Temperature Dependence of Microwave Acoustic Losses in Yttrium Iron Garnet

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The temperature dependence of the acoustic losses in single crystal yttrium iron garnet has been obtained at 500 and 1000 Mc/sec. The method of measurement involves propagation of plane shear waves in a cylindrical rod, the direction of propagation being along a [100] crystallographic direction. At both frequencies acoustic Q's of 2×10^5 have been obtained and these values are relatively insensitive to temperature for $T>100$°K. Below 100°K, the acoustic losses are dominated by an internal friction, $Q^{-1}(T)$, peak near 15°K.

ACOUSTIC Q's of 10^7 at 10 Mc/sec recently[1] have been obtained for single-crystal yttrium iron garnet (YIG) spheres at 300°K. It was therefore of considerable importance to examine the temperature dependence of the acoustic losses in high-quality single-crystal YIG in the microwave region. At 500 and 1000 Mc/sec, Q's of 2×10^5 have been obtained, and these values are relatively insensitive to temperature for $T>100$°K. At temperatures below 100°K, the acoustic losses are dominated by a process involving a $Q^{-1}(T)$ peak near 15°K.

A measurement technique was developed, using a single-crystal YIG cylindrical rod which required no bonds or contacts to the end faces. This is especially important in measuring Q's of $\sim10^5$ at microwave frequencies. The YIG crystal is a cylindrical rod 5.3 mm in diameter and 10.6 mm long, with optically flat end faces which are parallel to within a few minutes of arc. The dc magnetic field is applied parallel to the axis, which is along a [100] crystallographic direction, and perpendicular to the ends which lie in (100) planes. The microwave pulse energy is coupled into one end of the YIG rod by a fine wire loop terminating a coaxial line. A nonresonant technique is used which is similar to one developed by Bommel[2] for use with electric excitation in quartz. An acoustic pulse of shear waves is then generated in the YIG by a microwave magnetostriction process associated with ferromagnetic resonance.[3]

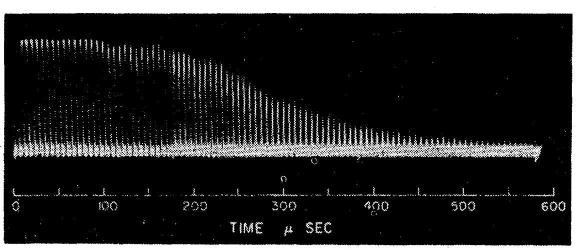

FIG. 1. Acoustic shear wave echoes propagating along [100] direction in a single crystal YIG rod 5.3 mm in diameter and 10.6 mm long. The data were taken at 500 Mc/sec and at 300°K. The figure is a composite of three oscilloscope pictures, the amplifiers being saturated for more than 100 μsec.

[1] R. C. LeCraw, E. G. Spencer, and E. I. Gordon, Phys. Rev. Letters **6**, 536 (1961).
[2] H. E. Bommel (to be published).
[3] H. E. Bommel and K. Dransfeld, Phys. Rev. Letters **3**, 83 (1959).

The acoustic pulse propagates down the rod, and by an inverse process generates a microwave pulse in a similar wire loop at the other end. It was found that for the lowest loss, and to avoid destructive wave interference effects, the loop must be oriented so that the microwave field is in a [110] direction in the plane of the end of the rod. The acoustic pulse travels back and forth in the YIG rod, being reflected off the ends, with only a small amount being sampled out. In this manner the assembly is an excellent microwave acoustic transducer requiring 10^3 less power than if the same size quartz rod were used with electric excitation. It may be noted here that a series of several pulses can be observed with less than 25 μw of rf power. Figure 1 is a composite photograph of three oscilloscope pictures showing a series of approximately 100 shear wave echoes at 300°K and 500 Mc/sec. The internal friction, Q^{-1}, was determined at each temperature by the decay time of the amplitude of the pulses using a calibrated rf attenuator.

Figure 2 shows Q^{-1} measured at 500 Mc/sec and at 1000 Mc/sec from 300°K to 4.2°K. The measured value of Q is about 2×10^5 at both frequencies for $T>100$°K. The Q obtained in reference 9 for the R_2 (compressional) mode involving longitudinal acoustic waves, taken in a vacuum, extrapolates by an f^{-1} relation to a value of 1.7×10^5 at 500 Mc/sec and to 0.85×10^5 at 1000 Mc/sec. It has been shown recently[4] that shear modes in the vibrating spheres can have magnetoacoustic Q's of the same order as the longitudinal modes. Considering the different acoustic conditions in the two experiments, i.e., standing waves in the sphere and plane-wave propagation in the rod, there is essential correlation of Q values with the f^{-1} relation.

In interpreting the data, it is desirable to know how much of Q^{-1} is purely acoustic and how much is magnetoacoustic. There is only a partial answer at this time. The initiating microwave pulses are 0.25 μsec wide and the resulting acoustic pulses are also 0.25 μsec wide. This confirms what could be expected, that the acoustic pulses are generated and detected only at the end surfaces of the crystal, in the manner of Bömmel and Dransfeld's thin ferromagnetic disks.[3] The sample is then at ferromagnetic resonance only at the small region

[4] R. C. LeCraw, E. G. Spencer, and E. I. Gordon, 1961 Conference on Magnetism and Magnetic Materials (unpublished).

on the ends since, because of demagnetizing fields, the internal dc field is much larger everywhere else in the rod. Also, the measured values of the dc field indicate that ferromagnetic resonance is being observed almost as if in a fairly thin disk. The losses in the bulk of the sample are then probably principally acoustic and spin-wave losses, if any, but do not involve acoustic coupling to ferromagnetic resonance of the uniform precession of magnetization.[5] Additional experiments on additional samples are needed to specify the dependence of Q^{-1} on the field H.

In ferrites[6–8] certain of the low-temperature Q^{-1} peaks have been identified as being due to a stress-induced relaxation due to electron exchange between Fe^{2+} and Fe^{3+} ions. Some of these processes have also been investigated by ferromagnetic resonance methods.[9–11] The single-crystal YIG was grown using Y_2O_3 containing several hundred parts per million Si as impurities. Since each Si^{+4} ion gives rise to a Fe^{2+} ion, the above $Fe^{3+}+e \rightleftarrows Fe^{2+}$ mechanism is a possible source of relaxation losses. From Fig. 2, reference 11, we have ferromagnetic resonance measurements on known ferrous ions at 16 500 and 9340 Mc/sec. In consideration of the Arrhenius relaxation equation, $\ln f$ was plotted vs T^{-1} for the line width maxima at 16 500 and 9340 Mc/sec and for Q^{-1} at 500 Mc/sec. The three points lie on a straight line, giving an activation energy of 0.006 ev. This is considerably lower than the 0.6 ev value obtained from conductivity measurements by Verweel and Roovers[12] in polycrystalline silicon-doped YIG. In comparing the magnitude of the Q^{-1} peak in YIG with a dc conductivity less than 10^{-10} ohm-cm, to the peaks obtained by Gibbons in, e.g., nickel iron ferrite with a dc conductivity of 10^{-2} ohm-cm, we find them to be of the same order of magnitude. If the dc conductivities are measures of the amount of ferrous ions present, then we might expect the YIG loss peak to be several orders of magnitude lower. Thus the evidence indicates that the loss peak is related to the loss peaks found in ferromagnetic resonance at much higher frequencies, which were shown to be associated with ferrous ions. This is apparently not correlated with the dc conductivity caused by ferrous ion impurities.

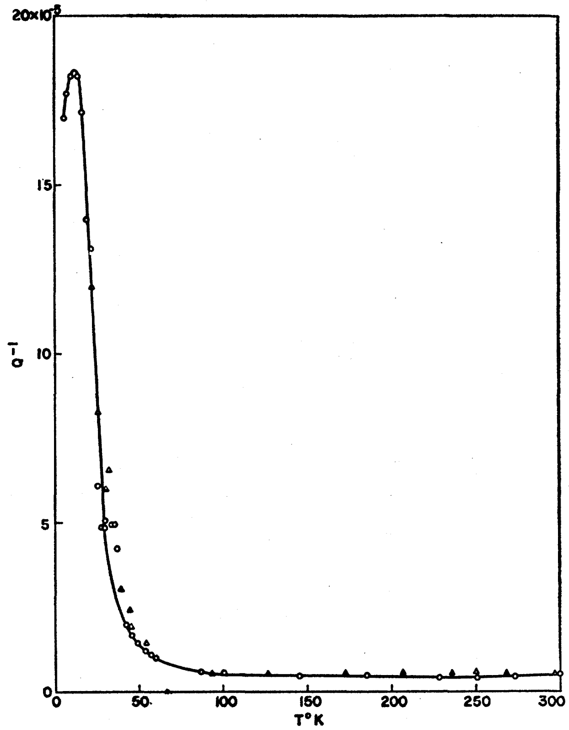

FIG. 2. Temperature dependence of internal friction, Q^{-1}, for shear waves along [100] axis in YIG. The smooth curve is drawn through the circles which represent 500-Mc/sec data. The triangles are for 1000 Mc/sec.

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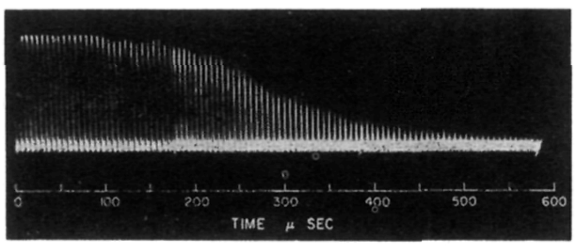
[12] J. Verweel and B. J. M. Roovers, *International Conference on Solid-State Physics, Brussels, June, 1958* (Academic Press Inc., New York, 1960), Vol. 3, p. 475.



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