Parametric excitation of spin waves by spatially localized pumping of tangentially magnetized yttrium iron garnet films

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An experimental investigation has been made of the processes of parametric excitation of spin waves in tangentially magnetized epitaxial yttrium iron garnet films by pumping with a microwave field localized inhomogeneously in space. The inhomogeneity was created by a microstrip electrode and its scale was of the order of $\approx 100\,\mu$m. The magnetizing field dependences of the parametric excitation threshold and the excitation efficiency were oscillatory due to the multimode structure of the spin wave spectrum in the film. Three series of oscillations were separated and attributed to the excitation of different groups of spin waves. The observed field dependence of the threshold made it possible to excite spin waves selectively corresponding to specific points in the spectrum. The pumping inhomogeneity increased the degree of selection of the parametrically excited waves because it strongly increased the thresholds for waves with a nonzero group velocity and these waves were displaced from the pumped zone.

Our aim was to investigate the characteristic features of parametric excitation of spin waves in yttrium iron garnet (YIG) films subjected to inhomogeneous pumping created by a microstrip converter. Linear (nonparametric) excitation of spin waves by a microstrip converter is known to be seriously limited with respect to the wave numbers q which can be excited: its efficiency falls steeply in the range $q > \pi/L$, where L is the converter strip width. On the other hand, parametric processes in ferromagnets can be used as sources of short-wavelength spin waves, which extends greatly the usefulness of these processes in experimental studies of magnetic materials.

Let us mention some of the known features of parametric excitation of spin waves in films. In the case of bulk samples (for example, spheres) slightly exceeding the threshold causes excitation of spin waves with a definite wave number q governed by the polar angle θ (θ is the angle between the direction of the magnetic field $\mathbf{H}$ and of the wave vector $\mathbf{q}$) and by different azimuthal angles φ (Ref. 1). In the case of tangentially magnetized films the strong shape anisotropy results in a much greater selectivity of the excited waves with respect to their propagation angles, but this approach results in simultaneous excitation of spin waves with different values of q. This is due to the multimode nature of the spectrum of spin waves in films. Different modes have different structures of the variable magnetization across the film thickness and, consequently, different dispersion laws. Therefore, if a sample is subjected to microwave pumping of frequency f_p, spin waves of frequency $f = f_p/2$ can be generated in the first parametric excitation zone and each mode is characterized by its own wave number. Moreover, the multimode nature results in lifting of the degeneracy of the frequency of the excited spin waves. In fact, if a pump quantum splits into two magnons corresponding to different modes, the frequencies of spin waves are $f = f_p/2 \pm \Delta f$, where the detuning Δf is governed by the mutual positions of the dispersion curves of the excited modes.

Experimental investigations of parametric excitation of spin waves in films have been proceeding along two avenues. In the first avenue a microwave pump is applied to a microstrip converter where a magnetostatic wave is excited linearly which propagates along the film. Three-magnon decay of a magnetostatic wave results in generation of short spin waves.[2–5]

The second avenue is characterized by parametric excitation of spin waves in a weakly inhomogeneous resonator field subjected to longitudinal pumping ($\mathbf{h}\|\mathbf{H}$, where $\mathbf{h}$ is a microwave magnetic field). It has been found[6–8] that in the case of tangentially magnetized YIG films the dependence of the threshold pump field h_{th} on H is oscillatory. Minima of $h_{\text{th}}(H)$ correspond to spin-wave resonance fields.

Parametric excitation of spin waves by spatially inhomogeneous longitudinal pumping was reported in Ref. 9: the pump radiation was generated either in a compact dielectric resonator (~ 1 mm) pressed against a film or in a converter formed by a wire 0.15 mm in diameter. The threshold for excitation of spin waves depended on the group velocity v_{gr} of the excited wave. An increase in the degree of localization of the pump increased the threshold for the waves with $v_{\text{gr}} \neq 0$, because the excited waves were driven out of the inhomogeneously pumped zone. However, oscillatory dependences $h_{\text{th}}(H)$ were not reported in Ref. 9. This was clearly due to the idiosyncrasies of the experimental method used, namely determination of the threshold from a split in the pump pulse and the inability to scan continuously the field H.

The present paper reports an investigation of parametric excitation of spin waves when microwave pumping was provided by a microstrip converter, so that the pump field was less homogeneous than in Ref. 9: the scale of the spatial variation was $\sim 100\,\mu$m. We observed and analyzed two new series of oscillations of $h_{\text{th}}(H)$ and considered new features of the known series[6–8] manifested in the case of inhomogeneous pumping. Some of the experimental results were reported partly in an earlier paper.[10]

1. EXPERIMENTAL METHOD

Our experiments were carried out on YIG films of thickness $d = 4$–$30\,\mu$m were grown epitaxially on gadolinium gallium garnet substrates with the (111) orientation.

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These films were subjected to a magnetizing field **H** tangential to their plane and were pressed against a microstrip converter $\sim 50\,\mu$m wide deposited on a Polikor (polycrystalline leucosapphire) substrate. The field **H** was a sum of a static field $\mathbf{H}_0$ and of an alternating field $\mathbf{H}_\sim$ ($\mathbf{H}_0 \| \mathbf{H}_\sim$), which was of 50 Hz frequency. The converter was subjected to microwave pumping of power P_{inc}. The pump frequency in a given magnetic field was above the upper edge of the spectrum of dipole spin waves. The coupling of the microwave field localized near the converter at a distance of $\sim 100\,\mu$m to short-wavelength exchange spin waves, of wavelength $< 1\,\mu$m, was weak. Microwaves were therefore excited very weakly in the linear regime. The position of the limit of the dipole spectrum and the absence of linear excitation of spin waves were checked using a second converter located parallel to the first. Hence the loss of energy because of the emission of spin waves was negligible and the microwave field existed only in the near-field zone of the converter.

The power P_{refl} reflected from the microwave converter passed through a circulator to a measuring channel where after detection it was applied to a selective amplifier operated in the wide-band regime. This amplifier did not transmit the constant component of P_{refl}. We investigated the magnetic-field dependence of the reflected power P_{refl}, which varied during one period of scanning with the magnetic field. This was done for different incident powers P_{inc}.

Typical $\delta P_{refl}(H)$ dependences are plotted in Figs. 1 and 2. Below the parametric excitation threshold $\delta P_{refl}(H)$ exhibits a smooth slowly varying behavior (Fig. 1a). When the incident power was increased, the threshold of parametric excitation of spin waves was reached, which manifested itself as a change in $\delta P_{refl}(H)$. When the dependence of the threshold power $P_{refl}(H)$ was oscillatory, the threshold was first reached in certain magnetic fields. The results obtained in this situation were plotted in Fig. 1b and revealed narrow dips in $\delta P_{refl}(H)$. The number of dips increased and widened as a function of the power (Fig. 1c), so that the parametric excitation threshold was exceeded in a wider range of the magnetic field. Further increase in the power (Fig. 1d) produced parametric excitation of spin waves practically throughout the full range of scanning of **H**. Only narrow zones (upward peaks) remained where P_{th} was not reached. A still further increase in the incident power showed that a noise signal was superimposed on $\delta P_{refl}(H)$, but even then the efficiency of parametric excitation varied with the field H, which made it possible to observe $\delta P_{refl}(H)$ which oscillated with the magnetic field.

A different characteristic experimental situation is demonstrated by the results of Fig. 2. Figure 2a corresponds to the absence of parametric excitation. In the situation illustrated in Fig. 2b the parametric excitation occurred only in a part of the scan of H, whereas in Fig. 2c it happened throughout the full range of the field. Beyond the parametric excitation threshold the dependences $\delta P_{refl}(H)$ were oscillatory, which was again associated with oscillations of the efficiency of parametric excitation of spin waves.

The following procedure was used to interpret the observed patterns. A magnetic field marker (representing an NMR signal from a magnetic induction meter) was applied to the second input of an oscilloscope. The pump frequency was measured with the aid of an electronic frequency meter. The next steps were as follows: a) at a fixed pump frequency

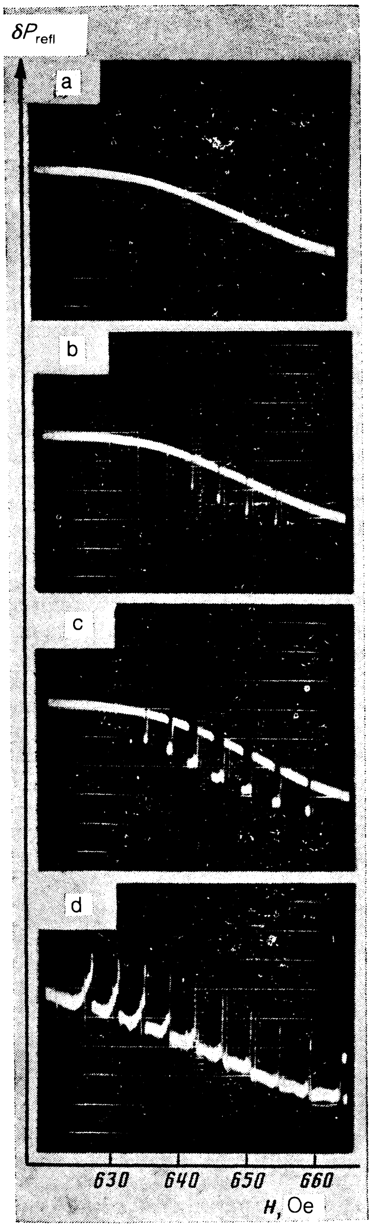

FIG. 1. Dependence $\delta P_{refl}(H)$ for a film $d = 30\,\mu$m thick subjected to pumping at $f_p = 5090$ MHz: a) $P_{inc} = 69\,\mu$W; b) $73\,\mu$W; c) $79\,\mu$W; d) $98\,\mu$W.

f_p the separation ΔH between neighboring dips was measured on the magnetic field scale (Fig. 1b) or the oscillation period was determined (Fig. 2c); b) when the magnetic field H was fixed, the frequency spacing of the dips was determined: $\Delta f_p = |f_n - f_{n+1}|$ [f_n and f_{n+1} are the pump frequencies corresponding to the coincidence of the nth and $(n+1)$th peaks with the magnetic field marker]; c) the ratio $\beta \equiv \delta f_p / \delta H$ was determined, where δH is the shift of a specific dip due to a change in the pump frequency of δf_p.

2. EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

Our investigations showed that there were at least three series of oscillations $\delta P_{refl}(H)$ of the power corresponding to parametric excitation of different groups of spin waves.

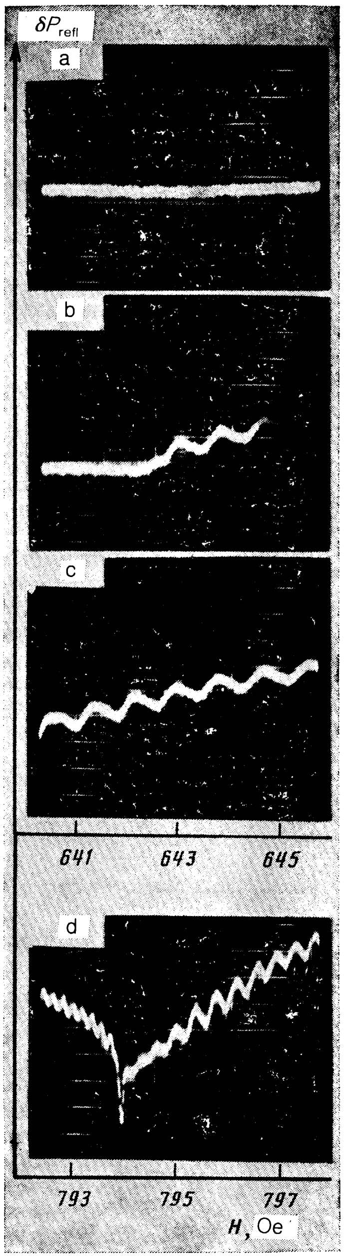

FIG. 2. Dependence $\delta P_{refl} = (H)$ for a film of thickness $d = 12.4\,\mu$m. The thickness of the structure was $D = 545\,\mu$m and the pump frequency was $f_p = 5000$ MHz: a) $P_{inc} = 0.62$ mW; b) 0.67 mW; c) 0.7 mW; d) 0.35 mW.

1. The first series was observed just above the threshold and was manifested by narrow dips similar to those shown in Fig. 1 and located in fields $H < H_c$, where H_c is the homogeneous resonance field of the tangentially magnetized film at $f = f_p/2$. This series had several hundred peaks; a general idea of the number and distribution can be obtained from Fig. 3. In explaining this figure one should mention that in the first series the average threshold power increased as H was reduced. Therefore, we recorded the maximum number of peaks by using fairly high values of P_{inc} (~ 10 mW). This P_{inc} corresponded to the attainment of the parametric excitation threshold at the lowest magnetic fields. It was much higher than the threshold power in higher fields. Therefore, in higher fields we observed a greater excess above the threshold, which resulted in superposition of a noise signal on the oscillations of $\delta P_{refl}(H)$.

This pattern was recorded in a wide range of magnetic fields by a somewhat different method. A static magnetic field H_0 was varied linearly at a low rate (~ 40 Oe/min) and the amplitude of the oscillatory component $H_{\sim}$ (of frequency ~ 30–70 Hz) was quite low (~ 0.1 Oe). The signal reflected from the converter passed through a microwave detector and a lock-in detector; it was recorded by an automatic plotter. This method allowed us to plot the derivative $\partial P_{refl}/\partial H$ free of the noise that appeared well above the threshold.

A characteristic feature of the first series was that ΔH increased as H was reduced, and the value of β was ~ 7–8 MHz/Oe at a pump frequency $f_p = 5$–5.6 GHz. By analogy with Refs. 6–8 we could expect the peaks of the first series to be due to the excitation of spin waves in spin-wave resonance (SWR) fields. In fact, in the presence of free spins on the surface the SWR frequencies satisfy the relationship[11]

$$\omega_n^2 = \left[\omega_H + \omega_M + \alpha\omega_M\left(\frac{\pi n}{d}\right)^2\right]\left[\omega_H + \alpha\omega_M\left(\frac{\pi n}{d}\right)^2\right], \quad (1)$$

where we have $\omega_H = \gamma H$, $\omega_M = 4\pi$, and $\gamma = 2\pi \times 2.8$ MHz/Oe; $n = 0,1,2...$ is the number of the SWR; $4\pi M$ is the saturation magnetization; and α is the inhomogeneous exchange constant. Hence, we found the field H_n corresponding to the nth SWR peak at a given frequency ω:

$$H_n = \left[\left(\frac{4\pi M}{2}\right)^2 + \left(\frac{\omega}{\gamma}\right)^2\right]^{1/2} - \frac{4\pi M}{2} - 4\pi M\alpha\left(\frac{\pi n}{d}\right)^2. \quad (2)$$

The difference $\Delta H = H_n - H_{n+1}$ obeyed

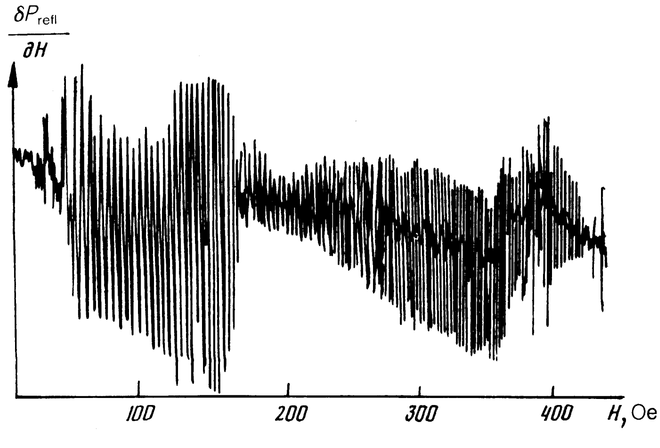

FIG. 3. Dependence of $\partial P_{refl}/\partial H$ on the magnetic field for a film of thickness $d = 20\,\mu$m pumped at a frequency $f_p = 5617$ MHz; $P_{inc} = 10$ mW.

$$\Delta H = \frac{4\pi M\alpha}{d^2}\pi^2(2n+1). \quad (3)$$

Therefore, ΔH increased with n and, consequently, with reduction in H. When the frequency ω was altered by $\delta\omega$, the SWR fields shifted by an amount δH, so that

$$\delta\omega = \frac{\partial\omega}{\partial H}\delta H = \xi\,\delta H, \quad (4)$$

$$\xi = \frac{\partial\omega}{\partial H} = \frac{\gamma^2}{\omega}\left[\left(\frac{4\pi M}{2}\right)^2 + \left(\frac{\omega}{\gamma}\right)^2\right]^{1/2}. \quad (5)$$

Hence, bearing in mind that $\omega = 2\pi(f_p/2)$, we obtain the expression for β describing parametric excitation of spin waves at SWR points:

$$\beta = \frac{\delta f_H}{\delta H} = \frac{\xi}{\pi} = \frac{\gamma^2}{\pi^2 f_p}\left[\left(\frac{4\pi M}{2}\right)^2 + \left(\frac{\omega}{\gamma}\right)^2\right]^{1/2}. \quad (6)$$

Substituting in Eq. (6) the characteristic frequencies $f_p = 5000$ MHz and the saturation magnetization $4\pi M = 1750$ G we found that the calculated value $\beta \approx 7.8$ MHz/Oe agreed well with the experimental results.

It was confirmed that the peaks of the first series were due to parametric excitation of spin waves in SWR fields. A similar effect was observed earlier[7,8] as a result of homogeneous longitudinal pumping. A special feature of our experiments was the excitation by a spatially localized microwave field, which made it possible to excite parametrically SWRs with high numbers ($n \sim 200$–300) employing an ordinary klystron oscillator with an output power of at most 10 mW. It should be pointed out that the relationship (3) could be used to identify the numbers n corresponding to the experimentally observed peaks. This estimate showed that in the case of thick films the first few tens of SWR modes were not resolved. It was possible to distinguish the peaks when the separation between them was $\geqslant 0.5$ Oe, i.e., when this separation exceeded the spin-wave relaxation parameter.

2. The second series of oscillations of the power $\delta P_{\text{refl}}(H)$ was observed in fields $H > H_c$. The characteristic form of $\delta P_{\text{refl}}(H)$ is shown in Fig. 1. The peaks in the second series were equidistant, i.e., ΔH was almost independent of H. On the other hand, the values of ΔH for films of different thickness were very different. We found that β amounted to ≈ 5.6 MHz/Oe.

These features of the dependence $h_{\text{th}}(H)$ had not been observed before in the range $H > H_c$. The appearance of the second series could be explained by noting that in fields $H > H_c$ there was a range of existence of bulk spin waves (reverse bulk magnetostatic waves observed in the dipole approximation[12]). We could assume that parametric excitation generated waves propagating approximately along the magnetic field direction (in agreement with the results reported in Ref. 13). The dispersion laws of these waves, plotted allowing for the dipole–dipole and exchange energies, are shown schematically in Fig. 4. For each spin-wave mode there was a point on the dispersion curve where the group velocity v_{gr} vanished. The field of the microstrip converter was spatially inhomogeneous so that we could assume that if there were spin waves with $v_{\text{gr}} = 0$ at the frequency $f = f_p/2$, the parametric excitation threshold was lower than when there were no waves at a given frequency with $v_{\text{gr}} = 0$. The peaks in the dependence $\delta P_{\text{refl}}(H)$ then corresponded to the fields in which the frequency $f = f_p/2$ was equal to the minimal frequency of the dispersion curve of any one mode.

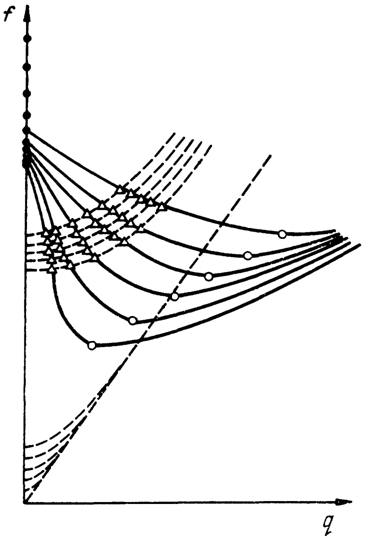

FIG. 4. Schematic dispersion laws of spin waves (continuous curves) and Lamb waves (dashed curves): ●) spin wave resonance frequencies; ○) points with $v_{\text{gr}} = 0$; △) points of intersection of dispersion curves of spin and Lamb waves.

The proposed explanation was tested by calculating the dispersion laws of spin waves propagating along the magnetic field in a tangentially magnetized film. The calculations were carried out numerically using the dispersion relationships in the form of infinite mathematical series similar to those obtained in Ref. 14. The results of these calculations demonstrated that the difference between the minimal frequencies of two adjacent modes $\Delta\omega^{\min} = \omega_{n+1}^{\min} - \omega_n^{\min}$ depended weakly on the number n and was governed primarily by the film thickness d. The value of β for parametric excitation spin waves with $v_{\text{gr}} = 0$ should be ≈ 5.6 MHz/Oe, which was again in good agreement with the experimental results. A comparison of the values of Δf_p found experimentally, obtained for different values of the thickness d, with the calculated dependence $2\Delta\omega^{\min}(d)$ also confirmed (Fig. 5) that the second series of peaks exhibited $\delta P_{\text{refl}}(H)$ represented parametric excitation of spin waves with $v_{\text{gr}} = 0$.

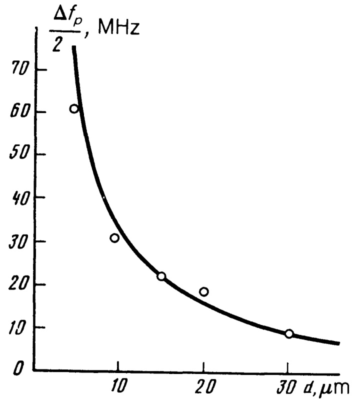

FIG. 5. Dependence of Δf_p on the film thickness d: ○) experimental points for peaks of the second series; the continuous curve is calculated.

3. The third series of oscillations were practically harmonic (Fig. 2) and were located, like the second series, in fields $H > H_c$. However, the period ΔH was considerably less for the third series than for the second and amounted to ~ 0.4–1 Oe. The value of ΔH depended strongly on the magnetic field. In certain magnetic fields the period changed abruptly (Fig. 2d). The value of β also depended on the magnetic field and was less than for the first and second series.

The minimal value of ΔH for the third series was an order of magnitude less than the width of the ferromagnetic resonance line of the investigated films. Hence we concluded that this third series was the result of interaction between spin waves and higher-Q oscillations in the spectrum of excitation of the solid (acoustic waves). Out of the great variety of acoustic waves we shall consider primarily the Lamb waves of a film–substrate structure since the interaction of spin and Lamb waves is the most probable reason for the appearance of oscillations of $\delta P_{\text{refl}}(H)$ characterized by low values of ΔH. In fact, for a standard structure thickness $D \sim 500\,\mu\text{m}$ with the velocity $v_{st} = 3.57 \times 10^5$ cm/s of transverse sound in gadolinium gallium garnet there were about 700 Lamb waves at the frequency of parametrically excited spin waves $f = f_p/2 = 2500$ MHz (the dispersion curves of the Lamb waves had a much denser distribution than that shown in Fig. 4). The interaction between the spin and Lamb waves was strongest at the points where their dispersion curves intersect, which resulted in hybridization of the waves and modification of the dispersion curves. The formation of the third series could therefore be described as follows. The presence of a large number of the dispersion curves of the Lamb waves produced a series of the wave numbers of the spin and Lamb waves at the frequency $f = f_p/2$. The efficiency of parametric excitation of spin waves depended on whether or not a given wave number of an excited spin wave coincided with a wave number of one of the Lamb waves.

Figure 6 shows a comparison of the experimentally determined dependence $\Delta H(H)$ with the calculated values of ΔH deduced on the basis of the proposed model. The numbers of the Lamb wave modes increased with ΔH. It was assumed that the presence of adjacent oscillations corresponded to intersection of the nth spin wave mode with mth and $(m+1)$th Lamb wave modes. It is clear from Fig. 6 that the abrupt change in the period occurred at the transition from excitation of the nth to the $(n+1)$th spin wave mode.

This mechanism accounted for the observed magnetic field dependence of the coefficient β. An increase in the pump frequency by δf_p increased the number of Lamb waves of frequency $f_p/2$ by an amount Δq_{LW}. The change in the wave number increased as the group velocity of Lamb waves decreased. At a given frequency the group velocity of these waves was less for the higher modes. On the other hand, an increase in the frequency of spin waves exhibiting a falling region of the dispersion curve reduced the spin wave number by an amount Δq_{SW}. Therefore, the spin and Lamb wave numbers could be made equal by increasing the magnetic field by some δH. The value of δH should correspond to a change in the spin-wave number q by an amount $\delta q = \Delta q_{\text{SW}} + \Delta q_{\text{LW}}$. Therefore, δq and δH should increase with the Lamb wave number, i.e., for a given spin wave number they should increase with reduction in H. Consequently, the coefficient $\beta \equiv \delta f_p/\delta H$ should vary with H. A comparison of the experimental and calculated values of β in the range of magnetic fields corresponding to the excitation of the fifth spin-wave mode (Fig. 6) is shown in Fig. 7.

We conclude by considering the mechanisms of parametric excitation of spin waves in the case when the pump is created by a microstrip converter. The microwave field **h** in such a converter has a component normal to the plane of the film, as well as a component lying in the plane of the film. Therefore, in a tangentially magnetized film there is always a pump component $h_\perp$ perpendicular to the static magnetic field, and as a rule **h** also has a component $h_\parallel$ along the magnetic field ($h_\parallel = 0$ if the strip is oriented along **H**). It follows from the above experiments that if $h_\parallel = 0$ holds, it is not possible to observe the first series at the pump power employed (~ 10 MW). Thus, the main role in the excitation of the first series is played clearly by the mechanism proposed by Schlomann,[15] i.e., excitation by longitudinal pumping.

The second and third series were observed also when the strip was oriented along **H**. Hence, it follows that spin waves can be excited in accordance with the mechanism discussed by Shul:[16] $h_\perp$ causes forced precession of the magnetization at the pump frequency and this in turn results in parametric excitation of spin waves in the first zone.

The agreement between the experimentally observed oscillation period in the second series with that calculated for $\mathbf{q} \| \mathbf{H}$ shows that the direction in which parametric spin waves propagate is close to **H**. One the other hand, these directions do not coincide exactly, because the second series was observed also when the strip was oriented along **H** and

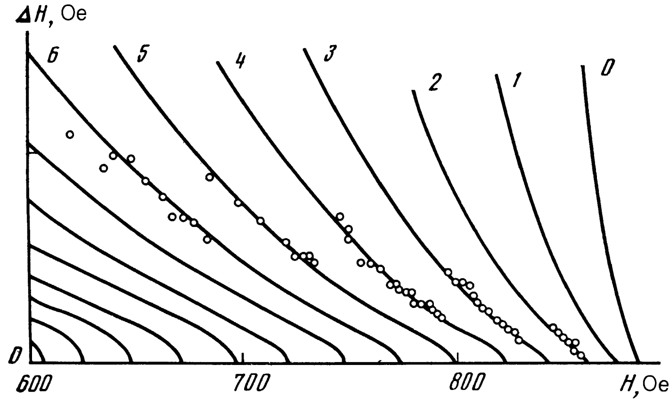

FIG. 6. Dependence $\Delta H(H)$ obtained for the third series of oscillations of $\delta P_{\text{refl}}(H)$: ○) experimental points; the continuous curves are calculated the numbers alongside the curves are the numbers of excited spin-wave modes. The frequency f_p and the parameters of the structure are the same as in Fig. 2.

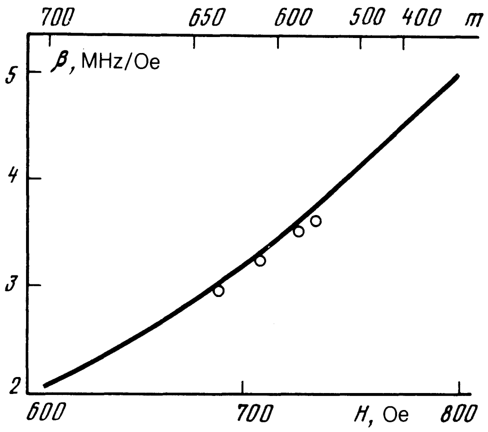

FIG. 7. Dependence of the coefficient β on H: O) experimental points; the continuous curve is calculated. The frequency f_p and the structure parameters are the same as in Fig. 2. The upper scale gives the numbers of the Lamb wave modes.

the excitation threshold could depend on v_{gr} only if spin waves were carried away from the pump localization region.

We assumed so far that the frequencies of spin waves formed as a result of decay of pumping were degenerate. It was thus assumed that decay produces two magnons belonging to the same spin wave mode. This assumption is not always justified.[4,5] If we assume that the second series is due to decay into nondegenerate waves characterized by $v_{gr} \to 0$, the period ΔH of the function $\delta P_{\rm refl}(H)$ remains unchanged, but the calculated positions of the fields at the peaks shift by an amount $\Delta H/2$. It is possible to fix reliably the presence or absence of such a shift if all the parameters of the material are known accurately (and this includes the saturation magnetization, the anisotropy field, and the inhomogeneous exchange constant) and, moreover, it is necessary to know the angles of propagation of spin waves generated when the threshold is exceeded slightly. This task meets with considerable experimental difficulties. Therefore, the question of whether degenerate or nondegenerate decay has the lower threshold would require a special investigation. All that we can say is that interpretation of the second series of oscillations as a manifestation of creation of waves with $v_{gr} \to 0$ applies to both cases.

3. CONCLUSIONS

These experiments demonstrate the following:

1. In spite of the multimode nature of the spectrum of spin waves in films, it is possible to excite parametrically in a selective manner separate groups of spin waves. An increase in the degree of relaxation is aided by the use of the spatially homogeneous (localized) microwave pumping.

2. An analysis of the processes of parametric excitation of spin waves in ferrite films should allow for the dipole–dipole and exchange energies. The situation is quite different from linear excitation of propagation of spin waves, when in the case of considerable thicknesses ($d \geqslant 10\ \mu$m) in the absence of spin pinning on the surface we can ignore the exchange energy. On the other hand, a model of essentially exchange spin waves in an infinite medium is also not very convincing. The observation of the second and particularly of the first series in the dependence $\delta P_{\rm refl}(H)$ shows that in the case of parametric excitation of spin waves in films the size effects are manifested even when the film thickness is tens or hundreds of times greater than the characteristic period of the distribution of the oscillatory magnetization of spin waves across the film thickness.

3. In the case of YIG films grown on plane-parallel gadolinium gallium garnet substrates the processes of parametric excitation of spin waves may be influenced greatly by the intersection of these waves with high-order Lamb waves in a film–substrate structure.

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