Bragg diffraction of light by parametrically excited magnetoelastic waves of the upper and lower branches of the hybrid spectrum

N. N. Kiryukhin and F. V. Lisovskiĭ

Institute of Radio Engineering and Electronics, USSR Academy of Sciences
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Direct experimental proof is obtained of the existence of quasidegenerate (at frequencies close to the pump) parametric excitation of hybrid magnetoelastic waves by magnetostatic waves. A procedure is developed for separate observation of the diffraction of light by each of the oppositely directed waves of the parametrically excited pairs. The possibility is proved of parametric interaction of waves belonging to a different branch of the hybrid magnetoelastic spectrum. It is shown that analysis of the amplitude, field, and polarization characteristics of the diffracted radiation makes possible a reliable identification of the modes that generate the diffraction.

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INTRODUCTION

The method of Bragg diffraction of light, which yields direct information on the dispersion law of the different modes, is extensively used in experimental investigations of the spectrum of elementary excitations in magnetically ordered crystals. In the first experiments of this type, the objects of the investigation were linearly (not parametrically) excited oscillations and waves in ferromagnets and antiferromagnets.[1-13] The method of magneto-optical diffraction has recently found extensive explication also for the study of processes of parametric excitation of spin waves (with and without exchange) in hybrid magnetoelastic waves.

Gaĭdaĭ, Solomko, and Maĭstrenko[14-16] have investigated the spectrum of magnetostatic (spin no-exchange) modes in rectangular prisms of yttrium iron garnet (YIG) with inhomogeneous internal magnetic field. Diffraction of light by parametrically excited spin waves with frequency equal to half the pump frequency was observed, and it was shown that the (transverse) pumping is produced in this case by the resonant magnetostatic modes.[14,15,17-20] The parametric excitation took place in that region of the crystal where the internal magnetic field corresponded to the bottom of the spin-wave spectrum at half the frequency.[20] The diffraction of the light revealed also parametric excitation of spin waves in the quasi-degenerate regime.[20-23]

Experimental observation of the scattering of light in YIG by spin waves parametrically excited by longitudinal pumping was reported earlier by Venitskiĭ, Eremenko, and Matyushkin.[24,25] Satellites shifted by half the pump frequency (relative to the incident-light frequency) were observed in the spectrum of the scattered light. The spatial distribution of the satellites indicated diffraction to be from parametric magnons propagating perpendicular to the magnetizing field. Zhotikov and Kreĭnes[26] observed inelastic scattering of light in antiferromagnetic $CoCO_3$ by thermal magnons amplified by transverse pumping near the boundary of the first parametric-excitation band. Observation of modulation of the longitudinal component of the magnetization accompanying parametric excitation of spin waves was reported in Refs. 27 and 28. It was shown in Refs. 29 and 30 that investigation of the magneto-optical modulation of light makes it possible to determine the distribution law of the magnons in quasimomentum space both under linear and parametric excitation.

We report here the results of an experimental investigation of Bragg diffraction of light in YIG from parametrically excited magnetostatic modes of magnetoelastic waves of the upper and lower branches of the hybrid spectrum (individual results were briefly reported earlier in Refs. 21–23).

1. EXPERIMENTAL SETUP

The experiments were performed with a setup consisting of a microwave, optical, and recording sections.

An assembly of YIG samples in the form of rectangular prisms was placed in the gap of an electromagnet. The direction of the magnetization vector of the magnetic field coincided with the long edge of the prism, parallel to which the magnetostatic, spin, or magnetoelastic waves propagated (the z axis).

In the microwave section of the setup we used an oscillator with maximum output power ~1 W, operating in the frequency band 1–2 GHz in a pulsed regime (pulse duration 10–500 μsec, repetition frequency 1 kHz). At one of the end faces of the YIG was placed the exciting rod antenna, which was the continuation of the inner conductor of the coaxial cable of the oscillator; the microwave magnetic field was in this case perpendicular to the z axis ("transverse" pumping geometry). To monitor the radiation passing through the crystal we used an antenna of similar construction.

The short-wave magnetostatic, spin, and magnetoelastic waves were excited by the long-wave electromagnetic radiation on account of the inhomogeneity of the internal magnetic field $H_i(z)$ in samples of nonellipsoidal shape.[31] The process of transformation of the electromagnetic waves at frequency ω_s into elementary excitations of a magnet with $\mathbf{k}_s \parallel \mathbf{M}_0$ depends in this case substantially on whether the sample has a turning point z_{tp} at which the group velocity of the nonexchange spin waves[1)] vanishes (see, e.g., Ref. 32).

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For a rectangular prism magnetized to saturation along the long dimension, the distribution of $H_i(z)$ has a maximum at the center of the sample ($z=0$). If $H_i(0) < H_{crit} \approx \omega_s/\gamma$, then there is no turning point in the sample, and the magnetostatic wave excited by the antenna at the irradiated end of the prism ($z=-L/2$, where L is the length of the prism) propagates over the entire sample. Its wave vector $\mathbf{k}_s$ initially increases, reaches a maximum at $z=0$, and then begins to decrease in such a way that $\mathbf{k}_s(+z)=\mathbf{k}_s(-z)$. After reaching the opposite end of the prism ($z=+L/2$), the magnetostatic wave is emitted in the form of an electromagnetic wave that can be registered with a receiving antenna.

At $H_i(\pm L/2) < \omega_s/\gamma < H_i(0)$, the sample has two symmetrically located turning points ($\pm z_{tp}$) and two magnetic crossover points[2)] ($\pm z_{cr}$). The mode transformation process proceeds in the following manner. The magnetostatic wave excited by the microwave magnetic field propagates from the end $z=-L/2$ to the turning point $-z_{tp}$, where it is transformed into a quasispin magnetoelastic wave of the upper branch of the hybrid spectrum, traveling in the opposite direction. At the point $z=-z_{cr}$ this wave is transformed into a transverse right-polarized quasielastic wave (of the same branch), which is reflected from the end $z=-L/2$, after which the conversion process proceeds in the opposite sequence.

In the optical part of the setup we used a source of coherent polarized light ($\lambda=1.15$ μm) of power ~10 mW. The light was passed at first through a quarter-wave plate and became circularly polarized. By using an additional polarizer it was possible, without changing the radiation intensity, to set the polarization plane in any position characterized by an angle ψ measured from the diffraction plane. The light beam was next focused on the surface of the sample by a lens producing in the focal plane a spot of diameter not larger than 0.2 mm. The polarization of the diffracted radiation was determined with an analyzer, the diffraction maxima were selected with a lens having a moving slit diaphragm. An additional short-focus lens focused the radiation in the chosen diffraction maximum onto the receiving area of the photoreceiver (a germanium photodiode). Since the modes were excited in the YIG prism by microwave pulses at a repetition frequency 1 kHz, the diffracted radiation was also modulated at the same frequency. This made it possible to register the output signal of the photoreceiver with a synchronous detector.

The electromagnet together with the YIG prism were placed on a rotating stage, which was connected through a system of gears to a bar on which the photoreceiver was located. The rotation axes of the stage and of the bar coincided, and the mechanical gear ratio was equal to two, thereby ensuring automatically satisfaction of the Bragg condition.

We used in the experiments rectangular YIG prisms of varying size and varying crystallographic orientation, magnetized in the direction of the long dimension. The results obtained for all the samples in the microwave-excitation frequency interval 1–2 GHz did not differ qualitatively. We shall therefore describe hereafter experiments performed at a frequency 1.2 GHz with a YIG prism measuring 10.7×3.0×2.9 mm, whose edges coincided with the crystallographic axes ⟨100⟩, ⟨010⟩, and ⟨001⟩. For this sample at 1.2 GHz, the magnetic field intensity H_{crit} corresponding to the appearance of a turning point at the center of the prism was ≈570 Oe, and the wave number k_{tp} at the turning point was $\approx 2\times10^3$ cm^{-1}.

2. LINEAR AND PARAMETRIC EXCITATION OF MAGNETOELASTIC WAVES OF THE UPPER BRANCH OF THE HYBRID SPECTRUM

In magnetic fields of intensity not higher than H_{crit}, magnetostatic waves were excited and propagated over the entire crystal. The characteristics of the diffraction of light by such waves were investigated in detail earlier.[33-35] When the magnetic field is increased above a critical value H_{crit}, turning points ($\pm z_{tp}$) appear in the sample and crossover points ($\pm z_{cr}$). In this case, when the sample region $-L/2 < z < -z_{tp}$ is probed with a light beam, diffraction by the magnetostatic waves should take place. In the regions $-L/2 < z < -z_{cr}$ and $-z_{cr} < z < -z_{tp}$ diffraction should take place from the quasielastic and quasispin waves, respectively, belonging to the upper branch of the hybrid magnetoelastic spectrum. In practice, however, more complicated phenomena are observed.

Figure 1 shows the angular distribution of the diffracted radiation (in the Bragg regime) at $z=-0.1$ mm and $\psi=0°$. It is seen that in addition to the diffraction by the magnetostatic waves (maximum I; owing to the high intensity, only the left wing of the maximum is shown). In the general case four additional diffraction maxima exist in the diffraction-angle interval[3)] $-30° \leq \theta \leq -5°$. Out of these, only the maximum III, the angle position of which is highly sensitive to the magnetic field (a 0.6-Oe change in H changes the diffraction angle θ by almost 5°) is due to diffraction of light by linearly (non-parametrically) excited quasispin waves of the upper branch of the hybrid spectrum. The maxima II, IV, and V are connected with waves of parametric origin.

The maximum III was observed in a region of maximum homogeneity of the internal magnetic field (near the center of the sample) in a narrow interval of the

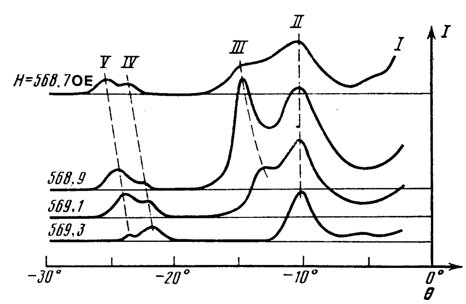

FIG. 1. Dependence of the intensity of the diffracted radiation on the diffraction angle at $z=-0.1$ mm, $P_{micro}=63$ mW, and $\psi=0°$.

magnetization fields (less than 1 Oe) and of the microwave excitation power P_{micro}. The lower limit at which the maximum III was observed was determined by the power of the employed light source (~10 mW) and by the sensitivity of the photoreceiver circuit (~10^{-10} W), while the upper limit was determined by the masking action of the intense diffraction maximum II connected with the parametrically excited waves. The dependence of the intensity I of the diffracted radiation on P_{micro} for the maximum III was the same as for the maximum I connected with the magnetostatic waves.

At a small (~0.1 mm) shift of the probing point from the center of the sample, the diffraction angle increased rapidly and the intensity of the diffracted radiation at a maximum III dropped abruptly. It sufficed to shift the probing beam by only 0.2 mm to cause the diffraction to vanish completely, so that values $\theta \gtrsim 16°$ could not be obtained. The experimental orientation dependences of the rotation angle $\Phi_F(\psi)$ of the polarization plane of the diffracted radiation and of the ratio of the intensities of the Stokes and anti-Stokes components $I_s/I_{as} = f(\psi)$ for the maximum III practically coincided with the values predicted by the theory (see Refs. 23 and 34) for the case of diffraction by traveling spin waves. An analysis of the form of these characteristics has established that in this case the diffraction is from waves that carry energy from the center of the sample towards the transmitting antenna.

These facts are indeed evidence that the maximum III corresponds to diffraction of light by linearly (non-parametrically) excited magnetoelastic waves of the upper branch of the hybrid spectrum (quasispin phase) in the region $-z_{cr} < z < -z_{tp}$. The reason why no diffraction was observed from waves in the quasi-elastic phase (diffraction angles $16° \lesssim |\theta| \leqslant 20.7°$; the upper limits corresponds to purely elastic transverse waves in YIG at a frequency 1.2 GHz) is that in YIG, at a fixed power flux, the spin waves near the crossover scatter the light more effectively than elastic waves. In addition, a certain part of the power is lost in the mode transformation process at the crossover point.

The diffraction maximum II ($\theta \approx 10°$ in Fig. 1) appears only if the microwave excitation power exceeds a certain critical value $P_{crit} \sim 10$ mW, corresponding approximately to the end of the linear section on the $I(P_{micro})$ plot for diffraction from magnetostatic waves. When P_{crit} is slightly exceeded, the maximum II behaves in a manner similar to maximum III. The diffraction angle has a strong dependence on H, diffraction is observed only when the center of the sample is probed, etc. With increasing power, however, the characteristics of the maximum II change.

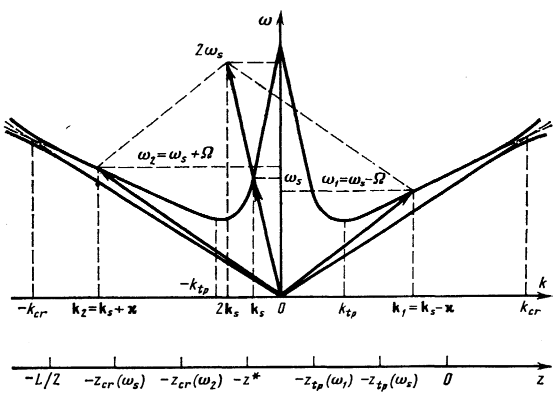

FIG. 2. Vector diagram of the process of parametric excitation of two magnetoelastic waves of the upper branch of the hybrid spectrum by a magnetostatic wave. In the lower part is shown the distribution of the characteristic points in the sample.

1. The $\theta(H)$ dependence becomes weakly pronounced (see, e.g., Fig. 1); an increase of the magnetic field causes mainly only a decrease of the intensity of the diffracted radiation.

2. The angle position of the maximum II remains practically unchanged when the probing point is displaced. The smallest angle width of the maximum is observed at the center of the sample, and when the probing beam approaches the exciting antenna the maximum II broadens and merges in practice with maximum I (this phenomenon was first described in Ref. 21 and called their "anomalous diffraction"). Nonetheless, measurement of the dependence of the intensity of the diffracted radiation on the angle of incidence of the probing beam on the sample, at a fixed diffraction angle, has shown that the light is scattered by waves with $\mathbf{k}_s \parallel \mathbf{M}_0$, and the width of the angle spectrum does not exceed 1°.

3. Immediately after its appearance, the intensity of the maximum II increases more rapidly than the microwave excitation power after which it saturates strongly.

4. The diffraction maximum II exists in a magnetization-field range that is exceedingly narrow at low microwave power (~1 Oe). The region broadens slowly with increasing P_{micro}.

5. The polarization characteristics $\Phi_F(\psi)$ of the diffracted radiation depend on the microwave power. Their form can be explained by assuming that when the light is diffracted by parametrically excited quasidegenerate (i.e., almost standing) spin waves, the photoreceiver registers a mixture of Stokes and anti-Stokes components.[23] The form of the polarization characteristics at low microwave power is therefore highly sensitive to the choice of the probing point.

Analysis of the experimental results makes it possible to state that the maximum II is the result of diffraction of light by parametrically excited quasidegenerate magnetoelastic waves of the upper branch of the hybrid spectrum. A possible scheme of such a process is shown in Fig. 2. The pump is a backward magnetostatic wave of frequency ω_s and wave vector $\mathbf{k}_s = -\mathbf{i}_z k_s$ (the energy flux for this wave is directed towards positive values of the z axis, i.e., away from the exciting antenna, $z = -L/2$, towards the center of the sample). At a certain point $-z^*(\omega_s)$, where the wave vector is equal to $\mathbf{k}_s$, this wave excites a pair of magnetoelastic (quasispin) waves of the upper branch of the hybrid spectrum, whose wave vectors $(\mathbf{k}_1, \mathbf{k}_2)$ and frequencies (ω_1, ω_2) satisfy the equations

$$\mathbf{k}_1+\mathbf{k}_2=2\mathbf{k}_s, \quad \omega_1+\omega_2=2\omega_s. \tag{1}$$

It follows from (1) that

$$\mathbf{k}_{1,2}=\mathbf{k}_s\mp\varkappa, \quad \omega_{1,2}=\omega_s\mp\Omega, \tag{2}$$

where Ω and $\varkappa$ are respectively the deviations of the frequencies and wave vectors of the parametrically excited waves from ω_s and $\mathbf{k}_s$. The possibility of realizing such a parametric-excitation process was confirmed indirectly earlier in Refs. 36 and 37.

The localization of the turning points and of the crossover points in the sample at constant H depends on the frequency of the wave. For the considered scheme, the relative location of the points $z_{tp}(\omega_i)$ and $z_{cr}(\omega_i)$, where i is equal to 1, 2, and s, takes the form shown in Fig. 2. The parametric-excitation point lies then in the interval $-z_{cr}(\omega_2)<-z^*<-z_{tp}(\omega_1)$.

After the excitation, the quasispin wave $(\omega_2, \mathbf{k}_2)$ propagates towards the crossover point $-z_{cr}(\omega_2)$ and is transformed into an elastic wave, while the quasispin wave $(\omega_1, \mathbf{k}_1)$ propagates towards the turning point $-z_{tp}(\omega_1)$, where it is transformed into a magnetostatic wave traveling towards the end point $z=-L/2$. Thus, when the probing light beam is localized in the region $z<-z_{tp}(\omega_1)$ it is possible to observe the diffraction by parametrically excited waves in the diffraction-angle interval $|\theta|\lesssim 20.7°$ defined by the condition $|k|\lesssim k_{cr}$. It is precisely these diffraction angles which are characteristic of the maximum II.

The difference between the frequencies corresponding to the crossover points and the turning points in YIG, under the considered experimental conditions, amounts to ~10 MHz (see, e.g., Ref. 32), which is equivalent to a change of the magnetic field by several oersted. When the threshold of the parametric excitation is slightly exceeded, a small increase of the magnetization field should lead to a strong decrease of the diffraction angle, as is indeed the case in the experiments. With increasing pump power, the number of pairs of parametrically excited magnons increases rapidly; the parametric-excitation frequency interval $\Delta\Omega$ also broadens, and this is accompanied by an increase in the spatial width Δz^* of the region of parametric excitation of the waves in the crystal. For this reason, at $P_{micro}\gg P_{crit}$ the angle position of the diffraction maximum II responds weakly to a change of the magnetic field (a large set of spin waves with $|k|\lesssim k_{cr}$ is present in a large interval of variation of H in the probing region).

With increasing magnetization field, the region of parametric excitation Δz^* shifts towards the end of the sample, where the gradient of the internal magnetic field is large enough (up to 10^2 Oe/mm and larger), causing the points z_{cr} and z_{tp} to approach each other rapidly. The probing the region of the parametric excitation with a light beam yields a diffraction maximum in which one observes the integrated effect of the interaction of the light with magnons whose wave vectors are distributed in a large interval of values $|k|\lesssim k_{cr}$. The shape of the directivity pattern of the diffracted radiation depends little in this case on the position of the probing region.

Each pair of parametrically excited waves is characterized by a separate position of the excitation point $-z^*(\omega_s)$ and of the points $-z_{cr}(\omega_{1,2})$ at $-z_{tp}(\omega_{1,2})$. When P_{crit} is significantly exceeded, and a large number of pairs is excited, these points form entire bands that merge with one another. Consequently, at $P_{micro}\gg P_{crit}$ there is produced in the crystal a region in which many oppositely directed waves with close values of the frequencies and wave vectors are present, consequently both Stokes and anti-Stokes components are present in one and the same diffraction maximum. It is this which causes the experimentally observed[22] form of the dependence of the polarization-plane rotation angle Φ_F of the diffracted radiation on the orientation of the vector **E** of the light incident on the crystal.

It follows from Fig. 2 that (at least for a slight excess above the threshold power P_{crit}) when a narrow region $-z_{tp}(\omega_1)<z<-z_{tp}(\omega_s)$ is probed by a beam of light, only diffraction by linearly excited (quasi)spin waves should be observed (the maximum III). This was confirmed by an experiment whose results are illustrated in Fig. 3. A transparent screen was placed in front of the sample and could be moved relative to the sample (along the z axis) with a micrometer screw. If the probed region was near the midpoint of the sample and the screen did not overlap the light beam at all, then at a definite choice of the magnetization field and of the pump microwave power simultaneous diffraction was observed by parametrically and linearly-excited spin waves (curve 1 of Fig. 3, maxima II and III; see also Fig. 1). The screen was then shifted (from the region $z<0$) towards the center of the sample, gradually "obscuring" the region of existence of parametrically excited waves. The intensity of the maxima II then decreased smoothly, and this maximum vanished completely at a certain position of the edge of the screen, whereas the intensity of the diffracted radiation in the maximum III remained practically unchanged. It was possible to establish in this manner that even under optimum experimental conditions the distance between the points $-z_{tp}(\omega_s)$ and $-z_{tp}(\omega_1)$ does not exceed 0.1 mm.

As follows from Fig. 2 [see also formula (1)], the difference between the wave numbers of the pair of parametrically excited waves should be equal to double the wave number of the pump, i.e.,

$$k_2-k_1=2k_s. \tag{3}$$

Observation of the existence of such pairs (and by the same token determination of k_s) became possible by

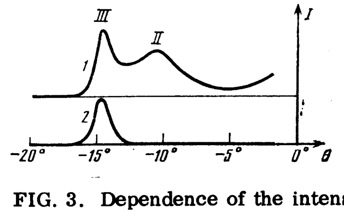

FIG. 3. Dependence of the intensity of the diffracted radiation on the diffraction angle at $z=-0.1$ mm: curve 1—without screen, 2—with opaque screen that obscures the crystal region $z<-0.1$ mm.

determining experimentally the dependence of the form of the angular diffraction spectra for the maximum II on the angle ψ. Plots of $I(\theta)$ for the cases of polarization of the light incident on the crystal parallel ($\psi=0°$) and perpendicular ($\psi=90°$) to the diffraction plane are shown in Fig. 4. Both curves show asymmetry in the angular position of the diffraction maxima: the maxima are observed at $\theta=-10°$ and $+12°$ for $\psi=0°$ and at $\theta=-12°$ and $+10°$ at $\psi=90°$.

The observed phenomena can be explained by recognizing that in the discussed case the parametrically excited modes are quasispin waves, for which the ratio of the intensities of the Stokes (I_s) and anti-Stockes (I_{as}) components of the diffracted radiation at $\psi=0°$ and $\psi=90°$ in YIG, at the employed experimental geometry, amounts to (see Refs. 10, 23, 34)

$$\frac{I_s(0°)}{I_{as}(0°)}=\frac{I_{as}(90°)}{I_s(90°)}=\frac{1-B}{1+B}, \tag{4}$$

$$B=2\alpha\beta_2 a_s/(\alpha^2 a_s^2+\beta_2^2). \tag{5}$$

Here α and β_2 are respectively the linear and quadratic magneto-optical constants, and a_s is the ellipticity of the spin wave. Using the known values (for YIG at wavelength 1.15 μm and $T=290$ K) $\alpha=-3.68\times10^{-4}$ and $\beta_2=-2.35\times10^{-4}$ (see Refs. 32 and 38), and assuming[4] $a_s=1$, we find that $I_s(0°)/I_{as}(0°)=0.0486$ and $I_s(90°)/I$ $(90°)=20.56$. Since the intensities of the Stokes and anti-Stokes components differ greatly at $\psi=0°$ and $\psi=90°$, the predominant contribution to the diffraction maxima at $\theta>0$ and $\theta<0$ is made by only one of the components. For example, at $\theta<0$ the contribution that predominates at $\psi=0°$ is from one of the waves of the parametrically excited pair, with frequency ω_1 and wave vector $\mathbf{k}_1=\mathbf{i}_z k_1$, while at $\psi=90°$ the other wave of the pair predominates (with frequency ω_2 and wave vector $\mathbf{k}_2=-\mathbf{i}_z k_2$).

By using an opaque screen that made it possible to obscure gradually the crystal regions, starting from the end excited by the antenna ($z=-L/2$), it was possible to eliminate the diffraction maximum corresponding to the angle $\theta=12°$ (see Fig. 4). The intensity of the maximum with $\theta=10°$ remained practically unchanged in this case. It follows from Fig. 2 that this occurred when the edge of the screen was located at the point $-z^*$.

From the difference ($\Delta\theta$) of the angular position of the maxima at $\theta>0$ and $\theta<0$ it was possible to determine the wave number of the pump, which turned out to be $\approx10^3$ cm^{-1}. Thus, the magnetoelastic waves of the upper branch of the hybrid spectrum are parametrically excited by magnetostatic waves that lie barely above the bottom of the spectrum ($k_{tp}\approx2\times10^3$ cm^{-1}).

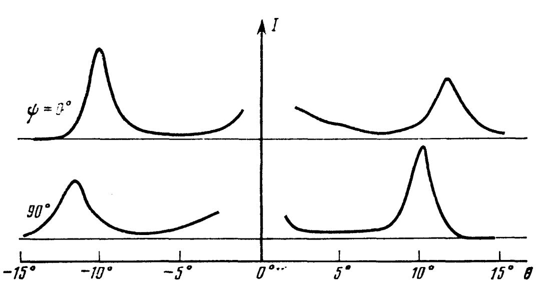

FIG. 4. Dependence of the intensity of the diffracted radiation on the diffraction angle for maximum II at $z=-0.1$ mm, $H=569$ Oe, and $P_{micro}=100$ mW.

3. PARAMETRIC EXCITATION OF MAGNETOELASTIC WAVES OF THE LOWER BRANCH OF THE HYBRID SPECTRUM

The diffraction maxima IV and V (see Fig. 1), which exist at $H\gtrsim H_{crit}$, correspond to diffraction angles θ that exceed the value $\theta\approx20.7°$ for light scattering by transverse elastic waves in YIG at a frequency 1.2 GHz. This is evidence that the modes generating the indicated maxima belong to the lower branch of the hybrid magnetoelastic spectrum. The optimal conditions for the observation of maxima IV and V are realized near the center of the sample, where the gradient of the internal magnetic field is negligibly small, and the linear (nonparametric) excitation of the waves of the lower branch of the hybrid spectrum is forbidden (see, e.g., Ref. 32). In addition, favoring the parametric mechanism of excitation of the waves that generate the maxima IV and V are the following facts.

1. The maxima IV and V appear at a microwave power exceeding a certain threshold value $P_{crit}\sim10$ mW. The dependence of the intensity of the diffracted radiation is nonlinear; in a definite interval of variation of P_{micro}, the intensity of the radiation at these maxima increases more rapidly than the microwave excitation power, followed by saturation. With increasing microwave power, the magnetizing-field regions in which the maxima IV and V exist become broader.

2. To each value of h corresponds a certain value[5] of z^* that separates the regions of the existence of the maxima IV and V: the maximum IV is observed at $-L/2<z<-z^*$, and V at $-z^*<z<+L/2$. The two maxima are observed simultaneously only if the probing beam covers the point $-z^*$. It is clear that this point must be identified with the point where the magnetostatic wave $(\omega_s,\mathbf{k}_s)$ that propagates from the end ($z=-L/2$) towards the center of the sample breaks up parametrically into a pair of magnetoelastic waves of the lower branch of the hybrid spectrum, whose frequencies (ω_1,ω_2) and wave vectors $(\mathbf{k}_1,\mathbf{k}_2)$ satisfy relations (2).

The parametrically excited wave with the higher frequency $(\omega_2,\mathbf{k}_2)$ goes off to the end of the crystal ($Z=-L/2$), while the wave with the lower frequency $(\omega_1,\mathbf{k}_1)$ is directed towards the crossover point $-z_{cr}(\omega_1)$, where it is transformed into an elastic wave. The elastic wave passes through the center of the sample ($z=0$) and from there to the conjugate crossover point $+z_{cr}(\omega_1)$, where it is transformed into a spin wave (Fig. 5). Generally speaking, parametric excitation of waves in accordance with the indicated scheme can take place also under conditions when there are no crossover points in the sample. Experiments show, however, that in this case the intensity of the diffracted radiation in the maxima IV and V decreases rapidly. This may be due to the increase in the threshold of the pa-

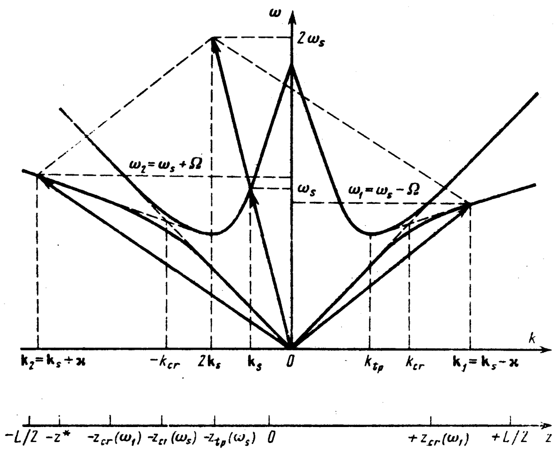

FIG. 5. Vector diagram of the process of parametric excitation of two magnetoelastic waves of the lower branch of the hybrid spectrum by a magnetostatic wave. The lower part shows the distribution of the characteristic points in the sample.

rametric excitation for waves with large k.

In contrast to maximum II, no "doubling" of which is observed at $\psi = 0°$ or $\psi = 90°$, the maxima IV and V, in an identical geometry, can coexist at a definite choice of the probing point and of the magnetizing-field intensity (see Fig. 1). This is particularly noticeable if the excited waves are quasielastic, when the ratio of the intensities of the Stokes and anti-Stokes components is close to unity (see Ref. 23). However, owing to the renormalization of the ellipticity of the spin component of the hybrid wave in magnetoelastic interaction, one can expect[23] also complete extinction of one of the components in the quasispin phase at

$$a_s^{(eff)} = a_s(1-w)^{-1} = (a_s)_{crit} = |\beta_2/\alpha|, \tag{6}$$

where

$$w = \varepsilon_0^2 p_{44} M_0(\omega/\gamma - H_{eff}) B_2^{-1}. \tag{7}$$

Here ε_0 is the dielectric constant, p_{44} is the photoelastic constant, ω is the frequency of the magnetoelastic wave, H_{eff} is the effective field, and B_2 is the magnetoelastic constant. The critical value of the ellipticity $(a_s)_{crit}$ for YIG under the chosen experimental conditions is 0.639 (Ref. 23). The effect of extinction of the Stokes (or anti-Stokes) component of the radiation scattered by the quasispin waves (i.e., the vanishing of the maximum IV or V) was indeed observed in practice.

The difference $\Delta\theta$ between the diffraction angles corresponding to the maxima IV and V yields information on the pump wave vector $\mathbf{k}_s$. It follows from Fig. 1 that $\Delta\theta \approx 2°$, i.e., $k_s \approx 2\times 10^3$ cm$^{-1} \approx k_{tp}$, therefore in this case the pump is a magnetostatic wave with a wave vector approximately corresponding to the turning point.

The dependences of the angle $\Phi_F(\psi)$ of rotation of the polarization plane of the diffracted-radiation anti-Stokes component on the orientation of the vector **E** of the light incident on the crystal are shown in Fig. 6 for the maximum V. Curves *1–3* were obtained for a field 650 Oe at three positions of the probing beam at

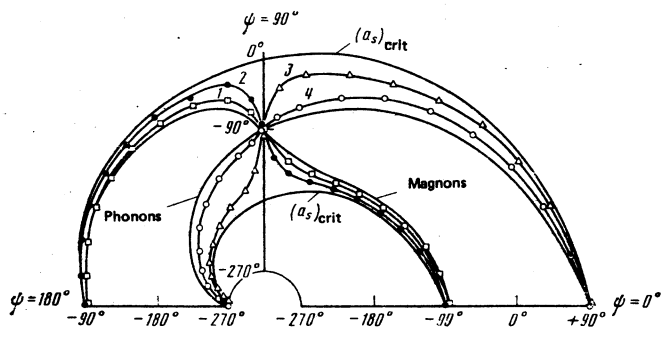

FIG. 6. Orientational dependences of the angle of rotation of the plane of polarization of the anti-Stokes component of the diffracted radiation for the maximum V at the following choice of the probing point and of the value of the magnetic field intensity: for h = 650 Oe: curve *1*—z = + 2.6 mm, *2*—z = + 2.1 mm, *3*—z = + 0.2 mm; for H = 703 Oe: curve *4*—z = + 0.2 mm.

points z equal to +2.6, +2.1, and +0.2 mm, respectively, while curve *4* was obtained at $H = 703$ Oe and z =+0.2 mm. The increase in the number of curves corresponds to conditions when the magnetoelastic wave gradually turns from a quasispin to a quasi-elastic wave. The transition from the spin phase to the elastic phase can lead to the theoretically predicted[23] change of the form of the function $\Phi_F(\psi)$, as can be clearly traced in Fig. 6, in which the theoretical relations are plotted in accordance with the formula

$$\Phi_F^{(as)} = \mathrm{Arctg}\left[\mathrm{ctg}\,\psi \frac{\beta_2 + a_s^{(eff)}\alpha}{\beta_2 - a_s^{(eff)}\alpha}\right] - \psi. \tag{8}$$

To reconcile experiment with theory we need only assume that the elasto-optical constant p_{44} in YIG is negative.

The orientational dependence of the ratio of the intensities of the Stokes and anti-Stokes components of the diffracted radiation for the maximum V at different values of the magnetic field and z =+0.2 mm are shown in Fig. 7. In magnetic fields greatly exceeding $H_{crit} \approx 570$ Oe, the diffraction is from quasi-elastic waves, and the ratio I_s/I_{as} depends little on the polarization of the radiation incident on the crystal. With decreasing

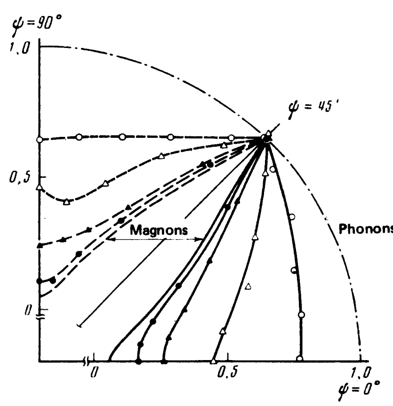

FIG. 7. Orientational dependences of the ratio of the intensities of the Stokes and anti-Stokes components of diffracted radiation for the maximum V at z = + 0.2 mm. Solid curve—(I_s/I_{as}); dashed—(I_{as}/I_s). The values of H on the curves are 569 (●), 590 (▲), 650 (△), and 703 Oe (○).

H, the spin component begins to predominate in the hybrid wave, and the $I_s/I_{as} = f(\psi)$ curves assume a form typical of diffraction by magnons. These results are also in good agreement with the theory,[23] which yields the following expression for the ratio of the intensities of the components:

$$\frac{I_s}{I_{as}} = \frac{1-B\cos 2\psi}{1+B\cos 2\psi}, \quad (9)$$

$$B = \frac{2\alpha\beta_2 a_s^{(eff)}}{\beta_2^2 + (\alpha a_s^{(eff)})^2}.$$

CONCLUSION

From the results of the investigation of the diffraction of light by magnetostatic and magnetoelastic waves we determined the $k(H)$ dependence for the investigated YIG sample at 1.2 GHz, which is shown in Fig. 8 (the dashed line shows qualitatively the course of the curves in regions inaccessible for measurement by the diffraction method). The wave numbers of the modes were calculated with the aid of the Bragg relation

$$k = 2k_L \sin(\theta/2), \quad (10)$$

where k_L is the wave vector of the light. For magnetostatic and linearly excited magnetoelastic waves of the upper branch of the spectrum, k was calculated by using directly the experimentally measured diffraction angles. The lower branch of the magnetoelastic spectrum was excited only parametrically, and this was accompanied by a shift of the frequency of the waves relative to the frequency of the exciting microwave signal ($\Omega \lesssim 10$ MHz). The wave number of this mode was therefore determined from formula (10) where θ was taken to be the arithmetic mean of the diffraction angles corresponding to the diffraction maxima IV and V.

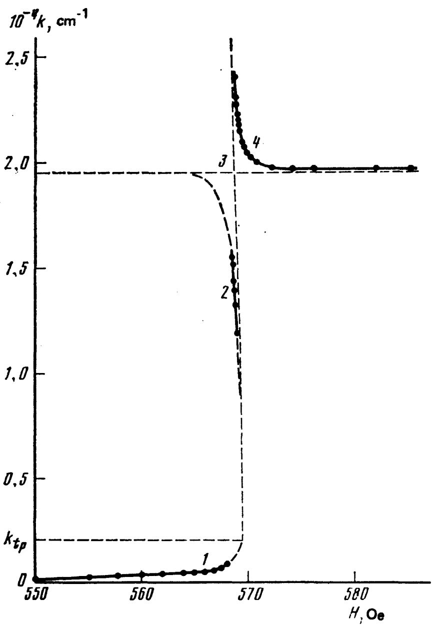

FIG. 8. Wave numbers of the modes with frequency 1.2 GHz, observed in YIG prism by diffraction of light, vs. the magnetic field at $z = -0.1$ mm: curve *1*—magnetostatic waves, *2* and *4*—magnetoelastic waves of the upper and lower branches of the hybrid spectrum, respectively, *3*—uncoupled elastic waves.

We succeeded in our experiments in observing (see Fig. 8) the diffraction of light by linearly (non-parametrically) excited magnetostatic waves with 1.5×10^2 cm^{-1} $< k < 10^3$ cm^{-1}, linearly excited magnetoelastic waves of the upper branch of the spectrum with 1.2×10^4 cm^{-1} $< k < 1.55\times10^4$ cm^{-1}, and parametrically excited magnetoelastic waves of the upper branch of the spectrum with $k \approx 10^4$ cm^{-1} and the lower branch with 2.0×10^4 cm^{-1} $< k < 2.4\times10^4$ cm^{-1}.

The microwave pump power threshold of parametric excitation of magnetoelastic waves in the employed sample at 1.2 GHz ranged from 10 to 100 mW. These (and even larger) values of the microwave power are typcial of practically all the earlier experiments on the diffraction of light by magnetic elementary excitations in YIG. It appears that it is precisely parametric effects which were the cause of many anomalies ("doubling" of diffraction maxima, the unusual dependence of the diffraction angle on the magnetic field, and others) which were reported earlier[5-8,11] and the nature of which remained unclear to this very day.

1) The position of the turning point in the sample can be approximately determined from the condition H_i $(z_{tp} \approx \omega_s/\gamma)$, where γ is the gyromagnetic ratio.[32]

2) By crossover point we mean here and elsewhere a point in the sample corresponding at the chosen frequency to the intersection of the dispersion curves for the magnons and transverse phonons.

3) The diffraction angle θ is equal to double the Bragg angle, i.e., the angle between the wave vectors of the incident and diffracted radiation.

4) This assumption is well satisfied in practice, since diffraction takes place from waves that propagate in a prism with square cross section along the vector of the resultant magnetization.

5) More accurately speaking, the Δz^* region whose width increases with increasing microwave excitation power.

1J. F. Dillon, H. Kamimura, and J. P. Remeika, J. Appl. Phys. **34**, 1240 (1963).

2J. T. Hanlon and J. F. Dillon, *ibid.* **36**, 1269 (1965).

3R. W. Dixon and H. Matthews, Appl. Phys. Lett. **10**, 195 (1967).

4R. W. Dixon, J. Appl. Phys. **38**, 3634 (1967).

5A. W. Smith, Appl. Phys. Lett. **11**, 7 (1967).

6B. A. Auld and D. A. Wilson, *ibid.* p. 368.

7A. W. Smith, Phys. Rev. Lett. **20**, 334 (1968).

8A. W. Smith, IEEE Trans. on Sonics and Ultrasonics, SU-15, 161 (1968).

9J. H. Collins and D. A. Wilson, Appl. Phys. Lett. **12**, 331 (1968).

10H. L. Hu and F. R. Morgenthaler, *ibid.* **18**, 307 (1971).

11B. Desormiere and H. Le Gall, IEEE Trans. on Magnetics, MAG-8, 379 (1972).

12A. S. Borovik-Romanov, V. G. Zhotikov, N. M. Kreĭnes, and A. A. Pankov, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 705 (1976) [JETP Lett. **23**, 649 (1976)].

13V. N. Venitskiĭ, V. V. Eremenko, and E. V. Matyushkin, Zh. Eksp. Teor. Fiz. **72**, 1517 (1977) [Sov. Phys. JETP **45**, 759 (1977)].

14Yu. A. Gaĭdaĭ, A. A. Solomko, and V. I. Maĭstrenko, Fiz. Tverd. Tela (Leningrad) **18**, 2205 (1976) [Sov. Phys. Solid State **18**, 1284 (1976)].

[15]Yu. A. Gaĭdaĭ, V. I. Maĭstrenko, and A. A. Solomko, *ibid.* **19**, 1466 (1977) [**19**, 854 (1977)].
[16]A. A. Solomko, Yu. A. Gaĭdaĭ, and V. I. Maĭstrenko, Opt. Spektrosk. **44**, 761 (1978) [Opt. Spectrosc. **44**, 444 (1978)].
[17]Yu. A. Gaĭdaĭ, I. I. Kondilenko, and A. A. Solomko, Pis'ma Zh. Eksp. Teor. Fiz. **21**, 575 (1975) [JETP Lett. **21**, 269 (1975)].
[18]Yu. A. Gaĭdaĭ, I. I. Kondilenko, and A. A. Solomko, Fiz. Tverd. Tela (Leningrad) **17**, 2941 (1975) [Sov. Phys. Solid State **17**, 1957 (1975)].
[19]Yu. A. Gaĭdaĭ, I. I. Kondilenko, V. I. Maĭstrenko, and A. A. Solomko, *ibid.* **19**, 1469 (1977) [**19**, 855 (1977)].
[20]A. A. Solomko, Yu. A. Gaĭdaĭ, and V. I. Maĭstrenko, Opt. Spektrosk. **45**, 127 (1978) [Opt. Spectrosk. **45**, 70 (1978)].
[21]N. N. Kiryukhin F. V. Lisovskiĭ, and G. V. Skobelin, Pis'ma Zh. Eksp. Teor. Fiz. **20**, 712 (1974) [JETP Lett. **20**, 329 (1974)].
[22]N. N. Kiryukhin and F. V. Lisovskiĭ, *ibid.* **24**, 485 (1976) [**24**, 445 (1976)].
[23]N. N. Kiryukhin and F. V. Lisovskiĭ, Radiotekh. Élektron. **25**, 467 (1980).
[24]V. N. Venitskiĭ, V. V. Eremenko, and É. V. Matyushkin, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 239 (1978) [JETP Lett. **27**, 222 (1978)].
[25]V. N. Venitskiĭ, V. V. Eremenko, and É. V. Matyushkin, Zh. Eksp. Teor. Fiz. **77**, 1965 (1979) [Sov. Phys. JETP **50**, 934 (1979)].
[26]V. G. Zhotikov and N. M. Kreĭnes, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 496 (1977) [JETP Lett. **26**, 360 (1977)].
[27]I. A. Deryugin, V. I. Mykityuk, A. A. Solomko, and V. N. Redchik, *ibid.* **11**, 573 (1970) [**11**, 396 (1970)].
[28]C. B. de Araujo, S. C. Ribeiro, and S. M. Rezende, Sol. St. Commun. **11**, 649 (1972).
[29]A. S. Borovik-Romanov, V. G. Zhotikov, N. M. Kreĭnes, and A. A. Pankov, Zh. Eksp. Teor. Fiz. **70**, 1924 (1976) [Sov. Phys. JETP **43**, 1002 (1976)].
[30]J. P. Jamet and H. Le Gall, Phys. Stat. Sol. (a) **31**, 547 (1975).
[31]E. Schlöman, J. Appl. Phys. **35**, 159 (1964).
[32]G. A. Smolenskiĭ, V. V. Lemanov, G. M. Nedlin, M. P. Petrov, and R. V. Pisarev, Fizika magnitnykh diélektrikov (Physics of Magnetic Dielectrics), Nauka, 1974, p. 454.
[33]N. N. Kiryukhin, I. N. Kotel'nikov, and F. V. Lisovskiĭ, Fiz. Tverd. Tela (Leningrad) **14**, 3686 (1972) [Sov. Phys. Solid State **14**, 3087 (1973)].
[34]N. N. Kiryukhin, F. V. Lisovskiĭ, and G. V. Skobelin, Opt. Spektrosk. **39**, 735 (1975) [Opt. Spectrosc. **39**, 416 (1975)].
[35]N. N. Kiryukhin and F. V. Lisovskiĭ, Fiz. Tverd. Tela (Leningrad) **18**, 278 (1976) [Sov. Phys. Solid State **18**, 163 (1976)].
[36]R. A. Sparks and E. L. Higgins, Appl. Phys. Lett. **7**, 41 (1965).
[37]M. Bini, L. Millanta, N. Rubino, and V. Tognetti, J. Appl. Phys. **40**, 1193 (1969).
[38]F. V. Lisovskiĭ, O. S. Markelova, and V. I. Shapovalov, Fiz. Tverd. Tela (Leningrad) **16**, 3570 (1974) [Sov. Phys. Solid State **16**, 2323 (1975)].

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