Excitation and propagation of exchange spin waves in films of yttrium iron garnet

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We investigate resonant microwave absorption in films of yttrium iron garnet (YIG) with magnetic properties varying through the film thickness. Using measurements of the spin-wave resonant absorption spectra for two different directions of the external magnetic field, we calculate the profile of this nonuniformity. In our investigation of the response of nonuniform films to a pulsed microwave signal, we observed the appearance of delayed pulses, which we interpret to be the result of propagation of exchange spin waves transversely through the film. We analyze the dependence of the time delay on frequency for various nonuniformity profiles, and compare the data obtained with the results of experiment. Our investigation of the spin-wave resonance spectra, as well as the results of our pulsed measurements, show that propagation of spin waves is accompanied by the excitation of acoustic waves. We conclude that ferrite films that vary in the transverse direction can on the one hand be used to efficiently excite short-wavelength exchange spin waves (with wave numbers $q \approx 3 \cdot 10^5$ cm^{-1}, and on the other hand to excite very high-frequency acoustic waves. © *1995 American Institute of Physics.*

1. INTRODUCTION

The transport of energy by spin waves in magnetoelastic media arises from two types of interaction between spins: dipole–dipole and exchange. The dipole–dipole interaction, as a rule, plays a fundamental role in the propagation of relatively long-wavelength spin waves with wave numbers $q \leqslant 10^3$ cm^{-1}, where the wavelength can be comparable to the characteristic size of the ferromagnetic sample. Such waves are customarily referred to as magnetostatic spin waves.[1,2] For shorter-wavelength spin waves (with $q \sim 10^5$ cm^{-1}) it is the exchange interaction that plays the fundamental role. In order to emphasize this distinction, we will refer to such waves as exchange spin waves. We note that the study of exchange spin waves is interesting both from the applications and fundamental points of view. Along with elastic and magnetostatic waves, exchange spin waves are "slow" waves, i.e., their phase and group velocities are small compared to the velocity of an electromagnetic wave. On the one hand, this is why exchange spin waves are promising candidates for use in making small-sized microwave engineering elements, similar to those that use surface acoustic waves and magnetostatic spin waves. On the other hand, the wavelength of exchange spin waves is comparable to that of sound and light; therefore, these spin waves could be important objects and instruments for investigating interactions between waves of various types.

The experimental study of exchange spin waves, which started more than thirty years ago, involves the use of three basic experimental methods: study of spin-wave resonance spectra in thin ferromagnetic films, measurement of frequency and field dependences of the threshold for parametric excitation of exchange spin waves, and investigation of the scattering of light by thermal or parametrically excited magnons.[2,3] However, up to now no paper has appeared that suggests the possibility of efficient artificial excitation of exchange spin waves with a given frequency and direction of propagation. Nevertheless, such exchange spin waves could find a variety of applications in electronics and in fundamental investigations. The goal of this paper is to address this problem to some extent. We have obtained experimental data that show that in YIG films that are nonuniform in thickness it is possible to efficiently excite exchange spin waves with wave numbers of order $3 \cdot 10^5$ cm^{-1}. We will also discuss distinctive features of the propagation of exchange spin wave pulses in such films. We have also investigated forward and reverse conversion of exchange spin waves into sound. Some of our results were published previously in Refs. 4–8. This article contains a further development of these papers. Let us begin with a short review of the basic methods for exciting spin waves.

2. METHODS FOR EXCITING SPIN WAVES

Exchange spin waves are difficult to excite because the wave numbers of electromagnetic and spin waves differ by four to five orders of magnitude. Therefore, these waves are practically noninteracting in the linear regime. In a uniform ferromagnetic medium exchange spin waves can only be excited parametrically, either directly by the decay of electromagnetic waves or indirectly by the decay of magnetostatic waves excited by the latter.

Let us discuss the new ways to excite exchange spin waves that become available when we take into account the finite size of the ferromagnetic sample and the presence of various transducers located at the sample boundary.

If the thickness of the ferromagnetic layer is sufficiently small and the spins at the surface of the layer are clamped, resonance excitation of exchange spin waves is possible with wave numbers $q = \pi n / L$, where L is the thickness of the layer and the mode number n labels the resonances. Note that in spin-wave resonance measurements[9] it is usually only

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the first spin-wave resonance mode that is excited, since the amplitude of the resonances falls off as n^2 as the resonant mode number n increases. Resonant excitation of exchange spin waves has also been observed in certain experiments involving the propagation of magnetostatic spin waves in thin films of YIG. As in spin-wave resonance, magnetostatic spin waves and exchange spin waves are coupled when the surface spins are clamped.[10,11]

From general considerations it is clear that we can excite a wave by creating a nonuniformity in the excitation field that is of the same order or smaller than the wavelength of the wave. Such methods have been used successfully to excite magnetostatic waves in ferrite–garnet films.[1] Here a segment of microstrip line acts as an antenna when placed on the film surface, creating a spatial nonuniformity in the high-frequency magnetic field with a characteristic size of the same order as the width of the microstrip line. This allows us to excite magnetostatic spin waves with corresponding values of the wave number, i.e.,smaller than 10^4 cm^{-1}. The exchange interaction is small for these wavelengths, and the dispersion of magnetostatic spin waves is determined, as a rule, by the dipole–dipole interaction. Thus, it is not possible to use a microstrip antenna to excite the shorter-wavelength spin waves.

Nonuniformities in the electromagnetic field with characteristic scales of 10^{-6} cm are associated with the skin effect at the boundary of a ferromagnetic metal.[12] However, the use of such a layer to excite propagating exchange spin waves cannot be efficient, since the dissipation of spin waves in a metal is extremely large. Spin waves in ferrite–garnets, e.g., YIG, have losses that are considerably smaller. The authors of Ref. 13 showed experimentally that it is possible to excite exchange spin wave pulses in an ion-implanted YIG film. The implantation was carried out to create a thin nonuniform layer at the surface of the film, which acts as the spin wave antenna.

A fundamentally different approach to obtaining short-wavelength spin waves is one in which rather long waves are excited at the first stage (which is easy to do using electromagnetic waves). In the next stage, these are converted into short waves as they propagate through a spatially nonuniform waveguiding structure. This is the approach we will use here.

The idea of using nonuniform magnetic media to excite short-wavelength exchange spin waves was proposed even in the 1960's, and was rather thoroughly discussed in the papers of Schlömann.[14,15] In essence, this method makes use of the fact that if the parameters of the medium vary slowly in space, the wavelength of the spin wave will depend on the coordinates. Then it is possible to create conditions under which the wave number of the spin wave will be small in a certain region of space, which ensures effective coupling with an electromagnetic wave. At the same time, as the wave propagates its wavelength decreases, which leads to the appearance of short-wavelength spin waves. In practice, this method was first implemented in experiments involving excitation of spin wave pulses that propagated along a rod of YIG placed in an external magnetic field (see, e.g., Refs. 16 and 17). The nonuniformity of the medium arises from the demagnetizing field near the end of the rod. Spin waves were excited in this experiment with $q \sim 10^4$ cm^{-1}. This excitation mechanism manifests itself in experiments on spin wave resonance as well when the layer under study is nonuniform in thickness. It has been shown that effective excitation of exchange spin waves with high mode numbers is possible in such layers. The authors of Refs. 18–23 investigated spin-wave resonance theoretically and experimentally in nonuniform magnetic films, setting as their goal the resolution of two fundamental questions: (1) how does nonuniformity affect the resonance spectrum, and (2) is it possible to recover the nonuniformity profile from the spectrum. We, however, have investigated similar films from a different point of view—as media in which it is possible to excite and propagate traveling exchange spin waves. As we have already noted, traveling exchange spin waves show promise both for fabricating new devices and for developing new ways to investigate magnetoelastic media. In what follows, we will discuss YIG films, since propagation losses for spin waves in this material are minimal. The films should be sufficiently nonuniform to ensure effective wavelength conversion. We have investigated the spin-wave resonance spectra for a selection of samples that satisfy these requirements.

3. SPIN–WAVE RESONANCE SPECTRA OF NONUNIFORM YIG FILMS

Our experimental setup consisted of a segment of 50 Ω asymmetric stripline of length ~1 cm, fabricated on a polycor substrate of thickness 0.5 mm. One electrode of this line, with a width of 0.5 mm, served as an exciter (antenna) of spin waves. The film and electrode were pressed together with a gasket between them that provided a gap of ~0.5 mm and decreased the coupling between the antenna and the sample. The external magnetic field H was directed either along the normal to the film plane (a "normal" field) or within the film plane (a "tangential" field). A microwave signal with frequency $\omega/2\pi$ was applied in the setup through a circulator. The power P of the reflected microwave signal was measured as a function either of frequency (at fixed magnetic field) or of the magnitude of the external magnetic field (at fixed frequency).

The samples under investigation were YIG films deposited by liquid-phase epitaxy on substrates of gadolinium–gallium garnet with orientations (111) or (100). The samples were given to us by A. V. Maryakhin and A. S. Khe. The film thicknesses were normally 10–20 μm, with dimensions in the plane of order several centimeters. For uniform films with these dimensions, the width of the absorption spectrum did not exceed 15–30 MHz, or 5–10 Oe, since high spin-wave resonance modes are not excited in uniform films with this thickness; the absence of a broad spectrum of magnetostatic oscillations was due to the large dimensions in the plane. Under these conditions, the width of the absorption spectrum for uniform films is determined by the region of existence of magnetostatic waves with $q < 50$ cm^{-1}, i.e., those waves that can be excited by the wide electrode of the stripline we are using. However, among the samples we investigated we observed some films in which the absorption spectrum was hundreds of megaherz. Within these spectra

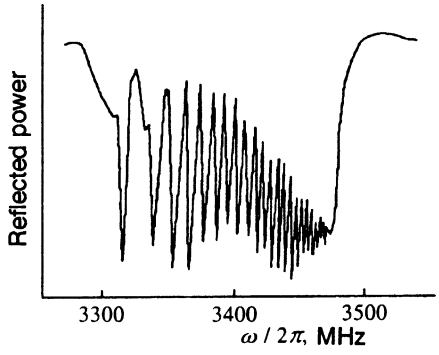

FIG. 1. Typical exchange spin wave spectra in a nonuniform film. The plots show the frequency dependence of the microwave power reflected from the sample, which was a tangentially magnetized YIG film with orientation (111) and thickness $L=12.5$ μm in an external magnetic field $H=563$ Oe.

we observed tens of resonance peaks. A typical spectrum for a tangential field is shown in Fig. 1. Spectra in a normal field were broader than in a tangential field, and could include up to 120 resonances.

Enumerating the peaks in their order of increasing frequency, we measured the dependence of the resonance frequencies ω_n of their mode number n. The results of these measurements are shown in Fig. 2 for two samples and two orientations of the external field. In the text that follows, and in the captions for the figures, we will refer to these films as samples "1" and "2." Using these films, we carried out experiments to determine the effect of the planar dimensions of the sample on the absorption spectrum. Our studies showed that the form of the functions ω_n does not change as the sample dimensions were varied from 1 mm to several centimeters. This allows us to assert that the absorption peaks are associated with thickness resonances, and not resonances over the sample width, i.e., we are observing spin-wave resonances. In uniform films, the distance between adjacent spin-wave resonance frequencies increases with the mode number as n^2. This clearly does not correspond to the dependence shown in Fig. 2. Consequently, we can assume that the film is nonuniform, i.e., its parameters change with thickness. We

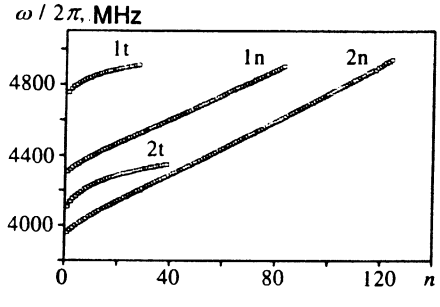

FIG. 2. Dependence of the resonance frequency on mode number. (1t)—sample 1, tangential field $H=895$ Oe; (1n)—sample 1, normal field $H=3588$ Oe; (2t)—sample 2, tangential field $H=808$ Oe; (2n)—sample 2, normal field $H=3505$ Oe [the YIG films had (111) orientation, $L=15$ μm (sample 1) and $L=17.2$ μm (sample 2)].

now present several theoretical estimates that allow us to verify the correctness of this assumption.

Let us consider a magnetic film of thickness L placed in an external magnetic field H, so that H is directed along the x-axis perpendicular to the plane of the film. We will assume that the parameters that can change significantly over the film thickness are the saturation magnetization $M_s(x)$ and the uniaxial anisotropy field $H_a(x)$. We will assume that the remaining film parameters, i.e., the gyromagnetic ratio $\gamma=2\pi\cdot 2.8$ MHz/Oe and the inhomogeneous exchange constant $D=4.6\cdot 10^{-9}$ Oe·cm^2 are constant, and we will ignore the cubic anisotropy. Let us introduce a certain effective parameter—the effective magnetization $M(x)$—which we define by the relation $4\pi M(x)=4\pi M_s(x)-H_a(x)$. Consider a high-frequency magnetization $m(x,t)=m(x)-\exp(i\omega t)$ that is uniform in the plane of precession. Then we find from the Landau–Lifshitz equations that $m(x)$ should satisfy the following equation in the magnetostatic approximation:[22]

$$D\frac{\partial^2 m}{\partial x^2}+\left(\frac{\omega}{\gamma}-H+4\pi M-\frac{D}{M_s}\frac{\partial^2 M_s}{\partial x^2}\right)m=0. \tag{1}$$

Estimates show that the effect of the last term in the curly brackets is small. Neglecting this term, we rewrite (1) in the form

$$\frac{\partial^2 m(x)}{\partial x^2}+q(x)^2 m(x)=0, \tag{2}$$

where

$$q(x)^2=\frac{\omega/\gamma-H+4\pi M(x)}{D}. \tag{3}$$

Recall that the general solution to Eq. (2) for a uniform film has the form $m(x)=a\cdot\exp(-iqx)+b\cdot\exp(+iqx)$, where a and b are constants and q is the wave number of a spin wave propagating along the normal to the film.

Exact solutions to Eq. (2) for nonuniform films were found in Refs. 18 and 22 for two special cases of the profile $M(x)$—parabolic and linear. However, we will investigate approximate solutions according to the WKB method for an arbitrary monotonic profile $M(x)$. Then $q(x)$, determined by the dispersion relation (3), depends on the local magnetization and has the physical meaning of a local wave number. We will assume that $M(x)$ varies with thickness monotonically, reaching its maximum value $M=M_0$ at $x=0$, and its minimum value $M=M_L$ at $x=L$. From Eq. (3) it is clear that if the frequency ω lies in the interval

$$\omega_0<\omega<\omega_L, \tag{4}$$

where $\omega_L=\gamma(H-4\pi M_L)$ and $\omega_0=\gamma(H-4\pi M_0)$, then there is a point within the film with a certain coordinate $x=d$ at which q reduces to zero. The eigenmode is a sinusoidal wave (with varying wave number) within the layer $0<x<d$,

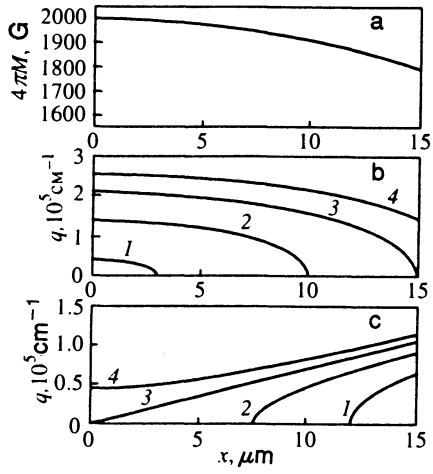

FIG. 3. Profile of magnetization variation (a) and the corresponding computed dependences of the change in wave number versus film thickness for the case of normal (b) and tangential (c) magnetic fields. As an example, we show in (a) a parabolic variation in magnetization. Curves *1–4* in Figs. (b) and (c) reflect the character of the change in wave number for successive increases in frequency.

where $q^2>0$, and an oscillation with exponentially decaying amplitude in the region $d<x<L$, where $q^2<0$. By analogy with the problems of particle motion in a potential well, we will refer to the point $x=d$ as a turning point. Note that the coordinates of this turning point depend on frequency, which is illustrated by Fig. 3b, where we show the form of the computed values of $q(x)$ for the case of a parabolic profile $M(x)$ shown in Fig. 3a. When $\omega\simeq\omega_0$, the turning point appears near the boundary with large magnetization $x=0$; as the frequency increases, it shifts into the bulk of the film. When $\omega=\omega_L$, the value of d reaches the second boundary of the film (curve 3 in Fig. 3b). The existence of a turning point within the film causes the spin-wave resonance modes to be localized in the layer $0<x<d$, in which $q^2>0$. As was shown in Ref. 22, these "local" modes are excited very efficiently. This latter circumstance is connected with the fact that the AC magnetization varies most smoothly with x near the turning point, so that the overlap integral of the excitation wave with the microwave field is a maximum. Therefore, the layer where $q\sim 0$ acts as an intrinsic spin-wave antenna. We may assert that the intense absorption of microwave radiation observed in our experiments occurs within a band of frequencies determined by the inequalities (4).

Using the WKB approximation, we can find the resonance frequencies ω_n by starting from the relation:

$$\varphi(\omega_n)+\varphi_0=2\pi n, \quad n=1,2,3..., \tag{5}$$

where

$$\varphi(\omega)=2\int_0^{d(\omega)} q(x,\omega)dx. \tag{6}$$

The physical meaning of the quantity $\varphi(\omega)$ is quite evident—it is the phase shift accumulated by the exchange spin wave as it propagates from the turning point to the boundary of the film and back. The quantity φ_0 can be treated as a phase jump that the wave acquires as it is reflected from the film boundary. The value of φ_0 depends on the degree of clamping of the spins at the film surface. For films with free spins we have $\varphi_0\simeq 3\pi/2$.[22] Comparing the frequency values found from Eq. (5) for a linear profile of $M(x)$ with the exact solutions found in Ref. 22, we can conclude that condition (5) gives us rather precise values of the resonance frequencies for all ω_n within the band determined by condition (4). The error is appreciable only for the last resonance ($\omega_n\simeq\omega_L$), where the turning point is located near the film surface.

Note that once we have set $q=0$ in (3), we can use the experimentally obtained frequencies ω_n to compute a series of values M_n corresponding to values of the effective magnetization at the turning point for frequencies ω_n. Now, in order to compute the profile $M(x)$, it is sufficient to find the coordinates of the turning point d_n for those values of the frequency. This can be done by assuming that the effective magnetization varies linearly on the segments $d_n<x<d_{n+1}$ (i.e., between turning points) and also on the segment $0<x<d_2$ adjacent to the film boundary. Then by solving Eqs. (3), (5), and (6) together, we determine the slope of the function $M(x)$ from the frequency difference $(\omega_2-\omega_1)$on the segment $0<x<d_2$, and consequently the coordinates d_1 and d_2. We then substitute the value ω_3 into Eqs. (3), (5), and (6) to find d_3; using ω_4 we then find d_4 and so on. The results of this processing of the spectrum of a normally magnetized film are shown in Fig. 4a. It is clear that the profile $M(x)$ we have constructed is close to a parabola with its vertex at the film boundary. Note that for this sample the dependence of the frequencies ω_n on the mode number n is practically linear (Fig. 2), i.e., the peaks are equidistantly spaced. We also note that the problem of spin-wave resonances in a film with parabolically varying uniaxial anisotropy along the thickness was discussed theoretically in the paper by Portis,[18] who showed that the spin-wave resonance frequencies should be spaced equidistantly for this nonuniformity profile as well. Thus, our results are in qualitative agreement with the conclusions of Portis' paper. Note, however, that in Ref. 18 the vertex of the parabola was assumed to lie at the center of the film. This shows that our assumption regarding monotonic variation of $M(x)$ requires additional justification. In order to carry out a detailed analysis, we use the spectrum of the same film in a tangential field.

The theoretical description of spin-wave resonance in a tangential field is somewhat more complicated, since in place of Eq. (1) we have a differential equation of fourth order with variable coefficients. Analysis shows that under conditions where the WKB approximation is applicable, this equation can be transformed into a system of two weakly-coupled differential equations of type (2), in which the quantities $q(x)$ coincide with the two different roots of the equation

$$\left(\frac{\omega}{\gamma}\right)^2=[H+Dq(x)^2][H+Dq(x)^2+4\pi M(x)], \tag{7}$$

which is in essence the "local" dispersion relation for exchange spin waves propagating perpendicular to a magnetic

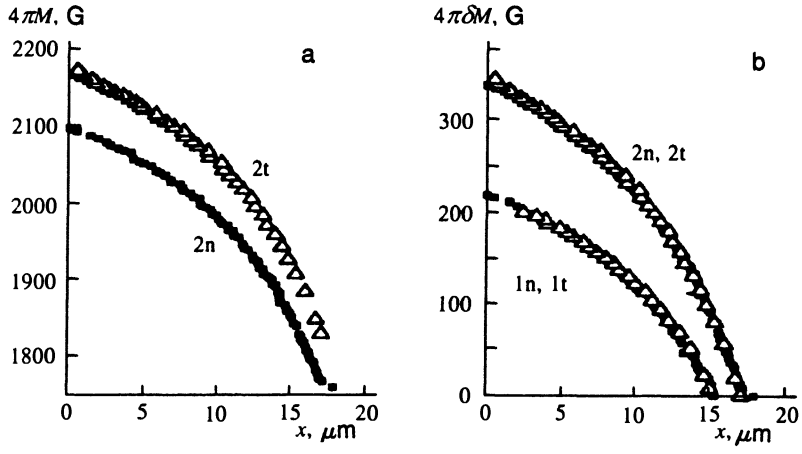

FIG. 4. (a) Profile of effective magnetization variation $4\pi M(x)$ for sample 2; (b) Profile of relative change of the effective magnetization $4\pi\delta M(x)$ for samples 1 and 2. These data were obtained by processing the spectra shown in Fig. 2. The points correspond to data calculated from spectra of normally magnetized films, the triangles are from spectra of tangentially magnetized films.

field. In the spectral range of interest to us, these roots differ significantly in their character and magnitude. Only one of them, specifically

$$q(x)^2=\frac{1}{D}\left\{\sqrt{\left(\frac{\omega}{\gamma}\right)^2+[2\pi M(x)]^2}-H-2\pi M(x)\right\}, \tag{8}$$

can have a turning point and a segment on which $q^2>0$. It is this root that is of primary interest to us. The second root describes an oscillation of the magnetization that decays rapidly in space ($q^2<0$, $|q|\sim 10^6$ cm^{-1}).

From Eq. (8) it is clear that the turning point, and consequently the spin-wave resonance spectrum, exists in the frequency range

$$\omega_{TL}<\omega<\omega_{T0}, \tag{9}$$

where $\omega_{TL}=\gamma\sqrt{H(H+4\pi M_L)}$, $\omega_{T0}=\gamma\sqrt{H(H+4\pi M_0)}$. In contrast to the case of a normally magnetized film, as the frequency increases the turning point shifts from the boundary with the smaller effective magnetization ($x=L$) to that with the larger magnetization ($x=0$). The wave number increases with increasing x; see Fig. 3c.

Let us introduce the effective magnetization drop $4\pi\Delta M=4\pi M_0-4\pi M_L$. From the definition of the frequencies ω_L and ω_0 [see Eq. (4)] it is clear that $4\pi\Delta M=(\omega_L-\omega_0)/\gamma$, i.e., the quantity $4\pi\Delta M$ is directly determined by the width of the spin-wave resonance spectrum in a normal field. On the other hand, the value of $4\pi\Delta M$ can be found independently from the frequencies that bound the spectrum in a tangential field, if we make use of the definitions of ω_{TL} and ω_{T0} (9). When we make the corresponding estimates for the values of $4\pi\Delta M$ (starting from the spectra shown in Fig. 2), we observe that the values of the drop obtained from the tangential and normal spectra agree to good accuracy. This agreement is confirmation of the correctness of our original assumption that the observed spin-wave resonance spectra are caused by nonuniformity of the effective magnetization over the film thickness. The value of $4\pi\Delta M$ was ~200 G for sample 1 and ~330 G for sample 2.

By analogy with the case of a normally magnetized film, we can construct a profile for the variation of the effective magnetization based on values of the resonance frequencies in a tangential field. The primary difference in procedure from the previous case is the fact that in place of (3) and (4) we make use of Eqs. (8) and (9), and the process of recovering the profile goes in the opposite direction—from the boundary $x=L$ (with the smaller magnetization) to $x=0$. The results of this calculation are shown in Fig. 4a. From this figure it is clear that the profiles recovered from the tangential and normal spectra are very similar. The primary difference is a disagreement in the absolute values of $4\pi M$, which are shifted by an amount ~70 G. This shift may be explained by the effect of the cubic anisotropy field, which we have not included in the calculation. In Fig. 4b we show the relative variation of the effective magnetization $4\pi\delta M(x)=4\pi M(x)-4\pi M(L)$ for samples 1 and 2. The good agreement of the profiles obtained from these spectra for various orientations of the magnetizing field shows that for these two films the assumption that the variation of $M(x)$ is monotonic is correct. We note that some of our samples had extremely nonmonotonic variations of $M(x)$. When their spectra were processed in accordance with the methods described above, significantly different results were obtained from the normal and tangential spectra. Apparently the profiles of these films cannot be recovered by the method of nondestructive testing. In order to solve this problem, we can use the method described in Ref. 20, i.e., analysis of spin-wave spectra measured measured during layer-by-layer etching. In processing the experimental data, we made a number of assumptions. Let us address the question of how correct these assumptions are.

First of all, we assumed that the gyromagnetic ratio γ does not change over the film thickness. From Eq. (4) it is clear that if the value of γ is not constant, the width of the spectrum of a normally magnetized film depends on the value of the external magnetic field. We did not observe any such dependence in our experiments.

Secondly, we assumed that the inhomogeneous exchange

constant was indeed a constant. We claim that even if D varies over the film thickness, it cannot be the sole and fundamental cause of the nonuniformity of the properties. The fact is that variation of D by itself does not lead to the appearance of a turning point, nor to the existence of the latter within a rather broad spectral interval. Consequently, variation of D cannot explain the presence of the extended spin-wave spectrum.

Thirdly, we assumed that spins at the film surface are free, and used a value of φ_0 equal to $3\pi/2$. For complete clamping of the spins, the value of φ_0 would be $\simeq\pi/2$.[22] Note that, in any case, the value of φ_0 lies within the interval from 0 to 2π, and the error in determining the resonance frequencies cannot exceed the distance between adjacent resonances. The experimental spectra numbered from 30 to 120 resonances; therefore, the form of the profile of $M(x)$ does not change appreciably, regardless of the value of φ_0 used.

Fourthly, in assuming that the maximum of $4\pi M(x)$ lies at the boundary $x=0$, we did not specify whether the point $x=0$ is a film–air boundary or a film–substrate boundary. In order to clarify this issue, it is necessary to investigate further. Let the point $x=0$ lie at the film–substrate boundary. Then etching the film will remove a portion of the sample (near $x=L$) with low effective magnetization. This implies that the spin-wave resonance spectrum will become narrower for both orientations of the field. In a tangential field, this narrowing of the spectrum occurs because the frequency of the first resonance increases, while for the normal field it is because of a decrease in the frequency of the latter (i.e., the number of resonances has decreased). However, for a normal field the frequencies of the remaining resonances should remain unchanged. Our previous analysis shows why this happens. The frequency of the nth resonance is determined by the profile of variation of the magnetization on the segment from $x=0$ to $x=d_n$. Therefore, as long as the thickness of the remaining film exceeds d_n, the frequency ω_n does not change. Then by etching the film we can attach the measured profiles to the proper sample boundary. These experiments showed that for our two films, whose profiles are shown in Fig. 4, the maximum magnetization is located at the film–air boundary, i.e., the real situation is exactly the opposite what we have assumed—successive etching implies that it is the spectrum in a tangential field that becomes narrower without changing the resonance frequencies of the remaining peaks.

4. EXCITATION AND PROPAGATION OF EXCHANGE SPIN WAVES PULSES

In the preceding section, we showed that there exist YIG films whose effective magnetization varies smoothly with thickness over a range of several hundred gauss. As is clear from Fig. 3, spin waves propagating along the thickness of these films can have wave numbers of order 10^5 cm^{-1}, i.e., they are exchange spin waves. Experiments on spin-wave resonance show that resonant excitation of such waves is possible. The existence of a turning point within the film allows us to assert that the efficiency of excitation of spin-

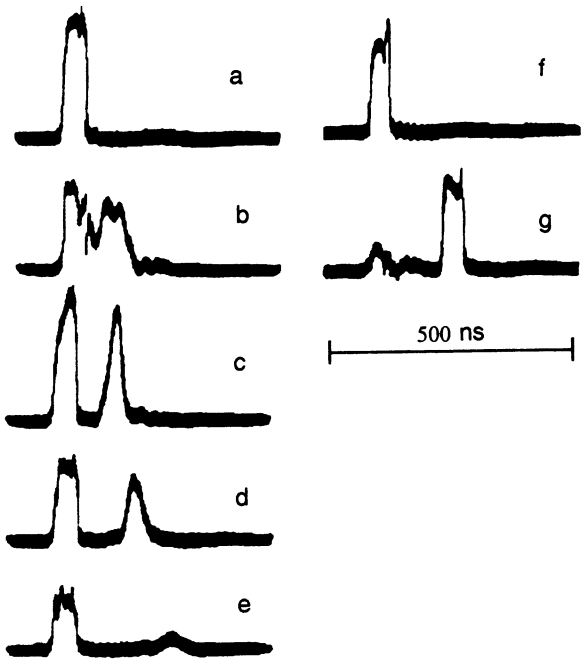

FIG. 5. Time dependences of the envelope of the reflected signal for sample 1. Traces a–e are for a tangential field with $\omega/2\pi=5124$ MHz; a—$H=0$, $K=0$; b—$H=1084$ Oe, $K=10$ dB; c—$H=1079$ Oe, $K=10$ dB; d—$H=1071$ Oe, $K=10$ dB; e—$H=1058$ Oe, $K=10$ dB. Traces f and g are for a normal field with $\omega/2\pi=5322$ MHz; f—$H=0$, $K=0$; g—$H=3790$ Oe, $K=7.6$ dB.

wave resonances will remain quite high for traveling spin waves as well. In order to verify this, we carried out a number of experiments in the pulsed regime.

Our measurement setup was analogous to that described earlier; the main difference was the fact that the gap between the film and the stripline antenna did not exceed 100 μm. This increased the coupling between the film and the antenna. We fed microwave pulses to this antenna with duration 10–100 ns, generated by a microwave modulator. The pulses reflected from the film were detected, amplified, and displayed on an oscilloscope.

For $H=0$, a microwave pulse fed to the setup was totally reflected. Within a certain range of magnetic fields (determined by Eqs. (4) and (9) for normal and tangential fields, respectively) the amplitude of the reflected signal dropped sharply, and a second pulse appeared that was delayed by a time τ. For a tangential field, the value of τ depended strongly on H, as demonstrated by traces 1–5 in Fig. 5.

For a normal field, delayed pulses were observed over a considerably broader range of magnetic fields. The delay time for the sample under study, which was independent of the value of H within a field interval of width $\sim$120 Oe, was $\sim$140 ns. Traces 6 and 7 of Fig. 5, which correspond to this case, show that the shape of the delayed pulse suffers little if any dispersive distortion.

Note that the photographs sown in Fig. 5 were all taken with the same amplification coefficient K over the receiver path. but with different amplitudes fed to the signal setup. The values of K given in the figure captions show the rela-

tive change in the power of the signal fed to the sample. Because the amplitude of the detected pulses is proportional to the microwave signal power, we can estimate the power ratios of the original and delayed signals by comparing the amplitudes of the pulses shown on the photographs.

The observation of a delayed pulse can be interpreted as evidence for excitation of exchange spin waves that then propagate along the film thickness. The excitation takes place near the turning point. The delay time is due to the time for propagation of the exchange spin waves from the turning point to the boundary of the film and back.

Let us first discuss the dependence of the time delay τ on the field H at a fixed frequency ω. It is clear from traces 2 to 5 in Fig. 5, that the delay time increases as H decreases. This result directly contradicts the data obtained in Ref. 13, where delayed exchange spin wave pulses were observed in films that were uniform (except for a near-surface layer). Furthermore, theoretical considerations based on use of the exchange spin wave dispersion law for a uniform medium imply that the exchange spin wave group velocity V increases as H decreases, and consequently the delay time τ must decrease with H. The increase in τ observed in our experiments is a direct consequence of the nonuniformity of the film properties with respect to thickness. The fact is that in a nonuniform film the value of τ depends not only on V but also on the path length traversed by the exchange spin wave pulse within the film. On this path we must satisfy the condition $q^2(x)>0$. Because the coordinate of the turning point changes as the frequency and magnetic field vary, the increase in group velocity can be compensated by an increase in path length, so that τ(H) will increase. The rate of displacement of the turning point as H or ω vary is determined by the profile $4\pi M(x)$. For a given profile, the time delay can be calculated from the relation

$$\tau(\omega)=\frac{\partial\varphi}{\partial\omega}, \tag{10}$$

where φ is the phase shift of the wave determined from Eq. (6) and one of the dispersion relations (3) or (8). (For the case of a tangential field, the integration in (6) goes over the segment $d<x<L$.) On the other hand, without recovering the profile we can estimate the delay time directly from the spin-wave resonance spectrum. From (10) it follows that

$$\tau\simeq\frac{\varphi_{n+1}-\varphi_n}{\omega_{n+1}-\omega_n}=\frac{2\pi}{\omega_{n+1}-\omega_n}=\frac{1}{\Delta f}, \tag{11}$$

where Δf is the frequency difference between adjacent spin-wave resonance peaks. The functions $\tau(\omega)$ constructed in this way are shown in Fig. 6. Experiments in which the pulses were observed confirm these estimates. The only exceptions are certain data obtained in a tangential field. Thus, in Fig. 6 the segments of the curves for $\tau>250$ ns are associated with a sharp drop in the amplitude of the delayed pulse (trace 5 of Fig. 5) and eventually its disappearance. This is probably associated with strong dispersive pulse-spreading. In normally magnetized films, the delay time depends weakly on frequency (see Fig. 6); consequently no significant distortion of the pulse shape is observed, as trace 7 of Fig. 5 shows.

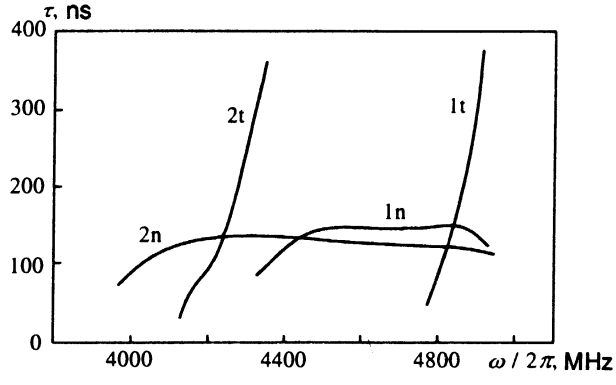

FIG. 6. Dependence of time delay on frequency for samples 1 and 2, computed from the corresponding spectra shown in Fig. 2.

Thus, the frequency dependences of the time delay that we obtain can be explained using the model discussed above. This confirms our assertion that the delay is due to propagation of exchange spin-wave pulses. Let us discuss the question of how the function $\tau(\omega)$ arises in more detail for various profiles of the change in effective magnetization.

Let us choose $M(x)$ in the form of a power-law function: $4\pi M(x)=4\pi M_0-4\pi\Delta M\cdot(x/L)^r$. Then for the case of a normally magnetized film, we obtain from Eqs. (6) and (3):

$$\varphi(\omega)=C(\delta\omega)^{(r+2)/2r},\quad \tau(\omega)=C\frac{r+2}{2r}(\delta\omega)^{(2-r)/2r}, \tag{12}$$

where $\delta\omega=(\omega-\omega_0)$,

$$C=\frac{2L}{\sqrt[r]{\gamma\cdot 4\pi\Delta M}\sqrt{\gamma D}}\int_0^1\sqrt{1-y^r}dy. \tag{13}$$

It is clear that within the frequency band (4) we can obtain frequency dependences of various types. For example, when r=2/3 the delay τ increases linearly with $\delta\omega$, when $r=2$ the delay time is independent of frequency, and for $r>2$ the delay decreases with increasing frequency. Our experiments confirm these conclusions. Figure 7 shows the profile $4\pi M(x)$ for three samples, and also the measured functions $\tau(\omega)$. From the figure it is clear that all three basic types of characteristics for $\tau(\omega)$—increase, decay, and constancy of the delay—can be realized in practice using films with various profiles. Note also that the band of frequencies in which the delayed pulse is observed can exceed 1 GHz. This is due to the large value of the drop $4\pi\Delta M$, which in one film reached 500 G. From (3) we estimate that the wave numbers of the exchange spin waves in such a sample can be around $\sim 3\cdot 10^5$ cm^{-1}.

The functions $\tau(\omega)$ can be analyzed analogously for various profiles $4\pi M(x)$ when the film is placed in a tangential magnetic field. In this case, the analytic expressions for $\tau(\omega)$ obtained are quite cumbersome; however, the calculations are easily performed numerically for any specific form of $M(x)$, by starting from Eqs. (8), (6) and (10). The results of these calculations are in good agreement with the experimental data. We will not pause to discuss them, but note only

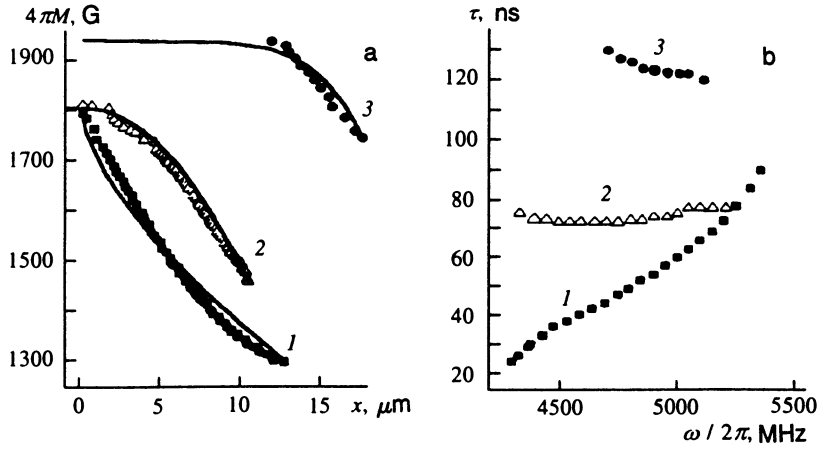

FIG. 7. Profiles of effective magnetization variation (a) for three films with orientation (100) and frequency dependences of the time delay measured on the same films (b). The solid curves *1–3* in Fig. (a) are attempts to approximate the experimental values using power-law functions with exponents $r=2/3$ (*1*), $r=2$ (*2*), and $r=6$ (*3*).

that, as follows from Fig. 6, the behavior of $\tau(\omega)$ is a strong function of what sort of field (normal or tangential) the film is placed in. This shows that it is possible in principle to control the frequency characteristics of the time delay by choosing the angle of magnetization. Meanwhile, from the point of view of practical use of exchange spin waves, it would also be interesting to discuss the possibility of controlling the absolute value of τ for a nondispersive delay line (i.e., for which $\tau(\omega)=$const).

Figure 7 clearly shows that when one of the films we investigated was placed in a normal field, it exhibited a roughly constant value of the time delay over a frequency band with a width of order 1 GHz. Fig. 8(a) shows that the absolute value of τ can be varied within certain limits by applying an external magnetic field H at a rather small angle α to the film normal. As we changed α, we adjusted the magnitude of the magnetic field, which was necessary in order to ensure a roughly constant value of the frequency at which the pulse delays are observed. As is clear from Fig. 8(a), the increase in time delay is accompanied by a significant narrowing of the frequency band in which the delayed pulses exist. In order to explain these experimental data qualitatively, let us discuss a simple model example.

Let an isotropic magnetized film with saturation magnetization M_S be placed in an external magnetic field H directed at an angle α to the normal. Then the equilibrium position of the magnetization makes an angle β with the normal, determined by the relation[24]

$$H\sin(\beta-\alpha)=2\pi M_s \sin 2\beta. \tag{14}$$

The frequency for uniform resonance ω is found from

$$\left(\frac{\omega}{\gamma}\right)^2=H_i[H_i+4\pi M(x)\sin^2\beta], \tag{15}$$

where H_i is the internal magnetic field, and $H_i=H\cdot\sin(\alpha)/\sin(\beta)$. As a model of a nonuniform film, let us consider a structure containing three layers with saturation magnetizations M_{s1}, M_{s2}, M_{s3}, such that $M_{s1}=M_{s2}-\Delta M/2$, $M_{s3}=M_{s2}+\Delta M/2$. Let us use Eq. (14) to find that dependence of the external field on α for which the frequency of uniform resonance (15) in the second layer is constant and equal, let us say, to $\omega_2/2\pi=5$ GHz for all values of the angle α. We then construct (Fig. 8(b)) the angular dependence of the frequency of uniform resonance in layers 1 and 3, using the quantity $H(\alpha)$ we have found as a parameter. We will see that for small angles α the condition $\omega_1>\omega_2>\omega_3$ is fulfilled, while for large α the frequency relation is reversed: $\omega_1<\omega_2<\omega_3$. There exists a range of angles for which all three frequencies are close; furthermore, in this range the resonance frequency of the second layer is the smallest: $\omega_2<\omega_{1,3}$. This example allows us to understand qualitatively

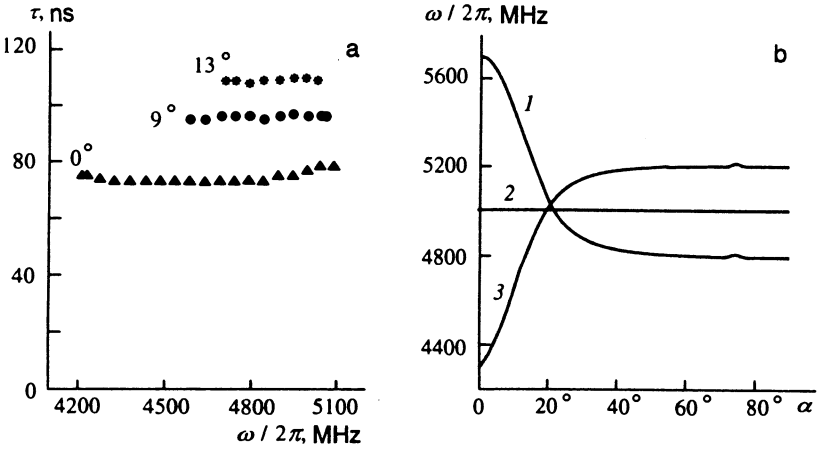

FIG. 8. (a) Measured frequency dependences of the time delay as the direction of the external magnetic field is varied; $H=3355$ Oe for $\alpha=0°$, $H=3140$ Oe for $\alpha=9°$, $H=2995$ Oe for $\alpha=13°$. The sample was a YIG film with orientation (100) and the magnetization profile shown in Fig. 7(a), curve 2. (b) Computed values of the ferromagnetic resonance frequency of a three-layer structure as the angle α varies. The numbers on the curves correspond to the layer labels.

why the band of frequencies where delayed exchange spin wave pulses are observed narrows. Excitation of exchange spin waves is possible only under conditions where a turning point exists. Near this point $q = 0$, so that the excitation frequency of the wave can be found by using the equation for uniform resonance in a layer with a magnetization equal to that at the turning point. Thus, Fig. 8(b) shows that in oblique fields the region of existence of exchange spin waves can turn out to be small even for sizable effective magnetization drops. Furthermore, it is interesting to note that the low-frequency boundary of the exchange spin wave spectrum corresponds to localization of the turning point in the region with large magnetization for a normal field, and one with small magnetization for the tangential field, and in the region with intermediate magnetization for an oblique field.

To summarize this section, we conclude that by using nonuniform YIG films we can bring about excitation of traveling exchange spin wave pulses. As is clear from the ratio of pulse amplitudes in Fig. 5, this excitation is quite efficient—the overall losses for excitation, propagation, and reception of the exchange spin waves are quite small, about 10 dB, for delay times of 100 to 140 ns. Note that the configuration of the external high-frequency field created by the microstrip antenna near the turning point can have a considerable influence on the excitation efficiency. A theory that would allow us to optimize the construction of the transducer does not exist at this time, and this question requires additional investigation. In this paper we note only that our experiments show that the efficiency of excitation of exchange spin waves depends both on the distance between the film and the transducer and on the antenna dimensions.

In the next section, we will discuss distinctive features of the interaction of spin waves with acoustic waves.

5. EXCITATION OF ACOUSTIC WAVES DURING THE PROPAGATION OF EXCHANGE SPIN WAVES

Let us first recall that the forward and reverse conversion of spin and acoustic waves was observed previously in experiments with YIG rods (see, e.g., Ref. 25), This nonuniformity, whose origin was the demagnetization field that exists at the end of a magnetized YIG rod, led to a gradual increase in the wave number of the spin waves to a value $q \sim 10^4$ cm^{-1}, which is sufficient to excite sound at frequencies of ~500 MHz. As we noted in the previous section, in our experiments on excitation of exchange spin waves in nonuniform films we achieved values of q that are an order of magnitude higher than this. Consequently, in our case synchronism between spin and acoustic waves is possible at frequencies from 1 to 10 GHz.

Let us first consider some data that suggest that the magnetoelastic interaction is present in exchange spin wave experiments. In Fig. 9 we show two spin-wave resonance spectra for the same YIG film placed in a normal field H. The spectra, which were taken while scanning the magnetic field, differ in their excitation frequencies ($\omega/2\pi$=7854 Mhz for the first spectrum, and $\omega/2\pi$=10300 Mhz for the second). For purposes of convenient comparison of these two spectra, we show the relative variation of H on this figure; the absolute values of the field H_0 corresponding to the right hand

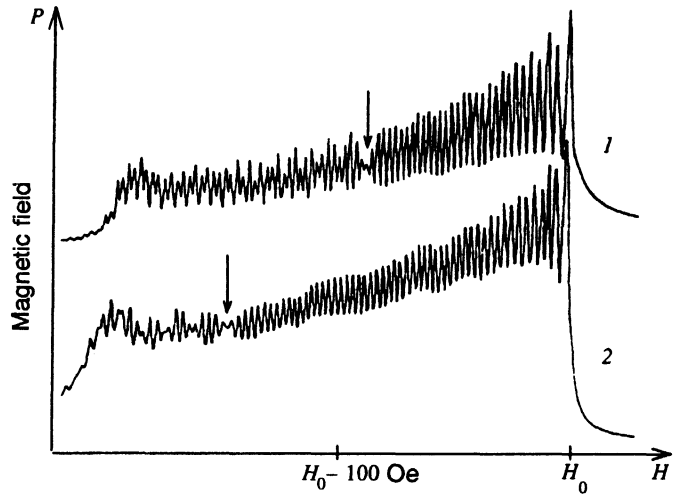

FIG. 9. Dependence of the power absorbed by a YIG film (sample 1) on the magnitude of the external magnetic field for (*1*) $\omega/2\pi$=7854 MHz, H_0=4814 Oe; (*2*) $\omega/2\pi$=10300 MHz, H_0=5587 Oe.

boundary of the spectrum are given in the figure caption. It is clear that the spectra are very similar, and have roughly the same width. However, within each spectrum we can identify two distinct regions. The boundary between the regions is shown by an arrow. To the right of the arrow, the dependence of the absorbed power P on magnetic field has the form of regular oscillations, while on the left the oscillation patterns are distorted. Let us denote the distance between the arrow and the right-hand boundary of the spectrum (i.e., the difference between the fields H_0 and the field corresponding to the beginning of the distortion) by ΔH. Then the basic difference between curves 1 and 2 is a change in the value of ΔH.

Recall that the spectra differ by their excitation frequency. Note also that the analysis given in Section 2 implies that for a normally magnetized film an increase in this frequency should lead only to a parallel shift of the spectrum toward higher fields. A change in the shape of the function $P(H)$ for the model under discussion is not predicted. Hence, we can assume that the distortion of the spectrum is caused by the magnetoelastic interaction, which we have not taken into account in our model. The magnetoelastic interaction should have its greatest impact when the spin and acoustic waves are synchronous, i.e., when their wave numbers are equal. Let us analyze the conditions under which it is possible to achieve this synchronism, and compare the results obtained with the experimental data.

The film we used in these experiments (sample 1) was the one with the effective magnetization profile shown in Fig. 4b. Accordingly, our discussion will be based on the model described in Section 3, i.e., we will assume that $M(x)$ varies monotonically with thickness. We will include the fact that the maximum effective magnetization is located at the film–air boundary, and assume that the elastic parameters of the film do not change with thickness. Then the wave number of the acoustic waves is coordinate-independent and determined by the wave frequency: $q_a = \omega/V_a$, where V_a is the

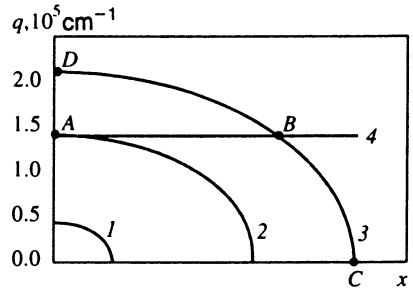

FIG. 10. Variation of the wave number for exchange spin waves along the film thickness. *1*—$\delta H < \delta H^*$; *2*—$\delta H = \delta H^*$; *3*—$\delta H > \delta H^*$. Curve *4*—wave number for acoustic waves.

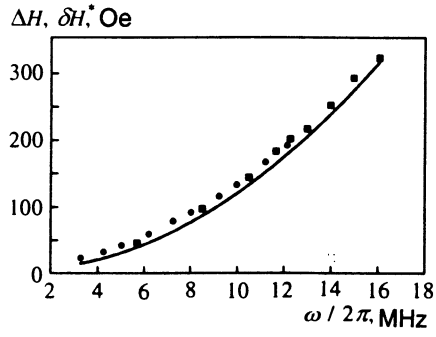

FIG. 11. Computed curve $\delta H^*(\omega)$ and experimental values of $\Delta H(\omega)$ for sample 1 (●) and sample 2 (■).

acoustic wave velocity. The exchange spin wave spectrum, as is clear from (3), lies within the range of fields

$$H_L < H < H_0 , \tag{16}$$

where $H_L = \omega/\gamma + 4\pi M_L$, $H_0 = \omega/\gamma + 4\pi M_0$. As the magnetic field decreases, the turning point shifts toward the boundary $x = L$, while Figure 10 shows that the magnitude of the local wave number for exchange spin waves $q(x)$ increases in the opposite direction. For a fixed magnetic field H, the maximum of $q(x)$ is reached at the boundary $x = 0$, and corresponds to

$$q(0) = \sqrt{\delta H / D}, \tag{17}$$

where δH is the detuning in field from the right-hand boundary of the spectrum: $\delta H = H_0 - H$. When $q(0) = q_a$, a point of synchronism for spin and acoustic waves appears in the film (point A in Fig. 10). This will occur when $\delta H = \delta H^*$, where

$$\delta H^* = D\left(\frac{\omega}{V_a}\right)^2 . \tag{18}$$

As the detuning δH increases, the point of synchronism shifts into the film bulk (point *B*).

Note that the width of the exchange spin wave spectrum equals the drop in effective magnetization $4\pi\Delta M$, as is clear from (16). This determines the maximum frequency ω_{max} for which we can simultaneously satisfy the conditions for the existence of a turning point and a point of synchronism in the film for a given magnetization drop:

$$\delta H^* < 4\pi\Delta M, \quad \omega_{max} = V_a \sqrt{\frac{4\pi\Delta M}{D}} . \tag{19}$$

The experimental value of ΔH corresponds to the width of that portion of the exchange spin wave spectrum that is free from distortion, and the computed value of δH^* is the width of that part of the spectrum where there is no point of synchronism between exchange spin waves and acoustic waves. Let us compare the frequency dependences of these quantities. From Fig. 11 it is clear that they are in good agreement when $V_a = 3.85 \cdot 10^5$ cm/s, which corresponds to the velocity of transverse sound waves in YIG. Consequently, the distortion of the spectrum is due to the interaction of exchange spin waves with transverse acoustic waves.

Note also that in a film with $4\pi\Delta M \simeq 200$ G, the irregular portion of the spectrum is observed up to frequencies ~12 GHz, while in a film with $4\pi\Delta M \simeq 340$ G it is observed up to 16 GHz. This agrees with Eq. (19).

Especially noteworthy is the fact that all the experimental values in Fig. 11 are shifted relative to the computed values in the direction of large ΔH. This shows that distortion (decreased amplitude) of the oscillations of $P(H)$ arises when the point of synchronism is located not at the boundary of the film but at a certain distance from its surface. Let us discuss this question in more detail by examining the structure of the spectral distortion. In Fig. 12, a fragment of the absorption spectrum is shown on an expanded scale. It is clear that the distortion of the spectrum is itself regular in character. The regions where the oscillations are attenuated (shown by arrows) are spaced regularly and separated by bands of intense oscillations of $P(H)$. This behavior of the spectrum can be explained as follows. At the point of synchronism (point *B* in Fig. 10) partial conversion of the exchange spin wave into an acoustic wave takes place, and also the reverse conversion of the acoustic wave into an exchange spin wave. We obtain information about processes that occur within the film from the amplitude of the signal at the turning point (point *C*). This amplitude is determined by the interference of two signals. One is a spin wave which propagates from the turning point to the surface (point *D*) and back. The second wave is a spin wave over the segment *C*–*B* and an acoustic wave over the segment *B*–*A*. At point *A* the acoustic wave is reflected, since $x = 0$ is the film–air boundary. At point *B*, the reflected wave is once again converted back into an exchange spin wave. If we omit the phase jump upon reflection, we can describe the phase shift of the first signal as $\varphi_1 = \int q(x)dx = 2S_{CD}$, where S_{CD} is the area under the

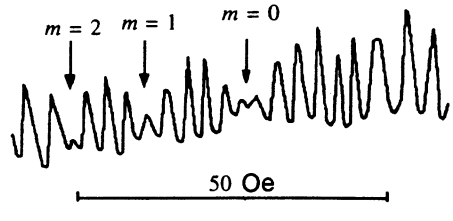

FIG. 12. Fragment of absorption spectrum. Sample 2, $\omega/2\pi = 8521$ MHz.

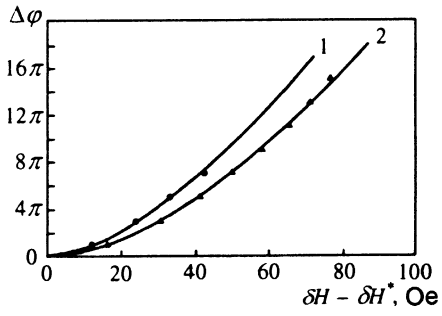

FIG. 13. Dependences of the phase difference on magnetic field. The solid curves are computed values of $\Delta\varphi(\delta H)$; the numbers on the curves correspond to sample number. Experimental values for the first (●) and second (▲) samples are shown for $\Delta\varphi$ determined using Eq. (20).

curve CD. For the second signal $\varphi_2=2S_{ABC}$, where S_{ABC} is the area under the curve ABC. We may assume that the total signal amplitude decreases when the signals add out of phase, i.e.,

$$\Delta\varphi=\varphi_1-\varphi_2=\pi+2\pi m, \quad m=0,1,2... \tag{20}$$

When $\delta H=\delta H^*$, the phase difference equals zero, since the points A and B coincide. As δH increases, the area ABD increases, i.e., $\Delta\varphi$ increases as well. We can calculate the function $\Delta\varphi(\delta H)$ only by knowing the profile of the magnetization change. We performed this calculation for samples 1 and 2, whose profile of saturation magnetization is shown in Fig. 4b. In these films, we measured the magnetic fields corresponding to the portions of the signal curves where the signal amplitudes interfered. We have labeled these zones (as shown in Fig. 12) starting with the label number $m=0$. Then, using Eq. (20), we obtain the experimental values of $\Delta\varphi$ for various magnetic fields. Let us compare them with the computed function $\Delta\varphi(\delta H)$, beginning with the measured magnetic field assigned to the point m=0, i.e., we will use the first experimental point as one end of the calculated curve for $\Delta\varphi=\pi$, and then plot the relative change in measured values of the magnitude of the magnetic field (Fig. 13) assuming that $\Delta\varphi$ varies according to (20). For both films there is good agreement between the experimental and computed values at $\Delta\varphi=3\pi, 5\pi, ...$, i.e., when the waves add out of phase, which validates the correctness of our assertions regarding the interference nature of the signal dips. We emphasize that in this discussion we have assumed that local conversion of exchange spin waves into acoustic waves takes place, that is, the waves interact only in a very narrow layer located near the point of synchronism. In the rest of the film volume, the exchange spin waves and acoustic waves propagate independently of one another. The good agreement between experiment and computed data shows that the use of this model is correct in the films we used, which have large gradients of $M(x)$. Thus, in these films there is no broad region where hybridized magnetoelastic waves exist. At first glance, it seems unlikely that it is possible to have efficient wave conversion in this situation. Nevertheless, the experiments show

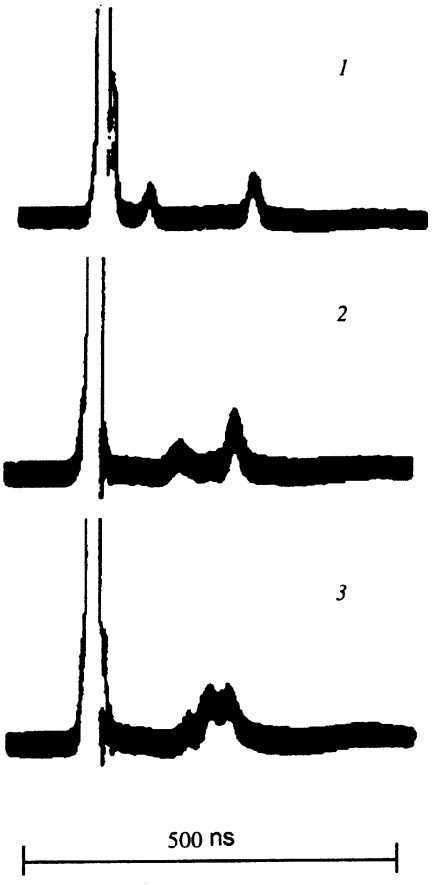

FIG. 14. Time dependence of the envelope of reflected signal for sample 1, $\omega/2\pi=3695$ MHz, normal field; (*1*) $H=2933$ Oe; (*2*) $H=3018$ Oe; (*3*) $H=3031$ Oe.

that the conversion efficiency of exchange spin waves to acoustic waves is quite high. This is revealed with particular clarity in the pulsed regime.

Our procedure here was analogous to what we described in Section 4: we fed a microwave pulse into a normally magnetized YIG film. In Fig. 14 we show the envelope of the pulses reflected from the sample. Two delayed pulses are clearly seen, separated by a time that depends on the value of the external magnetic field. For a certain value of the field, the pulses merge; see Fig. 14, curve 3. We may assume that the presence of the additional pulse is connected with excitation of an acoustic wave. Then the signal with the large time delay is naturally associated with the exchange spin wave propagation. The pulse with the small time delay is associated with a wave that propagates as an exchange spin wave on the sement between the turning point and the point of synchronism, and as an acoustic wave in the layer between the film surface and the point of synchronism. Knowing the effective magnetization profile of this film (Fig. 4b), we can compute the field dependence of the phase shifts of these waves $\varphi_1(H)$ and $\varphi_2(H)$, and use Eq. (10) to find the dependence of the time delay on magnetic field. Comparing the experimental data with the computed data (Fig. 15), we confirm this interpretation of the experiment. However, it is clear from Fig. 14 that the amplitudes of the delayed pulses

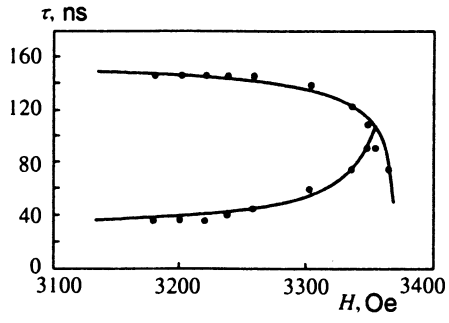

FIG. 15. Dependence of the time delay on magnetic field for sample 1, $\omega/2\pi=3698$ MHz, normal field. The solid curves are computed values of τ, the dots are experiment.

are comparable. Consequently, a significant fraction of the energy of the exchange spin wave pulses is converted into acoustic waves.

It should be noted that effective reflection of acoustic waves is observed only at the air–film boundary. The surface $x=0$ which corresponds to the maximum effective magnetization, could also have been located at the film–substrate boundary. (This situation is realized for films with the magnetization profile shown in Fig. 7(a)). Then the acoustic wave radiates into the bulk of the substrate, and no reflected pulse is observed. However, an additional delayed pulse appears when these films are placed in a tangential magnetic field, since the exchange spin waves and acoustic waves propagate toward the boundary with the smaller value of $4\pi M(x)$ in this case, see Fig. 3(c).

6. CONCLUSION

These experiments show that:

1. There exist YIG films that are simultaneously low-loss in the microwave region and appreciably nonuniform in their magnetic parameters with respect to thickness. In these films, effective excitation and propagation of exchange spin waves is possible with $q\sim 3\cdot 10^5$ cm^{-1};

2. The propagation of exchange spin waves along the thickness of these nonuniform films can be valuable in applications. This is because it is possible to obtain any required dependence of time delay on frequency by choosing the right nonuniformity profile, and also the magnitude and direction of the external magnetic field. There exist YIG films with qualitatively different nonuniformity profiles, which ensures that characteristics for $\tau(\omega)$ can be obtained that are of most interest in practice;

3. The use of nonuniform YIG films for excitation of exchange spin waves allows us to investigate the mutual conversion of spin and acoustic waves at high frequencies. At a point of synchronism of exchange spin waves and acoustic waves, the mutual conversion efficiency of these waves is high, even when the conditions of synchronism are satisfied only in a spatially narrow layer.

The analysis given here shows that the spatial scales on which the properties of the medium should vary appreciably in order to ensure excitation of short-wavelength exchange spin waves are units to tens of microns. This is because in order to obtain waves with large values of q it is first necessary to have a significant change in the parameters, and secondly to ensure fast conversion of the wavelength (within a time of order or smaller than the relaxation time). Thin-film structures can be made that satisfy these requirements, in particular YIG films.

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