Light scattering study of phonons parametrically excited in the weak ferromagnet $FeBO_3$[a)]

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We report on a new type of ferromagnetic resonance (FMR) instability which is due to the parametric excitation of phonons in $FeBO_3$, and its observation by inelastic light scattering. The new and most remarkable feature of the process is its low power threshold, since it appears even prior to the competing perpendicular pumping Suhl I magnon instability in the coincidence region. The measurements were performed at room temperature and X-band ⊥ pumping configuration. The FMR absorption saturates above a certain power threshold, simultaneously a strong generation of phonons at half the microwave frequency is observed by light scattering. Using a high contrast Fabry-Perot interferometer, the onset of the phonon generation could be measured starting from the thermal level. At higher microwave power the scattered light is so strong that it can be observed visually. It is thereby revealed that the phonons propagate in sharply defined directions as determined by the energy and momentum conservation conditions of the parametric process.

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INTRODUCTION

The usefulness of Brillouin scattering from thermal magnons to investigate magnetic materials has been demonstrated by several authors /1-5/. Another successful method is the study of parametric processes such as the Suhl type instabilities or parallel pumping. They are effective methods to generate magnetic, magnetoelastic or elastic waves /6-8/. The identification of the generated waves, however, in many cases is rather difficult. It is therefore promising to combine the two techniques, i.e. to observe parametrically pumped excitations by inelastic light scattering.

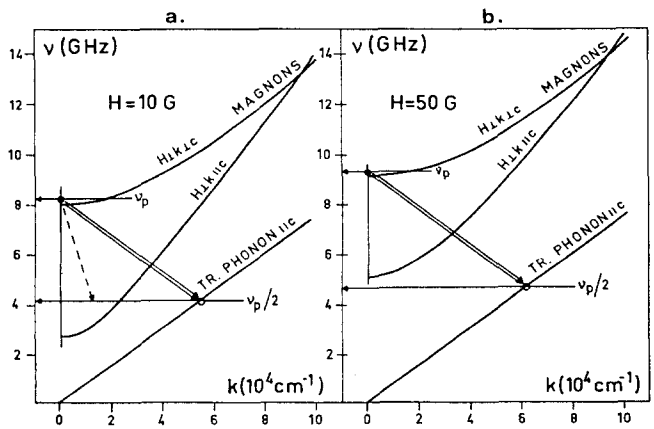

Fig.1 Phonon dispersion and spin wave band of $FeBO_3$ for small wavevectors at room temperature. Only transverse phonons propagating parallel to the c-axis are drawn. The magnetic fields are chosen for resonance of the uniform precession at (a) 8.2 GHz and (b) 9.2 GHz. Arrows indicate instability processes.

We have performed such measurements using the transparent (green) weak ferromagnet $FeBO_3$. The microwave (MW) properties of this material have been extensively characterized both by ferromagnetic resonance (FMR) /9/ and Brillouin scattering techniques /2,3/ Part of the results of references /2,3/ is quoted in Fig.1, showing the dispersion of transverse phonons and the spin wave band at two different magnetic fields H. Details of this figure shall be discussed below.

Our primary goal was to observe the second order perpendicular instability. This is the conversion of two magnons of the uniform precession (UP), driven resonantly at a microwave frequency ν_p, into a pair of degenerate magnons with wavevectors $\pm \vec{k}$.

Instead, we found that a pair of transverse phonons with frequency $\nu_p/2$ is generated. By suitable choice of the pump frequency we further assessed that the "phonon instability" has a threshold even lower than the first order perpendicular instability at coincidence. This is a situation where both the UP and the $\nu_p/2$ spin waves are resonant.

The identification of the parametrically excited phonons is accomplished by measuring both frequency and $\vec{k}$ by inelastic light scattering. As a particularly interesting feature we mention that the light scattered from the pumped phonons is strong enough to be inspected visually on a ground glass plate.

EXPERIMENTS AND RESULTS

The experimental setup is shown in Fig.2. The X-band cavity was fed by pulsed MW sig-

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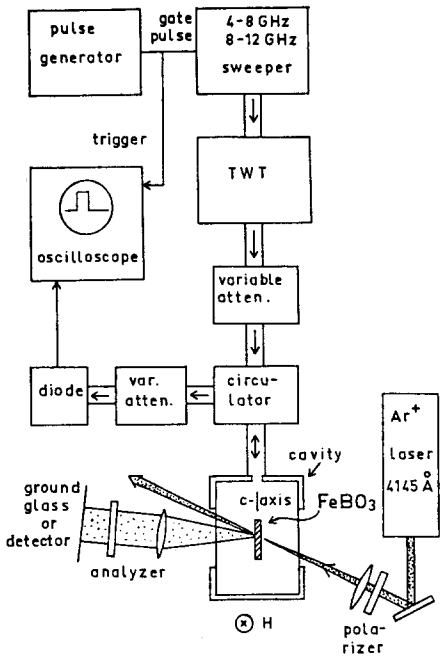

Fig.2 Experimental setup

nals ν_p = 8.2 or 9.2 GHz. These were generated by a sweeper and amplified by a TWT to give output pulses of about 20 Watt. To obtain cavity resonance at 8.2 GHz a polystyrene insert was used. The pulse length was 2 msec and the repetition rate 2 Hz in order not to heat the sample. The $FeBO_3$ single crystal with dimensions 8x8x.1 mm was positioned in the cavity in the maximum of the microwave field h, normal to the plate surface. H and the c-axis of the crystal were in the sample plane perpendicular to each other and to h.

The FMR linewidth is about 40 Gauss for small MW power /10/. Above a certain power threshold the linewidth increases indicating the onset of the parametric process. This strongly increased linewidth, though well observable at high power level, cannot be measured accurately, because such an investigation requires H to be scanned, whereby the parametric process itself is changed rather drastically. We therefore measured the microwave signal reflected from the cavity (normalized to the applied power) at the constant field for resonance of the FMR. As is seen in Fig.3, lower curve, this signal is constant at low power; above threshold it steadily declines.

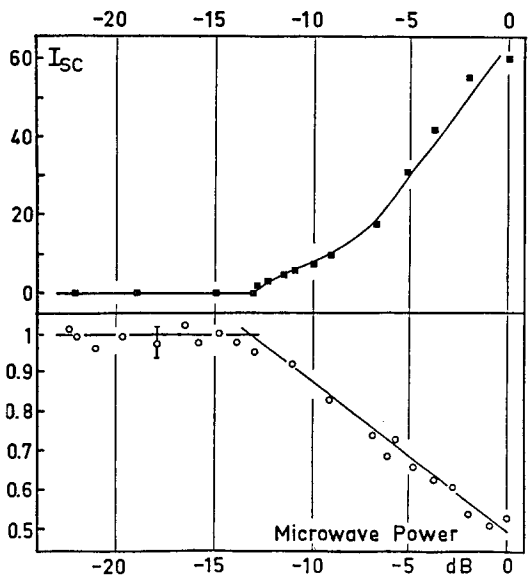

Fig.3 Lower curve: Normalized microwave signal reflected from the cavity at FMR as a function of microwave power. Upper curve: Dependence of light intensity inelastically scattered from phonons at half the microwave frequency on the applied microwave power.

In addition to the FMR measurements light scattering experiments were performed in order to determine the character of the instability. The side walls of the MW cavity had openings such that laser light could be focussed on the crystal and the scattered light could be detected, see Fig.2. The angles of the incident and scattered light with respect to the c-axis were chosen appropriate to observe phonons at $\nu = \nu_p/2$ propagating approximately parallel to the c-axis, with wavevectors shown in Fig.1 /3/. Analyzer and polarizer were crossed to benefit from the different polarizations of elastically and inelastically scattered light. Thereby the cw background caused by the elastically scattered light could be partially suppressed.

The intensity of the scattered light increases drastically above the same power threshold as determined by the FMR measurement. This is shown in the upper curve of Fig.3. From these observations it is clear

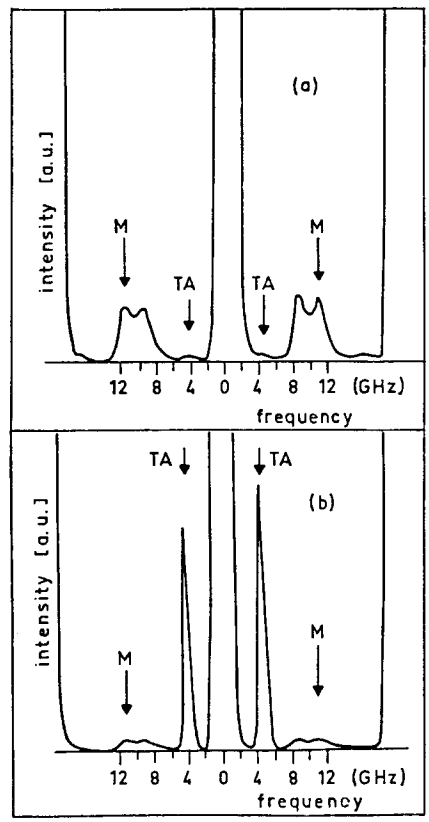

Fig.4 a) Brillouin spectrum of thermally excited phonons and magnons in $FeBO_3$. The scattering angle was adjusted to observe magnons and phonons propagating parallel to the c-axis, the phonon frequency being 4.6 GHz (see Fig.1 b)
Fig.4 b) Configuration as in a) but with a 5 msec microwave pulse of ν_p = 9.2 GHz applied to the crystal.

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that the enhanced scattering is due to parametrically generated excitations. Since the wavevectors involved are known from the scattering geometry, an independent measurement of the corresponding frequencies allows an unequivocal identification, using the dispersion curves given in Fig.1.

The final proof that the light scattering is due to phonons rather than magnons was therefore given by a frequency analysis in a Fabry-Perot interferometer /11/. Fig.4a shows the spectrum of the thermally excited phonons and magnons (no MW applied). When the MW was turned on, the intensity scattered from the phonons increased up to a factor of 10^5 above the thermal level, whereas the magnon lines remained almost unchanged. Fig.4b demonstrates a small fraction of this enhancement obtained by applying a few pumping pulses, while sampling the thermal background for a much longer time. The amount and the selectivity of the enhancement definitely rules out a mere thermal effect.

The scattered light was so intense that it could be observed directly by eye on a ground glass screen. Fig.5 shows a photograph of the scattered light. It appears as a X-shaped figure on the screen. The feature can be explained quantitatively using the data of the anisotropic elastic constants of $FeBO_3$ /2/. This analysis will be given in detail elsewhere.

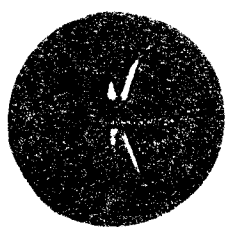

Fig.5 Photograph of light scattered from parametrically excited phonons in $FeBO_3$.

DISCUSSION

Phonon instabilities are brought about by magnetoelastic coupling. Thus they may occur at low threshold if the phonon dispersion intersects the spin wave band at the frequency of the final states. If no resonant magnetoelastic coupling exists, as is the case here, it is expected that phonons can be generated only if a suitable choice of ν_p and H ensures that all magnons have frequencies $\nu > \nu_p/2$. This precaution suppresses competing first order magnon instabilities and allows the FMR amplitude to grow sufficiently for the phonons to become unstable. This condition is met for ν_p= 9.2 GHz, whence H = 50 Gauss is necessary for FMR (Fig.1 b). Here the bottom of the spin wave band is seen to lie above $\nu_p/2$. Thus in this case the occurrence of the phonon instability is understandable, albeit the threshold is intriguingly low in view of the substantial separation between the phonon dispersion and the spin wave band.

As shown in Fig.1 a, a suitable variation of both ν_p and H provides for resonant spin waves at $\nu = \nu_p/2$. Now the first order coincident magnon instability is allowed, as indicated by the dashed arrow. Nevertheless, and contrary to our expectation, the phonon instability was observed again, at about the same power level, which means that the competing magnon instability has a higher threshold. This surprising result was further corroborated by a light scattering investigation. No unstable magnons could be observed.

The reason for this behaviour is not yet clear. The strong magnetoelastic effect of $FeBO_3$, as demonstrated by the field dependence of the sound velocity at low frequencies /12/and by the spin wave gap /3/ may be responsible. Theoretical studies are underway to understand the decay mechanism converting FMR magnons into phonons.

The quality of the photograph Fig.5 is not very good, because in reality the scattered light pattern is very sharp, as a result of the strict conditions $\nu = \nu_p/2$ (due to the parametric pumping) and $|\vec{k}_1| = \text{const.}$, where $\vec{k}_1$ are the wavevectors of the incident and scattered light outside the crystal. These circumstances facilitate a quantitative interpretation. In particular, it is easily demonstrated that the sound velocity, at $\nu_p/2$ does not depend on H. Thus the strong effect observed at 25 MHz /12/ does not persist at 4 GHz.

In conclusion, we hope to have shown that Brillouin scattering is a very useful tool to study parametric processes. FMR experiments alone in the present case do not reveal the type of instability involved. Moreover a direct evaluation of the anisotropic elastic constants will be feasible and a convenient and effective method to generate high frequency phonons is offered.

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