NATURAL MAGNETOELASTIC RESONANCE IN IRON GARNETS

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The frequency dependence of the attenuation of elastic waves in yttrium iron garnet and calcium-bismuth-vanadium iron garnet samples is measured between 100 and 1700 MHz. Sharp absorption peaks are observed in the absence of a magnetic field. These peaks disappear in strong magnetic fields and also at temperatures above the Curie point. Analysis of the experimental data shows that this phenomenon can be explained satisfactorily on the basis of natural magnetoelastic resonance, i.e., magnetoelastic resonance in the equivalent fields of the magneto-crystallographic anisotropy.

WE have reported earlier[1] on resonant absorption of elastic waves at frequencies of about 1000 MHz in crystals of yttrium iron garnet in the absence of an external magnetic field. The present paper presents more detailed results of an investigation of this phenomenon.

EXPERIMENTAL METHOD AND RESULTS

The measurements were made with the setup described in[2]. The elastic waves were excited by piezotransducers of quartz and lithium niobate about 100 μ thick. The transducers were affixed to the samples with ceresin or Canada balsam, and in the case of high temperature measurements[1] with water glass. The pulsed method was used. The pulse length was from 0.3 to 1.0 μsec, and the microwave power in a pulse was about 0.5 W. We measured the dependence of the attenuation of elastic waves on frequency in the range 100–1700 MHz. The samples investigated were several of yttrium iron garnet $Y_3Fe_5O_{12}$ cut in different crystallographic directions and two of calcium-bismuth-vanadium iron garnet $Ca_{2X}Bi_{3-2X}V_XFe_{5-X}O_{12}$ with $x \approx 1.3$.

The samples studied were in the form of cylinders of length 4 to 15 mm and diameter 2 to 4 mm. The direction of propagation of the elastic waves coincided with the cylinder axis.

Figures 1 to 3 show the results of measurements of the frequency dependence of elastic wave attenuation in samples of yttrium iron garnet of different orientation in the absence of a magnetic field and in a field of 4000 Oe. The experimental points in the figures represent an average over many measurements.

As is seen from the figures, in the absence of field one observes resonant absorption peaks several tens of MHz wide at certain frequencies; in the 4000-Oe field these peaks are absent. It should be mentioned that the attenuation at the absorption maxima is so huge that the elastic pulses practically disappear completely, so that it becomes impossible to measure the attenuation there. According to our estimates the magnitude of the absorption at the maximum is about 15 db/μsec.

It follows from Figures 1 and 2 that when the elastic waves are propagated along [111], two absorption peaks are observed at 180 and 850 MHz for transverse waves and one peak at 850 MHz for longitudinal waves. In the [110] sample there are two peaks (both for transverse and longitudinal waves) at 550 and 940 MHz, the first peak being very weak.

In the sample the results for which are shown in Fig. 3, the elastic waves were propagated along [113]. In this sample, as is seen from the figure, the absorption line has a complex shape and occupies a wide frequency interval from about 500 to 900 MHz.

The frequency dependence of absorption was also

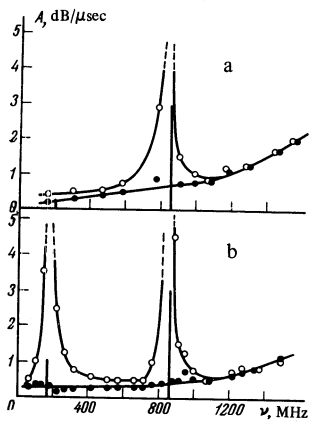

FIG. 1

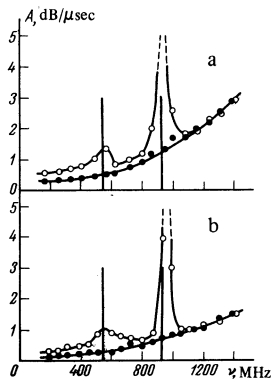

FIG. 2

FIG. 1. Frequency dependence of the attenuation of longitudinal (a) and transverse (b) elastic waves in yttrium iron garnet for propagation along [111]. ○ – H = 0; ● – H = 4000 Oe. The vertical lines in Figs. 1 – 3 give the calculated positions and relative intensities of the absorption lines.

FIG. 2. Frequency dependence of the attenuation of longitudinal (a) and transverse (b) elastic waves in yttrium iron garnet for propagation along [110]. ○ – H = 0; ● – H = 4000 Oe.

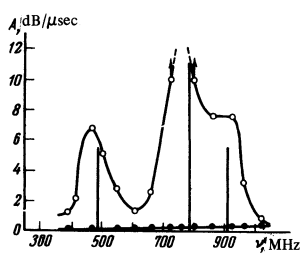

FIG. 3. Frequency dependence of the attenuation of transverse elastic waves in yttrium iron garnet for propagation along [113]. ○ – H = 0; ● – H = 4000 Oe.

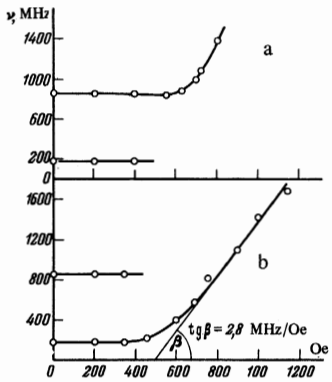

FIG. 4. Magnetic-field dependence of the magnetoelastic resonance frequency for transverse elastic waves propagating along [111]. Magnetic field parallel to a direction of the type ⟨111⟩. a – magnetic field is at an angle of 70° from the wave propagation direction; b – magnetic field is parallel to the propagation direction.

measured in samples cut along [100]. In these samples one sees a single peak at 750 MHz with a width of about 100 MHz.

Similar phenomena were also observed in the crystals of calcium-bismuth-vanadium iron garnet. The samples of this ferrite were oriented approximately along [111]. The frequency dependence of attenuation for these was measured in the 300–1500 MHz region. In this interval a strong absorption peak was found at about 500 MHz.

For the samples of yttrium iron garnet cut along [111] we also investigated the magnetic field dependence of the position and intensity of the absorption peaks. In this case the samples were placed in a sphere of polycrystalline yttrium iron garnet in order to obtain a homogeneous internal magnetic field.

Figure 4 shows how the frequencies corresponding to the two absorption peaks for transverse elastic waves depend on magnetic field. The magnetic field was parallel to a ⟨111⟩-type direction, and in one case (Fig. 4a) it formed an angle of 70° with the direction of propagation of the elastic waves; in the other (Fig. 4b), it was parallel to the propagation direction.

The intensity measurements show that in the first case the intensity of the low-frequency peak decreases with increasing field until it disappears completely at about 500 Oe. In the second case, the intensity of the high-frequency peak decreases with increasing field, and it too disappears in fields of about 500 Oe.

All the experiments described above were carried out at room temperature. As was shown in[1], when the temperature is raised, the absorption peaks move toward lower frequencies, the frequency of the peaks tending toward zero as the Curie temperature is approached. Additional work carried out during the present investigation show that the absorption peaks are completely absent above the Curie point.

DISCUSSION

As was already mentioned in[1], the character of the temperature dependence of the absorption peaks indicates that they are not associated with relaxation processes with definite activation energies, since in this case they would have to shift toward higher frequencies as the temperature is raised. The absence of the peaks above the Curie point, as well as in strong magnetic fields at room temperature, suggests that the absorption is magnetic in nature.

In[1] it was proposed that this phenomenon is one of natural magnetoelastic resonance, i.e., it is a magnetoelastic resonance occurring in the equivalent fields of the magnetocrystallographic anisotropy. As is known, magnetoelastic resonance results in the resonant absorption of elastic waves, at a frequency of the elastic waves that equals[3]

$$\nu = \gamma[H_k(H_k + 4\pi M \sin^2\alpha)]^{1/2}. \quad (1)$$

Here γ is the gyromagnetic constant, equal to 2.8 MHz/Oe, M is the saturation magnetization, α is the angle between the direction of propagation of the waves and the magnetization, and the field H_k is given by

$$H_k = H + H_d + H_A + Dk^2,$$

where H is the applied magnetic field, H_d is the demagnetizing field, H_A is the anisotropy field, D is the exchange constant, and k is the wave number. The last term can be neglected at our frequencies.

It follows from Eq. (1) that resonant absorption of elastic waves can occur even in the absence of an applied field, in the equivalent fields of the magnetocrystallographic anisotropy. The resonant frequency in this case is given by

$$\nu = \gamma[H_A(H_A + 4\pi M \sin^2\alpha)]^{1/2}. \quad (2)$$

We shall show that, using Eq. (2), it is possible to explain the experiments above if one takes the magnetization of the majority of the domains in zero external field to be along the directions of easy magnetization ⟨111⟩.

In our samples, the elastic waves were propagated along [100], [111], [110], and [113]. These directions are at definite angles with respect to the four possible directions of the type ⟨111⟩, and these angles correspond to the angles α in Eq. (2), since the magnetization is along ⟨111⟩.

The anisotropy field H_A for the direction ⟨111⟩ is $4K_1/3M$, where K_1 is the anisotropy constant. Using the values K_1/M = 45 Oe and $4\pi M$ = 1780 G for yttrium iron garnet,[4] we can calculate the resonant frequency for samples of different orientation from Eq. (2). The results of the calculations are given in the table. The experimental values of the resonant frequencies are also given in the table. It is seen from the table that the agreement between theory and experiment is quite good.

It is interesting that for the [111] sample the low-frequency peak at 180 MHz occurs only for transverse waves and is absent for longitudinal waves. The ex-

Resonant frequencies for samples of yttrium iron garnet of different orientation

Orientation of sample	d	ν, MHz	
		Calculated	Experiment
[100]	54°44′	760	750
	0	170	180
[111]	70°32′	870	850
[110]	35°16′	550	550
	90°	930	940
	30°	490	470
[113]	58°	790	750
	80°	910	900

planation is that, for propagation along [111] and at angles $\alpha = 0$, longitudinal elastic waves are not coupled to the spin waves, as an analysis of the equations of motion of coupled elastic and spin vibrations shows.[3] But for all the other cases in the table, both transverse and longitudinal elastic waves can couple with the spin waves.

The next question is what contribution is given to the absorption in zero field by those domains whose magnetization deviates strongly from the easy direction ⟨111⟩. From Eq. (2) it is seen that the greatest resonant frequency is 930 MHz ($\alpha = 90°$). Hence, the domains with arbitrarily oriented magnetization ought to give a contribution that is distributed over a wide range of frequencies approximately up to 900 MHz. In fact, Fig. 3 shows that at frequencies below 900 MHz the absorption in the absence of field exceeds that in a strong field, but at higher frequencies there is no difference.

On the basis of our model, it is easy to explain the data in Fig. 4 on the magnetic field dependence of the resonant frequencies for the [111] sample. In a ⟨111⟩ direction and at an angle of 70° to the wave propagation direction (Fig. 4a), the low-frequency peak, which corresponds to $\alpha = 0$, should disappear as the sample is magnetized by the applied field, since there will be only one value of $\alpha = 70°$ when the sample is magnetized to saturation. But the frequency of the peak corresponding to $\alpha = 70°$ should vary according to Eq. (1) as the field is increased. All of this actually takes place, as experiment shows.

In a ⟨111⟩ direction and parallel to the propagation direction (Fig. 4b), the high-frequency peak disappears as the field is increased, but the frequency of the peak corresponding to $\alpha = 0$, varies linearly with a slope equal to 2.8 MHz/Oe. This dependence should also be in accord with Eq. (1), which for this case reduces to the form $\nu = \gamma(H + H_d + H_A)$.

The crystals of calcium-bismuth-vanadium iron garnet, which were cut along [111], showed an absorption peak in the vicinity of 500 MHz, i.e., considerably lower than the corresponding peak in the yttrium ferrite cut along the same direction. This is easily explained by the smaller anisotropy and saturation magnetization of the calcium-bismuth-vanadium ferrite.

Finally, let us consider the question of the relative intensities of the natural magnetoelastic resonance lines.

The relative intensity of the absorption lines in a sample of a given orientation can be obtained by considering what fraction of all possible ⟨111⟩ directions is at a given angle α. Thus, it is easy to see that for the [113] sample, of all the possible ⟨111⟩ directions, one-fourth are at an angle of 30° to [113], one-half are at 58°, and one-fourth are at 80°. In accordance with this, the intensities of the peaks for the [113] sample at 490, 790, and 910 MHz (see the table) should be in the ratio 1 : 2 : 1. Similarly, we find that the intensities for the [111] sample are as 1 : 3, and for the [110] sample, as 1 : 1. In Figs. 1–3 the vertical lines correspond to these relative intensities. It is seen that good agreement is obtained for the [113] sample. For the [111] sample comparison is impossible, since the absorption at the maximum could not be measured, and for the [110] sample the intensity of the 550-MHz peak is considerably less than that of the 940-MHz peak, whereas, according to theory they should be the same. This discrepancy may be partially due, as we shall now show, to the great width of the line at 550 MHz.

The width of a magnetoelastic resonance line should be determined by the relaxation times of the phonons and magnons of the corresponding frequencies. As our measurements show,[2,5] these times are such that the width due to them is not greater than 1 MHz, whereas the experiment generally gives a width of the order of several tens of megahertz. A possible source of this broadening may be the circumstance that the magnetizations of most of the domains are not directed exactly along ⟨111⟩, as we assumed, but are distributed in some fashion close to these directions. This leads to a change of the resonant frequency because of a change in the angles α and in the anisotropy field in Eq. (2). The change in angles gives a somewhat greater contribution, which is easy to estimate by differentiating Eq. (2) with respect to α. In doing this, one finds that for angles $\alpha \approx 30°$, a change in α by 1° leads to a frequency change of 10 MHz, whereas when $\alpha = 0°$ and 90°, the same change in α gives an order smaller frequency change. Hence, the line at 550 MHz ($\alpha = 35°$) should be broad. The line at 760 MHz ($\alpha = 55°$) should also be rather broad, but the lines at 180 and 930 MHz ($\alpha = 0$ and 90°) should be considerably narrower. The experimental data agrees qualitatively with these estimates.

It should be pointed out that the line width will similarly depend on inaccuracy in the orientation of our specimens. A small error in orientation will lead to a strong broadening of the lines at 550 and 760 MHz but will have practically no effect on the width of the lines at 180 and 930 MHz.

Thus, the peaks that we have found in the absorption of elastic waves in ferrite crystals are easily explained as a magnetoelastic resonance in the equivalent fields of the magnetocrystallographic anisotropy.

We remark that this new phenomenon may be of value for measurements of saturation magnetization and anisotropy constants, as well as for investigations of the domain structure and magnetization processes in ferrites.

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