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ELASTIC-WAVE AMPLIFICATION IN YTTRIUM IRON GARNET AT MICROWAVE FREQUENCIES

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In this note we describe a series of experiments that have demonstrated parametric amplification of transverse and longitudinal elastic waves in ferrimagnetic garnets at microwave frequencies. The effects were observed at room temperature in single crystals of undoped and gallium-doped yttrium iron garnet (YIG) biased above magnetic saturation.

Parametric excitation of standing elastic-wave modes of ferrimagnetic garnet spheres has been observed,[1,2] and indirect observation of parametrically amplified traveling elastic waves in such materials has been reported,[3] but to our knowledge the experiments described in this note have provided the first direct observation of the amplification of elastic waves propagating in ferrimagnetic crystals. Two types of experiment are described. The first demonstrates parametric amplification of incoherent elastic waves present in the crystal as elastic-wave noise due to thermal agitation. The second demonstrates parametric amplification of coherent elastic waves injected into the crystal by an electromechanical transducer.

The essential details of our experiments are shown in Fig. 1. A single-crystal cylinder is located in a dc magnetic field with a small angle between the biasing field direction and the axis of the cylinder. An rf magnetic field may be applied to one end of the cylinder by means of a thin wire. A quartz plate is bonded to the other end. AC-cut plates were used to study transverse elastic waves, X-cut to study longitudinal waves.

Figure 2(a) shows a typical observation of the parametric amplification of elastic-wave noise. The lower trace shows the time during which a 1400-Mc/sec magnetic field was applied to an end face of a single-crystal cylinder of gallium-doped YIG ($4\pi Ms = 320$ G) 1.45 cm long and 0.43 cm in diameter. The upper trace shows a pulse of incoherent 700-Mc/sec elastic waves multiply reflected between the cylinder end faces. The delay time between pumping and first detection of the pulse shows that it originated at the wire end of the garnet cylinder.

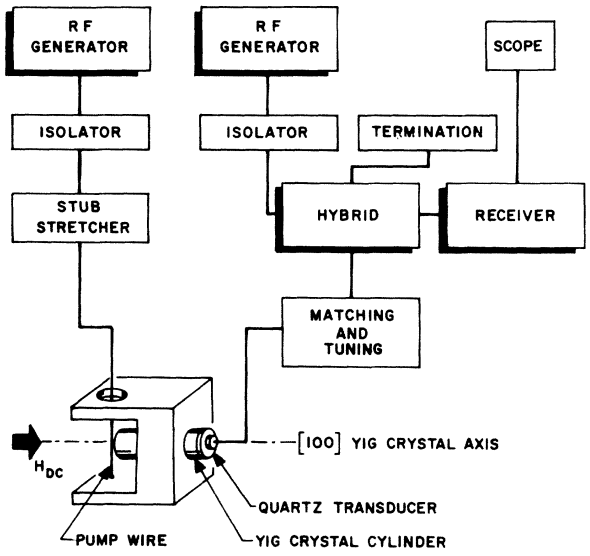

FIG. 1. Essential features of sample mounting and microwave circuitry used to observe parametric amplification of elastic waves.

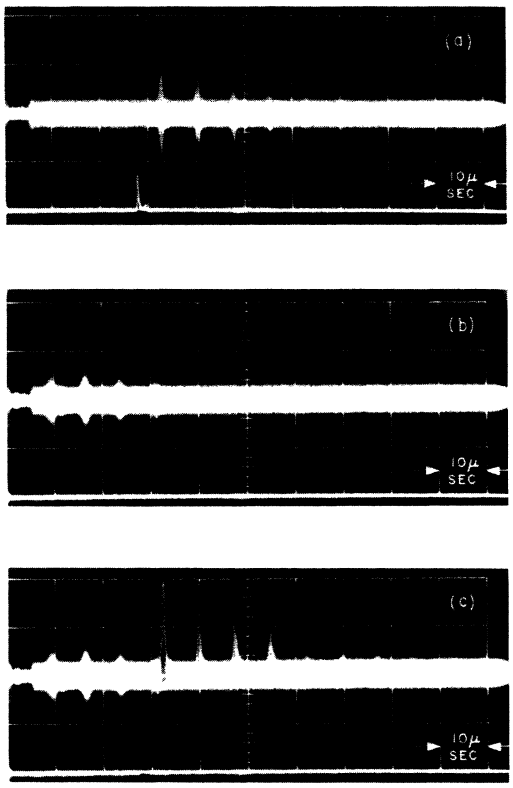

FIG. 2. Oscilloscope display of 700-Mc/sec transverse elastic waves in a YIG crystal cylinder: (a) noise parametrically generated by a 1400-Mc/sec magnetic field; (b) generated by a quartz transducer, and (c) amplified by a 1400-Mc/sec magnetic field.

To observe amplification of coherent elastic waves, a pulse of elastic waves is generated by the quartz transducer and propagated into the YIG cylinder. The pulse is multiply reflected between the cylinder end faces and is near the wire end of the cylinder during regularly spaced time intervals. The wire provides pump energy during one time interval when the elastic-wave pulse is near the wire. An amplified elastic-wave pulse then propagates away from the wire end of the cylinder and is multiply reflected between the end faces, and detected by the quartz transducer. A typical observation obtained with the previously described sample is shown in Fig. 2(b) and Fig. 2(c). A 700-Mc/sec linearly polarized transverse elastic-wave pulse was generated by an AC-cut quartz transducer. The detected pulse, with no pump applied, is shown in Fig. 2(b). Application of a 1400-Mc/sec pump field results in the amplification effect shown in Fig. 2(c). The lower trace shows the time during which the pump was applied. The effects displayed in Fig. 2 were obtained with a 520-Oe dc magnetic field nearly parallel to the axis of the garnet cylinder.

Parametric amplification essentially similar to that shown in Fig. 2 was also observed using an undoped YIG crystal cylinder 1.06 cm long and 0.53 cm in diameter. For both samples the cylinder axis coincided with a [100] crystal axis, and the end faces were polished flat and parallel.

These effects have been observed for longitudinal as well as transverse elastic waves in both samples. In all cases the dc biasing field was approximately the field required for maximum coupling between spin waves and elastic waves[4] near the end of the cylinder. Observation of amplified noise was not dependent on a critical adjustment of either the direction or the magnitude of the biasing field. However, in order to obtain amplification of a coherent elastic wave, adjustment of the magnitude at each direction was critical.

Amplification has been observed in both samples over the frequency range from 500 to 800 Mc/sec. In all cases the pump frequency was approximately twice the elastic-wave frequency, but a precise frequency adjustment was not required. Signal-to-pump phase locking was not attempted. The detected elastic-wave pulses increased in amplitude smoothly as pump field was increased, but attempts to measure the relation between pump field and elastic-wave amplitude were not conclusive. The effects displayed in Fig. 2 were obtained with a pump field of the order of 100 Oe at the cylinder end face, and could be observed with pump fields two orders of magnitude smaller. Measurements of electronic gain were not completely reproducible, but under some conditions appeared to be at least 30 dB.

The parametric effects described in this note are probably due to the coupling between spin waves and elastic waves.[5] Because of this interaction, the velocity of elastic waves in ferrimagnetic solids depends on the magnitude of the biasing field, and on the angle between the biasing field and the elastic-wave vector.[6] Parametric excitation of elastic waves in ferrimagnetic solids due to modulation of the magnitude of the biasing field, by a pump field parallel to it, has been reported.[2] In our experiments the pump field is applied transverse to the biasing field and modulates the direction of the bias field at the wire end of the cylinder. Auld has shown[7] that several mechanisms leading to instability of both transverse and longitudinal elastic waves are possible if the angle between the biasing field and the elas-

tic-wave vector is modulated. Unfortunately, the nonuniformity of the fields in the sample[8] makes specification of their magnitude and direction difficult, and our experiments have not yielded the data required for quantitative comparison with theory.

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ANOMALOUS NUCLEAR MAGNETIC RESONANCE LINEWIDTH IN LITHIUM*

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The existence of the nuclear magnetic resonance (nmr) linewidth anomaly in lithium and sodium, that the transverse relaxation time, T_2, is less than the longitudinal relaxation time, T_1, near the melting point, has been a puzzling question since it was first reported.[1] It is here shown that the anomalous decrease in T_2 observed in lithium is largely due to effects of self-diffusion of lithium in large magnetic field gradients which exist in the small particles used in the nmr experiments. These field gradients exist as a consequence of the bulk susceptibility of the metal.

By using the Carr-Purcell pulse technique[2] it has been possible to minimize the effect of diffusion on the measurement of T_2. The new measurements of T_2 in lithium are reported here.

The anomaly has existed on the high-temperature side of the diffusion-produced T_1 minimum. In this temperature region, the theory[3] predicts that $T_2 \approx T_1$. A value of T_2 that is appreciably less than T_1 implies the existence of some additional spin-spin interaction. If the anomaly is real, then the discontinuity in T_2 upon melting implies a drastic change in this interaction at the melting point. It is important in the study of liquid metals to understand these effects.

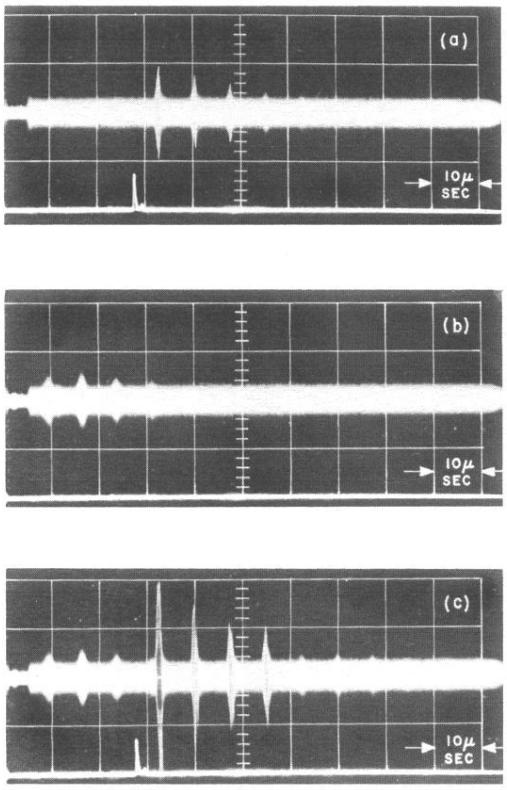
Drain[4] has demonstrated that, in a powdered sample, there is an inhomogeneous broadening, ΔH, due to the finite susceptibility of the sample. He concludes that a useful approximate expression for this contribution is $\Delta H \approx 3\chi H_0$, where χ is the magnetic susceptibility and H_0 is the applied external field. In sodium and lithium $\Delta H \approx 20$-40 milligauss in typical external fields of about 10^4 gauss.

In the presence of such an inhomogeneous broadening, the decay constant of a two-pulse (90°-180°) spin-echo envelope[5] should be the true T_2 if the effects of self-diffusion in magnetic field gradients are negligible. Since the distribution of internal fields in powder samples is partly due to irregular particle shape and partly due to random packing of particles, it can be assumed that the internal field should vary by a large fraction of itself over a dimension, R, characteristic of particle size. For 20-micron diameter particles and $\Delta H \approx 40$ milligauss, the estimated gradient, G, is $G \approx \Delta H/R \approx 20$ G/cm, which is not small.

The importance of the gradient appears in the expression[2] for the decay of the echo amplitude, $M(t)$,

$$M(t) = M(0)\exp[-t_e(1/T_2 + \tfrac{1}{12}\gamma^2 G^2 D t_e^2)], \qquad (1)$$

where γ is the nuclear gyromagnetic ratio, D is the self-diffusion coefficient, and t_e is the time between the 90° (first) pulse and the echo. In liquid lithium, D, estimated from the Stokes-Einstein relation, is $\sim 10^{-4}$ cm^2/sec, $\gamma^2 = 1.07 \times 10^8$, $G \approx 20$ G/cm, and t_e would be about 80×10^{-3} sec if $T_2 = T_1 = 80 \times 10^{-3}$ sec and a typical echo time is used. From these values the diffusion term is $(\frac{1}{12}\gamma^2 G^2 D t_e^2) \approx 2 \times 10^3$ sec^{-1} which is much larger than $(1/T_2) \approx 13$ sec^{-1} for the assumed value of T_2. [Of course, Eq. (1) was derived for



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