Investigation of the hard parametric excitation of magnons in antiferromagnetic $FeBO_3$

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An investigation was made of the phenomenon of "hardness" of paramagnetic excitation of magnons by the method of parallel pumping of the easy-plane weak ferromagnet $FeBO_3$. The experiments were carried out in the temperature range 1.2–7 K at pump frequencies of 35.6 and 26.3 GHz. An investigation was made of the influence of nonequilibrium magnons of other frequencies and of natural magnetoelastic oscillations excited in a sample on the hardness of the parametric excitation of magnons. The results obtained led to the conclusion that the hardness was due to extrinsic processes of relaxation of parametrically excited magnons.

Morgenthaler[1] and Schlömann, Green, and Milano[2] predicted in 1960 and confirmed experimentally, in the case of ferrimagnetic yttrium iron garnet (YIG),[2] the phenomenon of parallel pumping, meaning parametric excitation of magnons by an alternating magnetic field **h** directed along the magnetization of the magnetic material. Such a parametric instability can be regarded as decay of one photon at the pump frequency ω_p into two magnons with wave vectors **k** and $-$ **k** and with frequencies $\omega_{\mathbf{k}} = \omega_{-\mathbf{k}} = \omega_p/2$. The parametric excitation of magnons in antiferromagnets with the easy-plane magnetic anisotropy was observed experimentally later[3,4] and explained theoretically in Ref. 5. Like any other parametric process, this instability has a threshold. The threshold or critical microwave magnetic field h_c at which this parametric instability appears is directly proportional to the relaxation parameter $\Delta\omega_{\mathbf{k}}$ of the excited magnons;

$$\Delta\omega_{\mathbf{k}} = h_c V_{\mathbf{k}}. \quad (1)$$

The proportionality coefficient $V_{\mathbf{k}}$ represents the coupling between the microwave pump field and the excited magnons.

Experimental investigations of the kinetics of the parametric excitation of magnons have established that the process can be "hard" both in ferrites[6] and in easy-plane antiferromagnets.[7,8] This means that the threshold microwave field h_{c1} at which the parametric instability appears exceeds the minimum field h_{c2} necessary to maintain this instability and, therefore, a steady parametrically excited state of the spin system. In a quantitative description of this effect it is convenient to introduce the hardness coefficient $\xi = (h_{c1} - h_{c2})/h_{c2}$. The hardness effect is usually explained by postulating that the parametric excitation process involves saturation of some magnon relaxation mechanism, which reduces the relaxation parameter by an amount $\delta\omega_{\mathbf{k}}(n_{\mathbf{k}})$, dependent on the magnon density $n_{\mathbf{k}}$. The part of the relaxation parameter $\delta\omega_{\mathbf{k}}(n_{\mathbf{k}})$ which is then excluded is called the negative nonlinear damping. Le Gall *et al.*[9] showed that this negative nonlinear damping may be due to three-magnon processes of coalescence of parametrically excited and thermal magnons. Such a process may suppress part of the relaxation because of a reduction in the number of magnons participating in the coalescence process but not related to microwave pumping (the number of such magnons in the absence of microwave pumping is equal to the equilibrium thermal number). This hardness mechanism was considered theoretically for ferromagnets by L'vov.[10] He established a good quantitative agreement with the results of experimental investigations of the process of parametric excitation of magnons in YIG (Ref. 6).

In the case of easy-plane antiferromagnets the three-particle processes of coalescence of parametrically excited magnons with other magnons or different quasiparticles also make a considerable contribution to magnon relaxation. Contributions made to the negative nonlinear damping by the three-magnon coalescence process and by the process of coalescence involving phonons had been calculated theoretically in Refs. 11 and 12. However, when specific parameters of the investigated substances are substituted into the formulas of Refs. 11 and 12, the values of $\delta\omega_{\mathbf{k}}$ obtained in this way are at least an order of magnitude smaller than those found experimentally. Relaxation of magnons by interaction with magnetic impurities was investigated theoretically in Refs. 13 and 14. It was demonstrated there that this impurity relaxation process can also give rise to negative nonlinear damping. However, the temperature and field dependences of the suppressed component of the relaxation obtained in these investigations did not agree with the experimentally determined dependences.

We shall now mention the common features of the hardness effect observed in easy-plane antiferromagnets $CsMnF_3$, $MnCO_3$, $CoCO_3$, $FeBO_3$ and $CsMnCl_3$. Firstly, the hardness coefficient ξ rises rapidly as a result of cooling and becomes considerable at ≈ 1.2 K (in the case of $CsMnF_3$ and $MnCO_3$ it amounts to $\xi \approx 0.4$–0.7, whereas in the case of $CoCO_3$ and $FeBO_3$ it is $\xi \approx 10$). Secondly, the temperature and field dependences of the steady-state part of the relaxation parameter of parametric magnons deduced from the threshold field h_{c2} are (at least in the case of three investigated magnetic materials $MnCO_3$, $CsMnF_3$, and $FeBO_3$) in satisfactory agreement with the theoretical dependences of the intrinsic (i.e., those occurring in an ideal crystal) relaxation processes: in the case of $CsMnF_3$ and $MnCO_3$ this is the three-magnon coalescence process,[15,16] whereas in the case of $FeBO_3$ it is the three-particle process involving a phonon.[17]

We studied the influence of hard excitation of parametric magnons in the easy-plane antiferromagnet $FeBO_3$. Our aim was to determine experimentally whether this effect was

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dominated by the negative nonlinear damping suppressing intrinsic relaxation processes or whether it was due to suppression of extrinsic relaxation processes such as the scattering of magnons by impurities, boundaries of a crystal, and dislocations.

As pointed out already, the laws of conservation of energy and quasimomentum are satisfied by the intrinsic magnon relaxation processes. In this case we can expect suppression of a part of the intrinsic relaxation in the case of parametric excitation to occur for magnons of frequency $\omega_{\mathbf{k}}$ in the vicinity of $\omega_p/2$ in a narrow interval of magnitude of the same order as the relaxation parameters of quasiparticles on which these magnons are scattered. When the extrinsic relaxation processes are suppressed (for example, in the case of the magnetic impurity saturation mechanism proposed in Ref. 8), negative nonlinear damping $\delta\omega_{\mathbf{k}}(n_{\mathbf{k}_i})$ may not exhibit a resonance dependence on the frequency (wave vector) of magnons excited in a sample ($\mathbf{k}\neq\mathbf{k}_i$) and, therefore, part of the magnon relaxation is suppressed in a wide range of frequencies near $\omega_p/2$. We therefore investigated the influence of parametric excitation of magnons (by pumping at one frequency ω_{p1}) on the hardness of parametric excitation of magnons by a second pump wave (of the same or a different frequency ω_{p2}). The investigated material ($FeBO_3$) was selected because of the strong hardness effect at liquid helium temperatures and because its static and hf magnetic properties had been investigated quite thoroughly (see, for example, Ref. 18).

Similar investigations of the influence of parametrically excited magnons of one frequency $\omega_{p1}/2$ on the parametric excitation of magnons of different frequency $\omega_{p2}/2$ in $CsMnF_3$ were carried out by Smirnov.[19] He found that the excitation of parametric magnons reduced the suppressed part of the relaxation of magnons excited by the microwave field of the second frequency only if the frequencies of the excited magnons differed by no more than 1.5 GHz. When the difference was larger, one pump wave had no effect on the hardness of the excitation process by the other pump wave.

METHODS AND SAMPLES

Parametric excitation of magnons was investigated using a direct amplification spectrometer described in Ref. 8. We employed a high-Q ($Q\approx 10^4$) cylindrical cavity resonator in which two oscillation modes H_{011} and H_{012} with frequencies 26.2 and 35.4 GHz, respectively, were excited simultaneously through one coupling aperture. A sample was bonded to the bottom of the resonator cavity at an antinode of a magnetic microwave field $\mathbf{h}$; it was enclosed in a packet made of cigarette paper. This satisfied the conditions for parallel pumping $\mathbf{h}\|\mathbf{H}\perp C_3$ in the case of both modes.

Microwave oscillations were generated using cw klystrons. These klystrons could also be operated in the pulsed regime. The duration of the pump pulses and the delay between the pulses could be varied, which was convenient in the studies of the kinetics of the parametric excitation of magnons. The microwave pulses transmitted by the resonator with the sample were detected and displayed on the screen of an oscilloscope. The dependences of the amplitudes of these pulses on the static magnetic field H were recorded using an X–Y plotter. The threshold microwave field h_{c1} corresponding to the onset of the parametric excitation of magnons was deduced from the appearance of a characteristic dip in the pulse transmitted by the microwave resonator. Relative measurements of the field h for a given sample in the course of one series of measurements were carried out with a square-law detector, so that the voltage generated by this detector in the case of a small coupling coefficient of the resonator aperture was proportional to the square of the field h applied to the sample. The absolute value of the field h was calculated, using the familiar formulas for the distribution of the fields in the cavity resonator and the parameters of this resonator, from the microwave power applied to the resonator. This power was measured by a thermistor bridge. The error in the determination of the absolute value of h applied to the sample was $\approx 20\%$, but the error of relative measurements in one series of experiments was considerably smaller: $\approx 3\%$. A tunable detector section was used as a filter in order to observe a signal of specific frequency: this made it possible to attenuate the signal at one frequency by a factor of 100 compared with the signal at the other frequency.

We also carried out experiments in which we determined the influence of pumping at the antiferromagnetic resonance (AFMR) frequency on the hardness of the parametric excitation of magnons. We used the same cylindrical cavity resonator tuned to generate the H_{012} mode at a frequency of 35.6 GHz and a second coupling aperture was used to excite the H_{111} mode at a frequency 17.2 GHz. The polarizations of the fields $\mathbf{h}$ of these modes at the point of location of the sample were mutually perpendicular and this made it possible to create the parallel pumping as well as the perpendicular pumping necessary for the excitation of the AFMR.

In these experiments the threshold microwave field h_{c1} corresponding to the onset of the parametric excitation of magnons, was deduced from the appearance of a dip in the signal reflected from the microwave resonator. The threshold field was calculated, as in the case of the "transmission" measurements, from the microwave power applied to the resonator and from the resonator parameters. This method resulted in a somewhat greater error (compared with a transmission-type spectrometer) in the relative value of h_{c1}: the error was now $\approx 10\%$.

The power absorbed by the sample in the case of perpendicular pumping of the AFMR was found from the formula

$$P_{\rm abs}=P\beta_1\{[1+(1-\beta_1)^{1/2}]-(\Delta f_2/\Delta f_1)[1+(1-\beta_2)^{1/2}]\}[1+(1-\beta_2)^{1/2}]^{-1},$$

where P is the power reaching the resonator; Δf_1 and Δf_2 are the widths of the resonance lines of the resonator; β_1 and β_2 are the coupling coefficients of the entry aperture of the resonator. The indices 1 and 2 identify respectively the values of the coefficients in a magnetic field H when there was no absorption and in the resonance field. The relative measurements of the absorbed power were made employing a precision attenuator placed in the microwave channel in front of the resonator. The error in the absolute measurements of the absorbed microwave power was $\approx 50\%$, whereas the error of the relative measurements was $\approx 10\%$.

These measurements were carried out in the temperature range 1.2–4.2 K. Heat removal from the sample was improved by filling the resonator with liquid helium. The temperature of the sample was deduced to within ± 0.05 K from the saturated vapor pressure of helium.

Our samples were single-crystal plates with natural faces and transverse dimensions 2×2 mm; their thickness ranged from 0.5 to 2 mm. The color of the samples varied with their thickness from green to almost black. The large faces of the plates coincided with the basal plane of the crystal. The samples used were the same as those employed in the investigation reported in Ref. 17.

EXPERIMENTAL RESULTS

Figure 1 shows the records obtained using the X–Y plotter whose "Y" input received a signal proportional to the microwave power transmitted by the resonator. The "X" input received a Hall sensor signal proportional to the applied static magnetic field. These records were obtained when the microwave oscillator was operated in two regimes. The thick curve represents the dependences of the square of the microwave field h experienced by the sample on the static field H measured when the microwave oscillator was operated continuously. The jump in the absorbed power observed on reduction in the magnetic field indicated that the excitation process stopped and this made it possible to determine the threshold field $h_{c2}(H)$. The thin line represents the $h^2(H)$ dependences recorded when the microwave oscillator operation was interrupted for $\tau = 1$ msec at a frequency of 50 Hz. In the time τ the spin system of the sample relaxed to its unexcited state and when the microwave oscillator was switched on again the parametric excitation of magnons occurred only if the field h experienced by the sample exceeded h_{c1}. It is clear from the results obtained that the $h_{c1}(H)$ plot was jagged and the depth of the dip reached $\approx 40\%$ at 1.2 K. The inset show the dependence $h^2(H)$ on a larger scale in respect of the static field H.

Figure 2 gives the temperature dependences of h_{c1} and h_{c2} obtained in a field $H = 205 \pm 5$ kOe. The vertical segments represent indeterminacy in the value of h_{c1} associated with the jaggedness of the dependence $P(H)$. At $T \approx 7$ K the parametric excitation of magnons became "soft" ($h_{c1} = h_{c2}$). Moreover, the jaggedness decreased on increase in temperature.

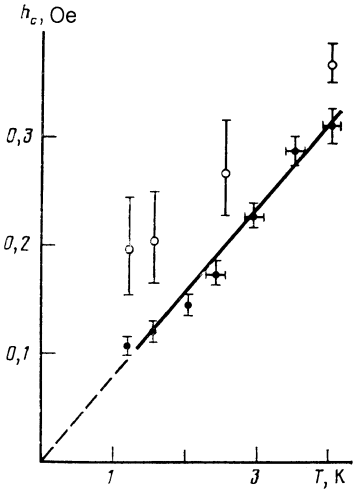

FIG. 2. Temperature dependences of the threshold fields h_{c1} (○) and h_{c2} (●) obtained for $H = 205 \pm 5$ Oe at $\omega_p/2\pi = 35.4$ GHz.

When two groups of magnons of frequencies $\omega_{p1}/2 = 2\times 17.8$ GHz and $\omega_{p2}/2 = 2\pi\times 13.25$ GHz were excited in the same sample, the following results were obtained. When a sample contained parametrically excited waves of one frequency ($\omega_{p1}/2$ or $\omega_{p2}/2$), the process of parametric excitation of the other group of waves became soft. This effect was observed in the full range of fields and temperatures in which it was possible to excite magnons by double pumping.

Parallel pumping excited magnons in a narrow frequency interval and the wave vectors of these magnons were large ($k \sim 10^4$–10^5 cm^{-1}). It seemed of interest to investigate the influence of the AFMR pumping (homogeneous precession) on the hardness of the parametric excitation of mag-

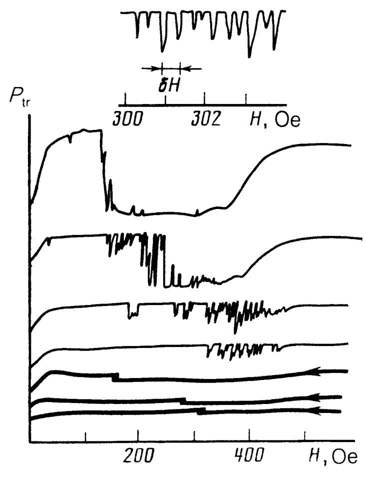

FIG. 1. Dependences of the amplitude of the microwave signal transmitted by the resonator on the static magnetic field H, obtained for different microwave powers using an X–Y plotter: the thick curves correspond to continuous operation of the microwave oscillator and the thin curves were obtained in the pulsed regime. The arrow indicates the direction of variation of the field H; $\omega_p/2\pi = 35.4$ GHz; $T = 1.2$ K. The top part of the figure shows the dependence of the transmitted power $P_{tr}(H)$ taken from Ref. 18 and obtained in the pulsed regime.

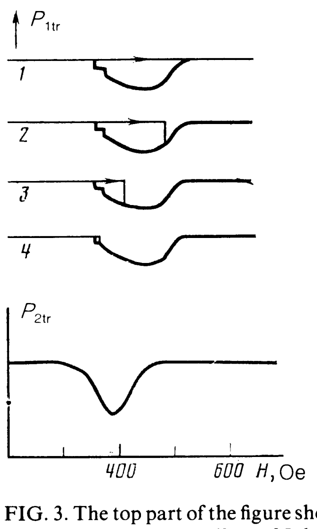

FIG. 3. The top part of the figure shows the microwave power transmitted by the resonator at $\omega_{p1}/2\pi = 35.6$ GHz for various values of the AFMR pump power of frequency $\omega_{p2}/2\pi = 17.52$ GHz. The curves are labeled 1–4 in the increasing order of the AFMR pump power. The bottom of the figure shows the absorption curve corresponding to the AFMR at ω_{p2}; $\mathbf{h}_{p1} \parallel \mathbf{H}$, $\mathbf{h}_{p2} \perp \mathbf{H}$, $T = 1.2$ K.

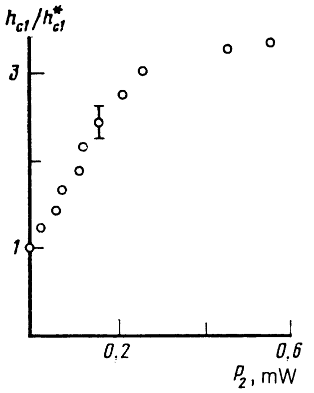

FIG. 4. Dependence of the ratio of the threshold field h_{c1} for the parametric excitation of magnons at $\omega_{p1}/2\pi = 35.6$ GHz to the threshold field h^*_{c1}, measured in the presence of AFMR pumping at $\omega_{p2}/2\pi = 17.52$ GHz, on the frequency ω_{p2} of the pump power absorbed by the sample; $H = 370$ Oe, $T = 1.2$ K.

nons. We plotted in Fig. 3 the power transmitted by the microwave resonace at a frequency $\omega_{p1}/2\pi = 35.6$ GHz using various powers to pump the AFMR at $\omega_{p2}/2\pi = 17.52$ GHz. The microwave oscillators were operated continuously. The various curves (1–4) were obtained for different values of the AFMR pump power ($P_2^{(4)} > P_2^{(3)} > P_2^{(2)} > P_2^{(1)}$). At the bottom of Fig. 3 we plotted an absorption curve corresponding to the AFMR at $\omega_{p2}/2\pi = 17.52$ GHz. It is clear from Fig. 3 that an increaase in the pump power reduced the AFMR threshold field h_{c1} right down to h_{c2}, whereas the threshold field h_{c2} remained constant within the limits of the experimental error.

Figure 4 gives the dependence of the ratio of the threshold field h_{c1}, measured in the absence of the antiferromagnetic resonance pumping, to h^*_{c1} measured in its presence on the microwave power of frequency ω_{p2} absorbed by the sample. In this field ($H = 370$ Oe) it was found that $h_{c1}/h_{c2} = 3.8$ (hardness coefficient $\xi = 2.8$).

In this experiment the detuning of the AFMR frequency $\omega_{\rm AFMR} = \omega_{p2}$ from $\omega_k = \omega_{p1}/2$ was slight (≈ 300 MHz). We carried out a similar investigation also when the detuning (frequency difference) was larger. This was done employing two resonators with a shared wall. One of them was cylindrical, exactly the same as that used in the experiments described above, and it was tuned to the H_{012} mode at $\omega_{p1}/2\pi = 35.6$ GHz, whereas the second was rectangular and was tuned to the mode H_{101} at $\omega_{p2}/2\pi = 15.3$ GHz. A sample was bonded into the aperture in the shared wall of these two resonators. The polarization of the microwave magnetic fields experienced by the sample and the direction of the static magnetic field were such that the microwave power at the higher frequency ω_{p1} performed parallel pumping, whereas the microwave power of the lower frequency ω_{p2} represented perpendicular pumping of the homogeneous precession in a field $H_{\rm AFMR}$.

The results of this experiment agreed qualitatively with those of the preceding experiment: as the AFMR pump power at ω_{p2} was increased, the hardness of the parametric excitation of magnons at $\omega\mathbf{k} = \omega_{p1}/2$ decreased. Quantitative measurements made in this experimental setup would be difficult to interpret because the AFMR pumping and the measurement of h_{c1} took place in different parts of a sample. Therefore, we did not carry out such experiments.

We shall now formulate the main experimental results.

1. The hardness coefficient ξ of parametric excitation of magnons decreased on increase in temperature and at $T = 7$ K the excitation process became soft.

2. The dependence of the threshold field h_{c1} on the static magnetic field H was jagged. At $T = 1.2$ K the depth of jaggedness of the threshold field h_{c1} reached $\approx 40\%$ of its maximum value.

3. When the parametric excitation of magnons of frequency $\omega_{\mathbf{k}1} = \omega_{p1}/2$ was already taking place in the sample, the parametric excitation of magnons of frequency $\omega_{\mathbf{k}2} = \omega_{p2}/2$ became soft at frequencies ω_{p1} and ω_{p2} differing by a factor of at least 1.5.

4. When the AFMR pump power of frequency ω_{p2} was increased, the hardness of the parametric excitation of magnons of frequency $\omega_{\mathbf{k}1} = \omega_{p1}/2$ decreased. Beginning from a certain AFMR pump power the process of parametric excitation became soft (within the limits of the experimental error).

DISCUSSION OF RESULTS

These experiments demonstrated that the hardness of the parametric excitation of magnons in $FeBO_3$ decreased when magnons of other (even considerably different) frequencies and wave vectors were already excited. Consequently, the negative nonlinear damping responsible for the hardness effect depended nonresonantly on the frequency and wave vector of the magnons excited in a sample and, as pointed out in the Introduction, the hardness effect was due to suppression of part of extrinsic relaxation processes. The similarity of the main features of these effects for different antiferromagnets, pointed out above, led us to the conclusion that hardness of the excitation in other materials ($CsMnF_3$, $MnCO_3$, etc.) was also due to extrinsic relaxation processes.

We shall now consider some magnon relaxation mechanisms which might give rise to the observed effect. An investigation of the temperature dependence of the intensity of microwave radiation emitted from a sample of $FeBO_3$ at the doubled frequency $2\omega_p$ when pumped at the AFMR frequency ω_p, described in Ref. 17, showed that our crystals contained the same magnetic impurity, as pointed out already in Refs. 20 and 21. The specific nature of this impurity was not determined in these investigations. The freezing point of this impurity was $T = 5$–7 K and this was close to the temperature below which the process of parametric excitation of magnons became hard. We could therefore postulate that the hardness was associated with suppression of part of the relaxation due to the interaction with this impurity.

The simplest possible mechanism which can suppress part of the magnon relaxation process is the overheating of a magnetic impurity by parametrically excited magnons, as suggested in Ref. 8 (heating of the impurity because of its direct interaction with the microwave pumping can be ignored because all the observed effects appear abruptly above the threshold of the microwave field h simultaneously with the excitation of magnons in a sample). We checked this hypothesis by determining the overheating of an impurity by parametrically excited magnons. According to the results of Ref. 20, the width of the AFMR line and its position at $T<8$ K depended strongly on temperature and in all probability were governed by the temperature of the impurity. Therefore, an investigation of changes in the profile and position of the AFMR line in the course of excitation of parametric magnons should make it possible to estimate the rise of the temperature of the impurity. Such experiments were carried out by us and they showed that the rise in the temperature of the impurity as a result of parametric pumping with magnons did not exceed 0.4 K when the helium bath temperatures was 1.2 K. The absence of significant heating was in our opinion to be expected because the characteristic relaxation frequencies of excited states of magnetic impurities in magnetically ordered samples at 1 K are usually high and amount to 10^9–10^{10} Hz (Ref. 22). Therefore, the hardness effect cannot be attributed to such an impurity. Nevertheless, we cannot exclude the possibility that it might be due to an impurity of a different kind which could also be present in $FeBO_3$ crystals.

Slow relaxation involving a magnetic impurity may also give rise to the negative nonlinear damping,[23] but the absence of a quantitative description of the effect (particularly of the temperature and field dependences of the hardness coefficient ξ) makes it impossible to compare this theoretical model with the available experimental results.

It therefore follows that the currently available data are insufficient to identify reliably which of the extrinsic relaxation processes accounts for the hardness of the parametric excitation of magnons.

We shall conclude by considering possible reasons for the jaggedness of the dependence $h_{c1}(H)$ in Fig. 1. The investigation reported in Ref. 24 demonstrates that the interval δH between neighboring dips (inset in Fig. 1) and its dependence on the magnetic field are the same as in the interval between the nearest fields H at which standing spin waves were excited in a sample and the number of half-wavelengths which could be fitted across the thickness of a sample was an integer. It was concluded on this basis in Ref. 24 that the size effect was observed. However, since the depth of the jagged dependence $\Delta\omega_{k1}(H)$ calculated from the threshold field h_{c1} exceeded the steady-state part of the relaxation parameter $\Delta\omega_{k2}(H)$ calculated from the threshold field h_{c2}, in all probability the observed jaggedness was not due to the damping of magnons at the boundaries of the sample.

The effect described above could be explained as follows. It is most probable that the hardness is due to the interaction of magnons with a magnetic impurity. In the case of parametric excitation of magnon pairs ($\mathbf{k}$, $-\mathbf{k}$; $\mathbf{k}\perp C_3$) forming a standing spin wave a magnetic impurity located near the nodes of this wave interacts weakly with the wave and, consequently, makes no contribution to the relaxation. However, in the case of excitation of traveling waves, all the magnetic impurities participate in magnon scattering. It should be pointed out that in this case the interaction of the magnetic impurity with oscillations of the magnetization should be a nonlinear function of the amplitude of the magnetization oscillations. This hypothesis is quite natural because the observed hardness of the parametric excitation of magnons is a consequence of this nonlinearity.

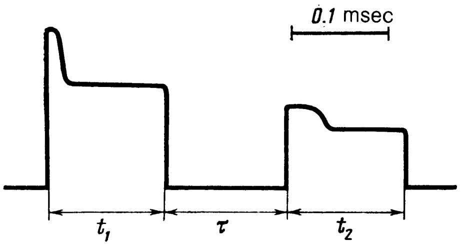

FIG. 5. Schematic representation of an oscillogram of the microwave signal transmitted by the resonator in the experiment with two pump waves applied at different times: t_1 and t_2 are the durations of the pump pulses at frequencies ω_{p1} and ω_{p2}.

INVESTIGATION OF TIME EFFECTS IN EXCITATION OF TWO GROUPS OF MAGNONS IN A SAMPLE

We discovered that the presence of parametrically excited magnons of frequency $\omega_{p1}/2$ had a considerable influence on the hardness of the parametric excitation of magnons of different frequency $\omega_{p2}/2$. It seemed of interest to investigate how fast the process of excitation of magnons at the frequency ω_{p2} becomes hard after switching off the microwave pumping at ωp_1.

We carried out the following experiment. Microwave oscillators O_1 and O_2 were operated in the pulsed regimes. The duration of the pulses t_1 and t_2 was 0.1 msec and the time interval between the pulses τ could be varied in the course of an experiment within the range 1–10^4 μsec (Fig. 5). The oscillator power O_1 exceeded the threshold power for the parametric excitation of magnons at the frequency ω_{p1} and the second pulse could be used to measure the threshold field h_{c1} for the parametric excitation of magnons at ω_{p2} as a function of the time τ. The frequencies of the oscillators O_1 and O_2 were selected to be the same as in the previous experiments: 26.3 and 35.6 GHz. The temperature of the helium bath was 1.2 K.

The following results were obtained in these experiments. Preliminary microwave pumping by the oscillator O_1 did not affect the threshold field for the parametric excitation of magnons during the action of the second oscillator O_2 throughout the investigated range of delay times $5<\tau<10^4$ μsec for the following values of the frequencies of the oscillators O_1 and O_2: $\omega_{01}/2\pi=\omega_{02}/2\pi=26.3$ GHz; $\omega_{01}/2\pi=\omega_{02}/2\pi=35.6$ GHz; $\omega_{01}/2\pi=26.3$ GHz; $\omega_{02}/2\pi=35.6$ GHz. In these experiments the microwave field created by the oscillator O_1 in the sample exceeded the threshold by ≈ 3 dB.

Preliminary pumping affected the hardness of the parametric excitation of magnons only when $\omega_{01}/2\pi=35.6$ GHZ and $\omega_{02}/2\pi=26.3$ GHz. We plotted in Fig. 6 (curve 1) a characteristic dependence $h^*_{c1}(\tau)$ for the microwave field created by the oscillator O_1, which exceeded the field h_{c1} by about 3 dB. This dependence $h^*_{c1}(\tau)$ was observed for almost all the values of the static magnetic field in which it was possible to achieve parametric excitation of magnons. However, in certain narrow intervals of the fields ($\delta H\approx 0.5$ Oe) we found that $h^*_{c1}(\tau)$ was more complex (curves 2 and 3 in Fig. 6). At $T=1.2$ K we were able to observe five such intervals for static fields $H=68$, 140, 178, 183, and 223 Oe. Within these intervals the field $h^*_{c1}(\tau)$ could increase or de-

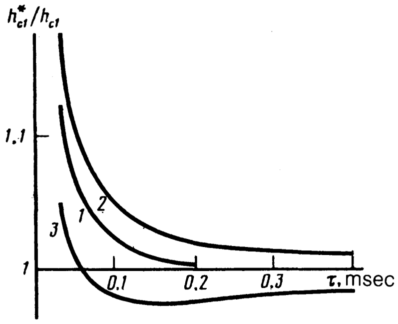

FIG. 6. Dependences of the ratio of the threshold field h^*_{c1} for the parametric excitation of magnons at $\omega_{p2}/2\pi = 26.3$ GHz, measured in the presence of preliminary pumping at $\omega_{p1}/2\pi = 35.6$ GHz, to the unperturbed value of h_{c1} on the time interval τ between the pulses ($T = 1.2$ K): 1) $H = 180$ Oe; 2) 183 Oe; 3) 183.5 Oe.

crease. The effect described here was small. In contrast to the effect described above and observed in the case of simultaneous action of two pump waves, in the present case the change in the hardness did not exceed $\sim 10\%$ (Fig. 6). Moreover, it was worth noting that a prolonged "aftereffect" was observed only when the frequency of the oscillator acting first (O_1) was higher than the frequency of the oscillator O_2.

It is clear from Fig. 6 (curve 1) that the threshold field $h^*_{c1}(\tau)$ usually relaxed to its unperturbed value h_{c1} at a rate characterized by a time constant $\tau_1^* \approx 30\,\mu$sec. In the narrow field intervals mentioned above the relaxation process had two characteristic times $\tau_1^* \approx 30$ and $\tau_2^* \approx 200\,\mu$sec (curves 2 and 3 in Fig. 6).

We shall now consider the reasons for such very long relaxation times of $h^*_{c1}(\tau)$ after the action of microwave pumping of frequency ω_{p1}. The most effective process of magnon relaxation in $FeBO_3$ at helium temperatures is the three-particle process involving a phonon.[17] The characteristic relaxation time of this process is $\sim 1\,\mu$sec. According to the estimates given in Ref. 17, all the other processes are much less effective. The three-particle processes in question—decay of a magnon into a magnon and a phonon and coalescence of a magnon with a phonon to form a new magnon—result in a rapid redistribution of nonequilibrium magnons that appear in the parametrically excited spin system throughout the spectrum.

Since such three-particle processes do not alter the number of magnons, the relaxation of this number to the thermal value is due to other processes and it is quite natural that the characteristic time of this relaxation is much longer than the lifetime of the parametrically excited magnons.

The change in the magnetization δM of a sample of $FeBO_3$ due to parametric excitation of magnons was determined in Ref. 25 and it was found that δM was at least 10 times greater than the change in the magnetization calculated on the assumption that only the parametrically excited magnons were not in equilibrium. Hence, the number of secondary magnons in a sample was at least 10 times greater than the number of parametric magnons. Thus, knowing the relaxation time of the parametrically excited magnons ($\sim 1\,\mu$sec) we could conclude that the relaxation number of the total number of magnons exceeded 10 μsec, in agreement with the relaxation time of the field h_{c1} ($\tau_1^* \approx 30\,\mu$sec). Therefore, the observed increase in the threshold field h^*_{c1} at the pump frequency ω_{p2} could be explained by an increase in the relaxation parameter of the magnons excited by such pumping because of the interaction of these magnons with the paramagnetic magnons that remained after the action of the first microwave pump pulse. The question how the nonequilibrium magnons were distributed over the spectrum in the case of excitation of a narrow spectral packet had not been investigated. It is possible that a theoretical study of this question would give the answer why the aftereffect had been observed only for $\omega_{01} > \omega_{02}$.

We shall assume that a different process resulting in a slow influence of the first pumping on the field h_{c1} of the second pumping and characterized by the time constant τ_2^* is due to the excitation of intrinsic elastic vibration modes of a sample. This hypothesis is based on the observation that the relaxation times of magnetoelastic oscillations in $FeBO_3$ are long in the investigated range of temperatures and can reach $\sim 500\,\mu$sec (Ref. 26), whereas other long-lived excitations were not known to us. Moreover, an investigation of the spectrum of electromagnetic radiation generated by parametrically excited magnons demonstrated[27] that not only magnons, but intrinsic magnetoelastic oscillations were excited in the sample.

This hypothesis was checked by investigating the influence of magnetoelastic oscillations on the threshold field h_{c1}. A method described in Ref. 26 was used to excite the magnetoelastic modes and to measure simultaneously the threshold field h_{c1}. The results of these experiments indicated that the excitation of magnetoelastic oscillations in a sample could both increase the threshold field h_{c1} or reduce it (the sign of the effect depended on the oscillation frequency, on the magnetic field, and on the temperature of the sample). The interaction of magnons with magnetoelastic oscillations has not yet been allowed for in the theoretical descriptions of the parametric excitation of magnons although, as demonstrated in Ref. 27 and in the present study, they have a considerable influence on the nonlinear properties of magnons.

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