta M = M_1 - M_0$ and σ is the distribution function parameter.

Figure 1 presents the magnetization profile in the transition layer calculated at a given value of $\sigma = 10^{-5}$ cm.

The case of tangential magnetization of an YIG film by a DC external field $H_0 = 2000$ Oe was considered. The processes of ESW excitation by a uniform microwave magnetic field were modeled. The linearized Landau–Lifshitz

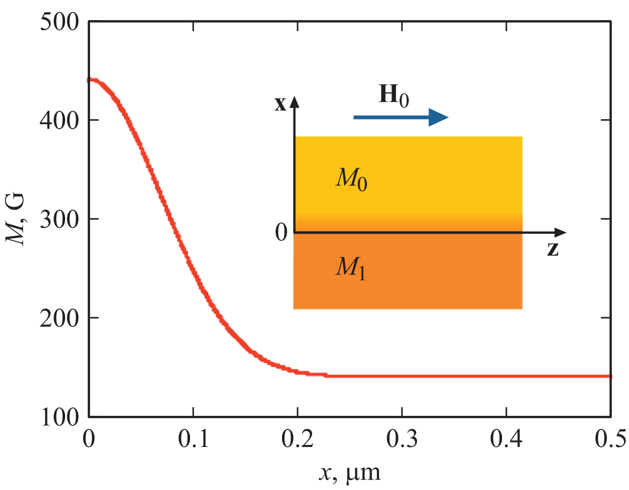

Figure 1. Distribution of magnetization over the transition layer thickness.

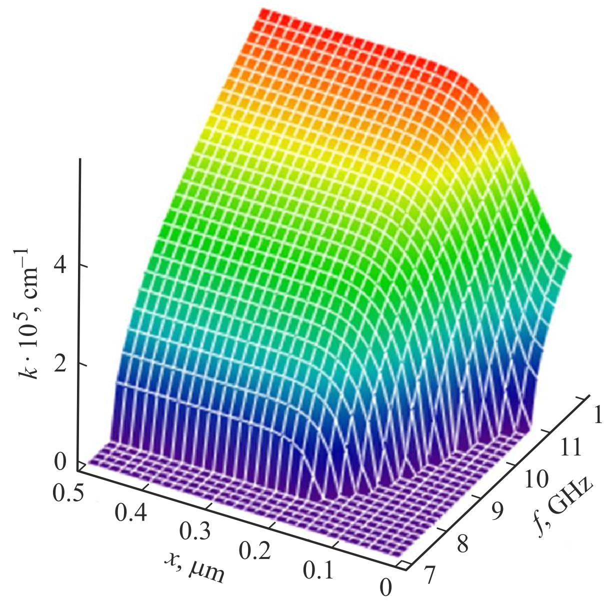

Figure 2. Dispersion of a precession wave in the transition layer of a bilayer YIG film.

equation (written with account for nonuniform exchange) and the system of Maxwell equations were solved jointly for the purpose. The solution was sought in the form of a plane wave of precession of the magnetization vector propagating in the transverse direction: $\mathbf{m} \propto \exp[i(\omega t - kx)]$, where $\omega = 2\pi f$ is the angular frequency and k is the wave vector. The crystallographic anisotropy of films and dissipative processes were neglected.

The dispersion relation derived with these restrictions taken into account

$$(\omega_H + \eta k^2)^2 + \omega_M(\omega_H + \eta k^2) - \omega^2 = 0, \quad (1)$$

had a simple analytical solution

$$k = \sqrt{\frac{1}{\eta}\left[\sqrt{\frac{\omega_M^2}{4} + \omega^2} - \left(\frac{\omega_M}{2} + \omega_H\right)\right]}, \quad (2)$$

where $\omega_H = \gamma H_0$, $\omega_M(x) = 4\pi\gamma M(x)$, $\gamma = 1.76 \cdot 10^7$ Oe$\cdot$s^{-1} — gyromagnetic ratio, $\eta = 0.0764$ cm$^2 \cdot$ s^{-1} — is the nonuniform exchange constant.

Figure 2 shows the 3D plot of dispersion law $k(f, x)$ calculated within the transition layer.

It can be seen that the ESW wave numbers become zero in a fairly wide frequency band along the line of intersection between dispersion surface $k(f, x)$ and plane $k = 0$. This implied that the condition of phase synchronicity (matching) between ESWs and the external uniform microwave field was satisfied. A precession wave originated at synchronicity points and transformed gradually into a short-wave ESW in the course of propagation.

The processes of generation and propagation of exchange waves are illustrated in Fig. 3. Figure 3, *a* shows the 3D ESW plot $m(f, x) \propto \sin[k(f, x)x]$, calculated in the vicinity of origin points of a precession wave. Figure 3, *b* shows the frequency dependences of group $v_g(f) = [dk(f)/d\omega]^{-1}$ and phase $v_p(f) = [k(f)/\omega]^{-1}$ ESW velocities calculated far from origin points in the region of uniform magnetization of an YIG film.

It is seen clearly in Fig. 3, *a* that the front of an excited ESW forms in accordance with the curvature of the origin line of a precession wave. The wave front straightens somewhat with distance from origin points, but the wave vector still deviates from the normal to the interface of contacting layers. The group ESW velocities do not exceed 10^5 cm/s (Fig. 3, *b*); i.e., they are an order of magnitude lower than the speed of sound in YIG single crystals.

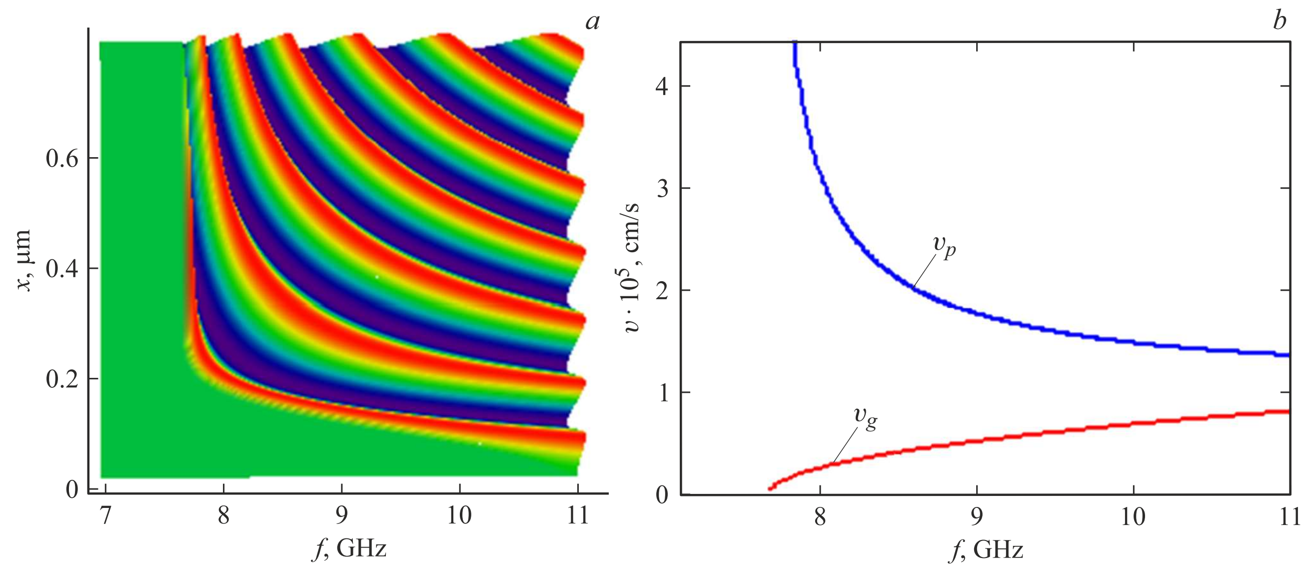

Figure 3. Diagram of excited ESWs in the vicinity of origin points (*a*) and frequency dependences of group v_g and phase v_p ESW velocities far from origin points (*b*).

Thus, it was demonstrated that short-wave ESWs travelling into the bulk of the film layer with reduced magnetization may be excited in the transition layer of a tangentially magnetized bilayer YIG film. Since the studied waves have exceptionally low propagation velocities, they provide a real opportunity to construct a compact controllable delay line for microwave signals.

Funding

The study was supported by the Ministry of Education and Science of the Russian Federation under the state assignment (project No. FSRR-2023-0008).

Conflict of interest

The authors declare that they have no conflict of interest.

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