attenuation vs frequency response has a sharp discontinuity (Fig. 2). The oscillations occur for dc field values somewhat above that required for ferromagnetic resonance, as expected. Furthermore, no oscillations occur without a microwave cavity, even though the frequency response curve does show the discontinuous "jump" phenomenon. Finally, an experiment was tried with a thin rod 0.007 in. in diamter by 0.070 in. long and the oscillations occurred at dc field values somewhat above that required for resonance. This is in accord with the fact that the foldover of the response curve for a rod is in the opposite direction to that of a disk.

Similar effects have been observed on manganese ferrite spheres at much higher signal power levels (in the kilowatt range). For spheres, the foldover in the response curve comes about not from demagnetizing terms in the ω_{res} vs H equation but from anharmonic terms in the crystalline anisotropy which is a function of M_z, as shown by Suhl.[3]

The possibility of low-frequency acoustic resonance effects causing the above phenomena was considered. However, experiments were performed which showed that no such effects were present in our case.

I wish to thank A. G. Fox, E. H. Turner, and R. F. Trambarulo for helpful discussions and K. M. Poole and J. F. Dillon, Jr., for providing the YIG samples.

[1] P. W. Anderson and H. Suhl, Phys. Rev. 100, 1788 (1955).
[2] H. Suhl, Proc. Inst. Radio Engrs. 44, 1271 (1956).
[3] H. Suhl (private communication).

MAGNETOACOUSTIC RESONANCE IN YTTRIUM IRON GARNET

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Polished spheres of single-crystal yttrium iron garnet (YIG) have been observed to resonate acoustically in the 5-Mc/sec to 30-Mc/sec region by applying a 9300-Mc/sec or a 3000-Mc/sec electromagnetic signal under proper conditions.[1] The ferromagnetic resonance line width of the samples used is 0.5 oe (full width).[2] The following observations and conclusions have been made.

A polished sphere of single crystal YIG, 0.0141 in. in diameter is placed loose on the bottom of a quartz tube in a microwave cavity ($Q_L = 500$) in a position of maximum rf magnetic field. The microwave energy transmitted through the cavity is detected and displayed on a high-speed oscilloscope. An 8.966-Mc/sec signal is observed. The signal is sufficiently large to modulate the microwaves by as much as 50%. The oscillation can be observed with microwave power incident on the cavity as low as 4 milliwatts.

In order to identify the oscillation as being acoustic, the following were measured:

(1) the acoustic resonance as a function of sample size;

(2) a fundamental acoustic resonance by acoustic techniques;

(3) the small pulling of the acoustic resonant frequency due to changes in microwave power and dc magnetic field;

(4) changes in acoustic loading by varying the air pressure on the YIG sphere;

(5) the frequency spectrum of the acoustic resonances;

(6) acoustic resonance as a function of microwave frequency.

For acoustic vibrations, the frequencies generated in the spheres would vary inversely as the ratio of the diameters. This turned out to be the case; e.g., for an 0.0141-inch sphere and an 0.0175-inch sphere the frequencies are 8.966 and 7.222Mc/sec, respectively, which are exactly in inverse ratio to the diameters.

Measurements of a fundamental acoustic resonance of the 0.0141-inch sphere were made by McSkimin using a pulsed ultrasonic technique.[3] Sound wave pulses generated by a barium titanate transducer having a spherical surface are focused on the YIG sphere, the sphere and transducer being immersed in a small tank of water. The sound waves reflected from the sphere disappear when the frequency is adjusted so as to excite acoustic resonance. The frequency of acoustic resonance is 8.685 ±0.005 Mc/sec which is only a quarter of a megacycle lower than the resonance generated by microwave methods. Because of the wavelength of sound in water relative to that in YIG, it is possible for the reactive loading of the sphere to be small while the resistive loading remains large. This is probably the reason the frequency is not lowered more due to the acoustic loading of the water. No other resonances appear in the pass band of the equipment, which is 7.5 to 11.5 Mc/sec. It is concluded that the acoustic resonance observed is the same fundamental vibrational mode which is excited by microwave methods.

In the microwave experiment, as the power is slowly increased, the oscillations suddenly appear at approximately full amplitude. As the power is further increased the range of the dc field over which the oscillations occur is also in creased. At about 80 mw the range of the variation of the dc field is about 30 oe. Over the entire range of microwave power and dc field, the oscillation frequency changes by no more than 20 kc/sec. The small amount of pulling implies a high-Q phenomenon and strongly suggests that it is acoustic.

Additional evidence that the oscillations are acoustic is given by the change in frequency due to small changes in acoustic loading of the YIG sphere. The loading is changed by evacuating the sample tube with a vacuum pump. The frequency of the oscillation increases by about 500 cycles as the pressure decreases from atmospheric pressure to a micron of pressure and at the same time the rf power necessary to excite the oscillation is considerably reduced by the reduction in pressure.

A sphere can vibrate acoustically in longitudinal modes, transverse modes, and modes involving a combination. The mode spectrum thus consists of three or more fundamental vibrations with their associated series. An acoustic vibration can also generate, electrically in the YIG, harmonics which have integral frequency relations. Using the 0.0175-inch sphere, the mode spectrum was measured as a function of the microwave power incident on the cavity. At a low power (13 mw) the oscillation frequencies observed are 7.222, 14.444, 21.666, and 28.888 Mc/sec. After increasing the power to 22 mw, either this series or another can be obtained by adjusting the dc field. The second series is 13.660 and 27.320 Mc/sec. By increasing the power to 80 mw, over 20 resonances not integrally related were tabulated in the band from 0-30 Mc/sec. The two frequencies 7.222 and 13.660 Mc/sec are exceptionally strong and are believed to be the fundamental spheroidal and radial elastic modes of vibration. Calculations of these frequencies, for an isotropic sphere and using sound velocities measured by McSkimin[3] in stoichiometric polycrystalline YIG, agree to within 3% with measured values.

Most of the experiment was performed at 9300 Mc/sec. Additional measurements at 3000 Mc/sec show that the frequency of the acoustic resonance is unchanged when the microwave frequency is varied. This demonstrates that body resonances and propagation effects in the YIG are not involved.

It is of interest to inquire as to the mechanism of the excitation of this acoustic resonance. Magnetostriction provides the coupling from the magnetic spin system to the mechanically vibrating modes. There is good evidence that parametric amplification[4] is involved to enhance greatly the amount of effective coupling. When the microwave excitation is sufficient to overcome all losses, the system breaks into oscillation at frequencies defined by

$$f_a + f_i = f_p, \qquad (1)$$

where f_p is the microwave or pump frequency, f_a is the acoustical frequency, and f_i is the difference. Measurements show that the dc field for acoustic resonance is the field required for uniform precessional resonance at f_i. This is illustrated by Fig. 1. Thus, if the acoustic re-

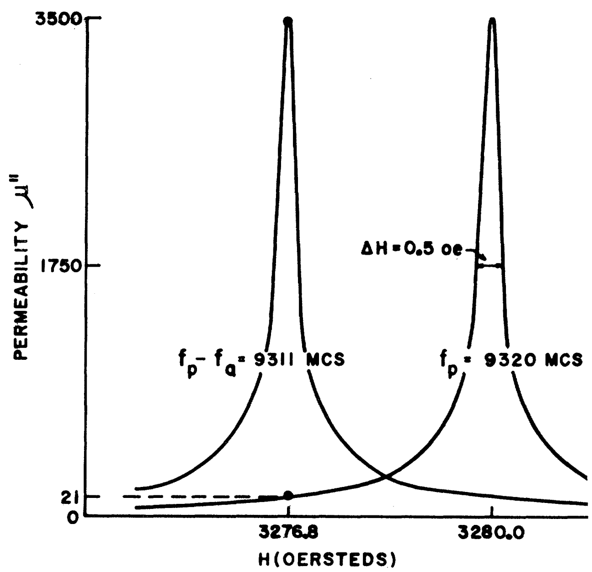

FIG. 1. Magnetoacoustic mode of amplification is illustrated for a YIG sphere 0.0141 inches in diameter. The pump frequency f_p is higher than the idler frequency by the frequency of acoustic resonance f_a. The field at which acoustic resonance is experimentally observed (for the lowest pumping power) is the field required for uniform precessional resonance at the idler frequency.

sonance is regarded as the signal frequency, then the uniform precession (or a long-wavelength Walker mode) at f_i acts as the idler. The amplifier then has one magnetostatic mode and one acoustic mode of operation.

In parametric amplification a fourth frequency is generated at $f_p + f_a$. The phase relations are such that $f_p - f_a$ signals are intensified, while those at $f_p + f_a$ are diminished. In our case, measurements with a spectrum analyzer show that the signal at $f_p - f_a$ is 30 db larger than the signal at $f_p + f_a$.

We especially wish to thank M. T. Weiss and A. G. Fox for discussions of their work previous to publication; H. J. McSkimin for his acoustical measurements and discussions; J. H. Rowen and R. C. Fletcher for their encouragement and suggestions; and C. S. Porter of the Diamond Ordnance Fuze Laboratories for allowing us to use the same samples on which we have previously reported.

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[1] An outwardly similar, but different, effect discovered earlier by M. T. Weiss is described in the preceding Letter [Phys. Rev. Lett. 1, 239 (1958)].

[2] LeCraw, Spencer, and Porter, Phys. Rev. 110, 1311 (1958).

[3] H. J. McSkimin (to be published).

[4] H. Suhl, J. Appl. Phys. 28, 1225 (1957).

DIFFUSION ALONG DISLOCATIONS*

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Hart[1] has pointed out that low-temperature diffusion measurements utilizing single crystals should produce values of D elevated a few percent by the effects of dislocations, while exhibiting normal penetration profiles. Indeed, Tomizuka[2] has recently re-analyzed earlier measurements of the diffusion of antimony in silver and has demonstrated the effects discussed by Hart. From a somewhat different point of departure, experiments on the diffusion of rare earth tracers into silver and lead[3] have revealed anomalous penetration profiles, one feature of which is a structure-sensitive tail which appears even in single crystals diffused at temperatures near the melting point. Presumably, this effect involves atomic mobility along dislocations, enhanced in this case by the very small bulk diffusion coefficients and solubilities of rare earths in these metals. It is of interest to inquire if similar dislocation effects could be demonstrated in "well-behaved" systems.

Accordingly, the following rather abnormal type of experiment was performed. Thin layers of Au^{198} were deposited on the ends of cylindrical single crystals of silver and diffusion measurements were made using the standard sectioning procedures, but with these modifications:

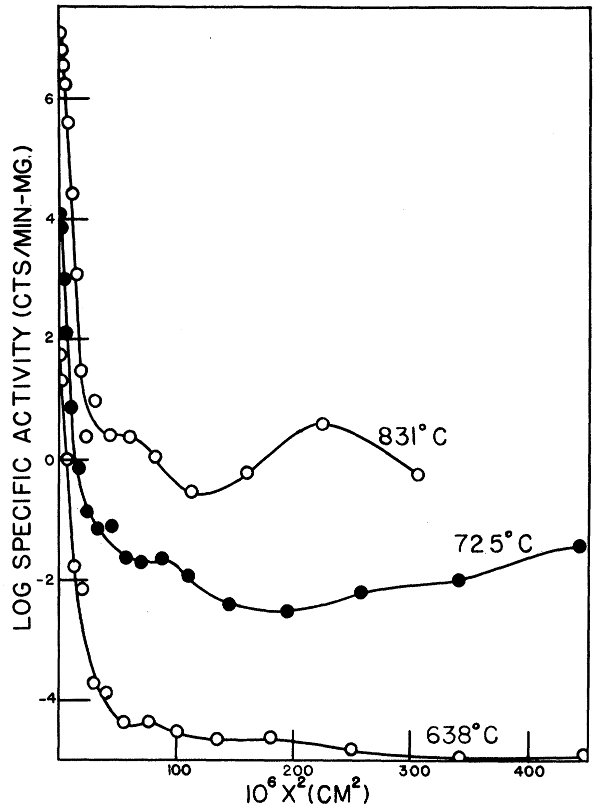

FIG. 1. Penetration plots at three temperatures. For clarity, the upper curve has been shifted upward 3 cycles and the lower curve downward 2 cycles. The statistically predicted counting errors are well within the diameter of the circles.

(a) greater activity, about 20 microcuries, was deposited on each specimen;

(b) diffusion anneal times were so short that $(Dt)^{\frac{1}{2}}$ was only about 10 microns; and

(c) with a thin-window beta counter with a background of only $4\frac{1}{2}$ counts/min, the tracer concentration after diffusion was followed through a range of several million.

The results obtained at three different temperatures are shown in Fig. 1. The diffusion coefficients calculated from the steep region agree with values obtained by conventional experiments[4] to within the rather large error imposed by the very small penetration depth employed here. At the lowest tracer concentrations, an unmistakable tail is apparent, being more pronounced the lower the diffusion temperature. It was not practical to follow this tail more deeply into the specimen than as