Excitation of gigahertz magnetoelastic waves in terbium films: Field dependence*

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Transverse magnetoelastic excitations in polycrystalline terbium films have been observed using pulse-echo spectrometers with a dc magnetic field applied normal to the film, and an rf field applied in the film plane. A coupled magnetoelastic model analysis, with one adjustable parameter, correctly predicts the observed signal intensity, field dependence, mode, and frequency. Since the magnon energy gap lies well above the operating frequencies, the observed signals result from the magnetic excitation of "phononlike" normal modes.

Experiments on terbium were conducted to verify the validity of a coupled magnetoelastic mode model which has proven extremely successful in predicting experimental pulse-echo and spin-phonon results in dysprosium films.[1-3] Although terbium and dysprosium have strikingly similar magnetic characteristics, the signals observed in pulse-echo studies are substantially different; in Tb, the phonon signals are more intense and vary rapidly with applied field. Using a realistic estimate of the magnetoelastic coupling constant β^6, and published data for all other constants,[4-8] the model predicts the signal intensity within a factor of 2. Field dependence, mode, and excitation frequency[9] are also correctly predicted.

The full development of the normal-mode analysis treating the coupled magnon-phonon modes, and the development of the time-dependent perturbation theory appropriate to transverse magnetoelastic wave excitation has been given elsewhere[1,2]; only the principal results will be reproduced here. This analysis is appropriate to easy-c-plane rare earths with the magnetization in the c plane. The Hamiltonian includes Zeeman, exchange, demagnetization, anisotropy, magnetoelastic, and elastic terms. For waves propagating along the c axis, only one transverse-phonon mode is coupled to the magnons. For this case, an analytic solution has been obtained.[1,2] For more general propagation directions, all three phonon modes may be coupled to the magnon mode and the resultant eigenvalue problem can only be treated numerically. The approximation dealt with here ignores the more general cases of propagation direction which may be unimportant owing to the enormous uniaxial anisotropy in each of the crystallites. The polycrystalline character of the film is explicitly considered by imposing the results of a magnetostriction averaging process. In this way, the cancellation of phonon signals for crystallites of differing orientation can be estimated. The magnetostriction average requires that the theoretical signal for a single crystal be multiplied by a factor of $(\frac{4}{15})^2$.[1] Thus the transverse acoustic power generated in a polycrystalline film can be approximated by[1,2]:

$$P_{\text{acous}} = (\tfrac{4}{15})^2(2\omega_0 d C_1^2)\,|f(q)|^2\,|S_{14}(q)+S_{24}(q)|^2 \times [S_{33}(q)S_{44}^*(q)]/\hbar V_{q,T}\,, \tag{1}$$

where

$$f(q) = \frac{1-\exp[id(q+1/\Delta)-d/\Delta]}{d[1/\Delta - i(q+1/\Delta)]}\,, \tag{2}$$

$$C_1 = g\mu_B H_{rf}^0 (\tfrac{1}{2}JN)^{1/2}\,. \tag{3}$$

For a particular value of the applied field, q is determined by the solution of $\Omega^-(q)-\omega_0=0$. Here Ω^- is the angular frequency of the "phononlike" magnetoelastic mode, S_{ij} are the elements of the transformation matrix S which diagonalizes the unperturbed Hamiltonian, and H_{rf}^0 is the amplitude of the rf perturbation field at the sample.

Using time-dependent perturbation theory, transforming the magnon operators to normal mode operators,[1,2] and recognizing that a pulse-echo experiment measures the square of the transition rate,[10] the pulse-echo signal intensity is given by[3]:

$$P_{\text{echo}} = (\tfrac{4}{15})^4\,|f(q)|^4\,|S_{14}(q)+S_{24}(q)|^4 (g\mu_B H_{rf}^0)^4 \times \left[\frac{64q^2d^2J^2N^2\,|S_{33}(q)S_{44}(q)|^2}{P_{in}\hbar^2(2+\rho_f V_f/\rho_s V_s+\rho_s V_s/\rho_f V_f)}\right], \tag{4}$$

where P_{in} is the input power, ρ is the density and V is the phonon group velocity in the material. The subscripts refer to the film and substrate, respectively.

The samples for this investigation were prepared by evaporating high purity (99.9%) Tb, under high vacuum, $P<10^{-7}$ Torr, onto one end of an ultrasonic delay line, and then over-laying the Tb film with 0.5 μm of SiO to protect it from oxidation. The delay lines, c-axis sapphire single-crystal cylinders, 15 mm long by 3.17 mm in diameter,

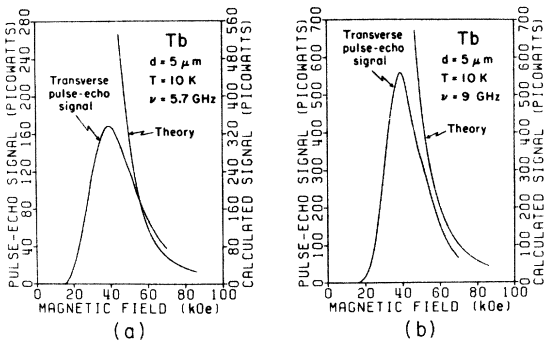

FIG. 1. Typical pulse-echo spectrometer signals and computed signals in polycrystalline Tb films as a function of applied field with the static magnetic field applied parallel to the film normal. The left-hand scale refers to the experimental values, and the scale on the right corresponds to the signal computed from the coupled mode model. The correct shape of the signals, as well as the absolute signal intensities, are accurately predicted.

have both ends polished optically flat and parallel within 0.1 arcsec.

A conventional pulse-echo spectrometer, with an absolute sensitivity of −120 dBm, was employed to determine the polarization and to measure echo signal intensity as a function of the applied magnetic field. A tuneable spin-phonon spectrometer was used to verify that the excitations occurred at the rf driving frequency.[9] Both spectrometers have been described in detail elsewhere.[1-3]

Since the films are not "saturated"[11] for applied fields less than $4\pi M$, no attempt was made to compute signals less than 40 kOe; the signals were calculated as a function of applied magnetic field from 40–90 kOe. As the applied field is increased, the rapid variation of the absorption with the applied field can be explained as follows: The energy gap of the "magnonlike" branch of the dispersion curves increases, which leads to a decrease in the relative coupling between the magnon and the transverse-phonon branches at low (~10 GHz) frequencies. Thus, as the character of the "phononlike" dispersion curve branch becomes less magnetic, the matrix elements diminish, and the transition rate for the excitation of "phononlike" magnetoelastic waves by an rf magnetic field is reduced.

The results of these calculations, along with typical experimental data, are shown in Fig. 1. The agreement between theory and experiment is excellent, both for signal intensity and for the magnetic field dependence.

The magnetoelastic coupling constant β^e apparently has not been measured to date; thus β^e is the model's only adjustable parameter. The value used in these computations

$$\beta^e = 2.0 \times 10^{-15} \text{ erg/cm}^3$$

is of the same order of magnitude as Dy (3.3×10^{-15} erg/cm^3).

As previously mentioned, the theoretical pulse-echo signal has been multiplied by a factor of $(\frac{4}{15})^4$ to include the polycrystalline magnetostrictive average in the film. Thus, if these experiments were performed on single crystals of Tb, the signal intensity could be enhanced by approximately a factor of 200.

It is concluded from these investigations, and from the results of spin-phonon spectrometer studies[9] that the coupled magnetoelastic normal-mode model provides the correct description of the microwave frequency properties of terbium.

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[11]For example, in crystallites oriented with a hard c axis parallel to the applied field, the enormous uniaxial anisotropy prevents the magnetization from aligning parallel to the applied field. As a result, the magnetization in a polycrystalline specimen is substantially smaller than in single crystals.