Observation of fast magnetoelastic waves in thin yttrium-iron garnet wafers and epitaxial films

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The fine structure of the interference bands of magnetostatic and ordinary electromagnetic waves, which is attributed to magnetoelastic resonance at phase velocities that exceed the velocity of sound in an unbounded crystal by an order of magnitude and more, has been observed experimentally for the first time in yttrium-iron garnet (YIG) wafers and films which are saturated in an external magnetic field H.

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We have investigated the excitation and propagation of direct magnetostatic bodywaves (DMBW) in YIG samples. The samples were plane-parallel, optically polished wafers and epitaxial films with typical dimensions of 5.5 × 4 × 0.35 mm and 7 × 4 × 0.004 mm, respectively, and having an FMR line width of ~1 Oe. The films were deposited on a 430-μm-thick gadolinium-gallium garnet (GGG) [111] substrate; the various wafer orientations that were chosen had no basic effect on the results. The samples were placed in a magnetic field H which was normal to the large surfaces areas and which was adjustable. Wire antennas (copper with a diameter $w \approx 70$ μm) were attached to the surfaces; one end of these antennas was grounded while the other was connected via a transmission line either to a microwave-frequency generator or to a microwave receiver (see insets in Figs. 1 and 2). Sweep generators with frequencies in the 50 to 1250-MHz and 2 to 4-GHz bands were used. The receiver measured the amplitude-frequency response characteristics (AFC) and made possible the simultaneous screen display of the characteristics of the signal that was reflected from the sample and transmitted through it.

At $H = 0$ the AFC of the transmitted and reflected signals consisted of a series of smooth peaks, the width of each being ~50–100 MHz. The frequency position and height of these peaks could be controlled by changing the matching conditions of the sample to the generator and receiver. Such an AFC represented the passage of ordinary electromagnetic waves in the system ("induction"). When a sufficiently large field H was applied ($\gtrsim 2$ kOe for the thin-film sample), we observed a dip with a width of ~200 MHz in the spectrum of the reflected signal, against the background of which the induction peaks were visible. As H was increased, the dip shifted toward higher frequencies. The location of the dip for a constant H corresponded to the interval of the DMBW.^{1} This showed that the dip appeared because of the excitation of these waves and because of the resultant reduction of the microwave power reflected from the sample. In this case bands of interference between the induced and the phase-delayed DMBW signal appeared in the spectrum of the transmitted sig-

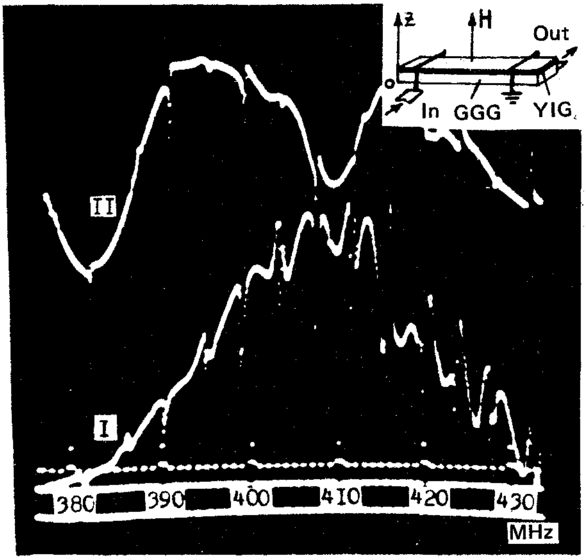

FIG. 1. Amplitude-frequency response characteristics. I—Signal at output antenna; II—signal reflected from input antenna; the amplitude is plotted in arbitrary units on the *Y* axis and the frequency is plotted in MHz on the *X* axis (this also pertains to curves I and II in Figs. 2 and 3).

nal within the induction peaks. If the scale of the frequency axis is expanded, leaving only one induction peak on the screen (see Fig. 1), then we observe the fine structure of the interference bands–narrow peaks with a width of ~1–2 MHz. The

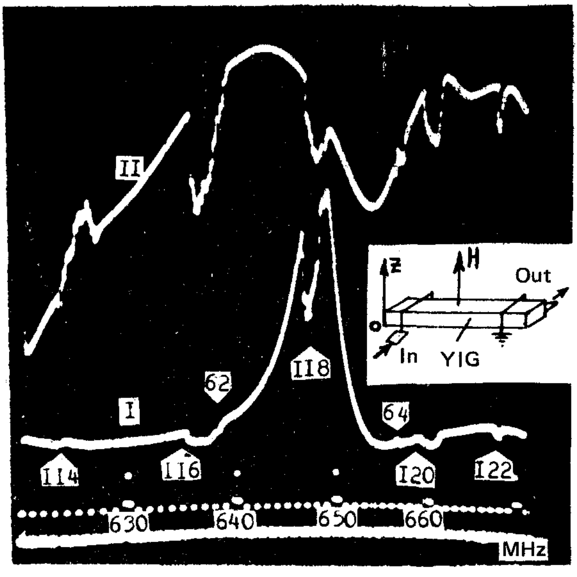

FIG. 2. Magnetoelastic resonances of a ferrite wafer—the numbers of the longitudinal and transverse elastic waves are shown.

interference bands have been observed previously (Ref. 2 and elsewhere). Until now, however, there have been no reports of observation of their fine structure. Narrow peaks were also observed in the reflected signal (Fig. 1) at the same frequencies as the peaks of the transmitted signal. The observed narrow peaks arise presumably because of a magnetostrictive resonant interaction of elastic Rayleigh-Lamb waves or Love waves[3] with the DMBW. Such a resonant interaction was investigated theoretically in previous papers.[4,5] So far as we know, however, it has not been detected experimentally until now.

The coincidence between the frequencies of the narrow peaks and the cutoff frequencies of the longitudinal (f_l) and transverse (f_t) elastic waves confirms that the resonance in question was observed by us[3]

$$f_l = \frac{v_{sl}}{4h} m , \qquad f_t = \frac{v_{st}}{4h} n, \tag{1}$$

where v_{sl} and v_{st} are the velocities of longitudinal and transverse sound, h is the half-thickness of the elastic layer, and m and n are the wave mode numbers. We prove this first for the ferrite wafer which has the symmetry plane $z=h$ (Fig. 2). According to Ref. 5, symmetry leads to selection rules ("conservation of parity")—waves with even (or odd) magnetic potential interact only with odd (or even) elastic waves. In Eq. (1) an even elastic wave corresponds to odd m and even n numbers; an uneven wave corresponds to even m and odd n numbers.[3] Hence, a magnetoelastic resonance should be observed at frequencies separated from each other by $\Delta f_l \approx v_{sl}/2h$ or by $\Delta f_t = v_{st}/2h$ ($\Delta n = \Delta m = 2$). Substituting the experimental value $\Delta f_l \approx 21$ MHz and $\Delta f_t \approx 10.8$ MHz, we obtain $v_{st} = (3.78 \pm 0.73) \times 10^5$ cm/sec and $v_{sl} = (7.36 \pm 0.73) \times 10^5$ cm/sec, in agreement with the known sound velocities in YIG (according to Ref. 6, $v_{sl} = 7.21 \times 10^5$ cm/sec and $v_{st} = 3.85 \times 10^5$ cm/sec). Conversely, using the known v_{sl} and v_{st} (the error is $< 1\%$ in Ref. 6), we calculate the numbers m and n from Eq. (1). For the peaks in Fig. 2 we obtain $m = 62$ and 64 and $n = 114$, 116, 118, 120, and 122. It can be seen that the wave mode numbers increase by two, i.e., parity is conserved, and and even DMBW interacts with an odd longitudinal elastic wave, while an odd DMBW interacts with an even transverse wave. A thin-film structure has no symmetry plane (Fig. 3). Therefore, the magnetoelastic interaction occurs without parity conservation. Assuming that the numbers of adjacent peaks differ by one, we obtain from Eq. (1) $v_{sl} = (6.7 \pm 1.0) \times 10^5$ cm/sec and $v_{st} = (3.6 \pm 0.3) \times 10^5$ cm/sec, in agreement with the known sound velocities in GGG (according to Ref. 6, $v_{sl} = 6.36 \times 10^5$ cm/sec and $v_{st} = 3.57 \times 10^5$ cm/sec). A calculation of the numbers n and m analogous to the previous calculation gives the results in Fig. 3—the numbers have no definite parity. The accuracy of our estimates of v_{sl} and v_{st} ($\sim 10\%$) is limited by the observable width of the narrow peaks, which is considerably greater (by a factor of ~ 30) than the value estimated from theory.[5] The observed width is explained by irregularities of h, which are $\lesssim 1$ μm in our samples. In accordance with theory[5]: 1) The peaks of the longitudinal waves have a much lower intensity that the transverse peaks; 2) as the frequency is increased, the peaks of no signal transmission can be replaced by transmission peaks (Fig. 1). The drops of alcohol on the wafer surface caused the disappearance of longitudinal-wave peaks, which subsequently reappeared as the alcohol evaporated. As H was increased, the

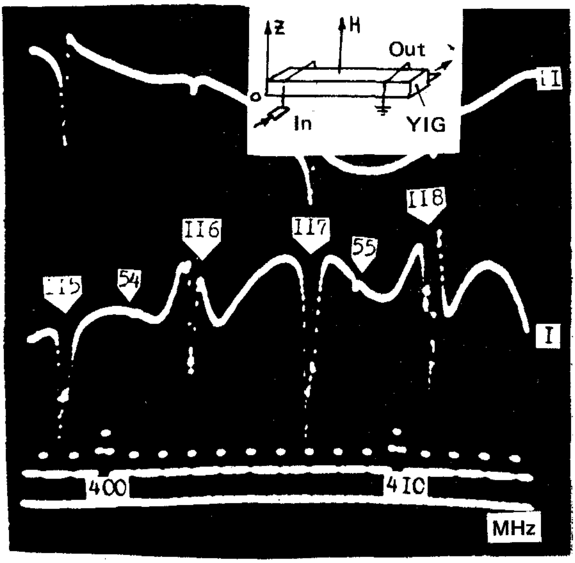

FIG. 3. Magnetoelastic resonances of a thin-film structure.

frequency band of DMBW shifted outside the limits of the induction peak, and the interference bands and acoustic peaks disappear, as should be the case for coupled magnetoelastic waves. The phase velocity ν_{ph} of such waves is close to that of DVMSW.[5] This makes it possible to estimate ν_{ph} from the interference pattern in Figs. 2 and 3. If f_1, q_1 and f_2, q_2 are the frequencies and wave numbers of two adjacent interference peaks and l is the distance between antennas, we obtain from the relation

$$\frac{2\pi}{l} = |q_2 - q_1| \approx \frac{2\pi |f_1 - f_2|}{|\nu_{gr}|}, \qquad (2)$$

the group velocity $|\nu_{gr}| \sim 10^7$ cm/sec for the wafer and $|\nu_{gr}| \sim 1.5 \times 10^6$ cm/sec for the film. Such a decrease of $|\nu_{gr}|$ with decreasing thickness (on going from a wafer to a film) is characteristic of exchange-free DMBW.[1] The exchange-free nature of the DMBW is also clear from the excitation method—an antenna with a wire diameter w excites only waves with $q \lesssim \pi/w \sim 450\ \text{cm}^{-1}$. From the dispersion laws for exchange-free DMBW[1] it follows that $|\nu_{ph}| > |\nu_{gr}|$. In our experiments, therefore, $|\nu_{ph}|$ exceeds ν_{sl} and ν_{st} by an order of magnitude and more.

In summary, very fast, exchange-free magnetoelastic waves, for which $|\nu_{ph}| > |\nu_{gr}| \gtrsim (10^6 - 10^7)$ cm/sec $\gg \nu_{sl}$ and ν_{st}, propagate in saturated YIG layers in an external magnetic field. The discovery of such waves broadens our understanding of the spectrum of excitations in an elastic ferromagnetic material and demonstrates a new way of converting electromagnetic energy into elastic energy.

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