

## Magnetoelastic Interaction in EuIG\*

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The magnetoelastic behavior of  $\text{Eu}^{3+}$  ion has been studied in the magnetic garnets by means of the stress-induced shift in the FMR. At low temperatures the energy of the  $\text{Eu}^{3+}$  ion is determined by the exchange interaction which mixes excited  $J$  multiplets into the  $J=0$  ground state. The anomalously large strength of the magnetoelastic interaction of  $\text{Eu}^{3+}$  may be understood in terms of a relatively simple model which involves strain-induced variations in the anisotropic  $\text{Eu}^{3+}$ - $\text{Fe}^{3+}$  exchange coupling. The stress-induced shifts in the FMR of EuIG may be attributed, mainly, to a change of order  $\chi H_{ex}^2 (\partial/\partial \epsilon) (\ln H_{ex})$  in the magnetic energy. The model successfully accounts for the variations in the magnetoelastic behavior for the mixed crystal system  $\text{Eu}_{3-x}\text{Y}_x\text{Fe}_{5-y}\text{Ga}_y\text{O}_{12}$ .

THE magnetoelastic behavior of the  $\text{Eu}^{3+}$  ion in the magnetic garnets has two particularly interesting aspects. First, the europium containing iron garnets are unique in that they are the only materials to exhibit both anomalously large magnetoelastic constants<sup>1</sup> and extremely small magnetic losses.<sup>2</sup> Second, it represents one of few cases where a microscopic theory of the magnetoelastic interaction may be developed quite directly. Such a theory is possible, since the energetics of the  $\text{Eu}^{3+}$  ground state are determined mainly by the anisotropic  $\text{Eu}^{3+}$ - $\text{Fe}^{3+}$  exchange interaction and the strain variations in this interaction dominate the magnetoelastic behavior. In this paper, we present some observations on magnetoelastic effects in mixed crystals of the system  $\text{Eu}_{3-x}\text{Y}_x\text{Fe}_{5-y}\text{Ga}_y\text{O}_{12}$  determined

by means of uniaxial stress-induced shifts in the ferromagnetic resonance.<sup>3</sup> This technique is particularly useful for these materials, since the induced shifts for small stresses are comparable to the resonance line-width.

The  $\text{Eu}^{3+}$  ions, which are at sites of rhombohedral symmetry, may be considered as paramagnetic additions to the YIG host. At low temperatures, the magnetic properties of the europium ion are determined by its ( $J=0$ ) ground state. The  $\text{Eu}^{3+}$ - $\text{Fe}^{3+}$  and  $\text{Eu}^{3+}$ - $\text{Eu}^{3+}$  exchange interactions plus the Zeeman interaction cause an admixing of excited states (mainly  $J=1$ ) into the ground state and give rise to energy-perturbation terms in even powers of the total effective field acting on each  $\text{Eu}^{3+}$  ion. Following the treatment of Sekerka<sup>4</sup> for the FMR of EuIG, we have developed a microscopic theory for the stress-induced shifts in the FMR in terms of strain variations in an anisotropic

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<sup>1</sup>S. Iida, Phys. Letters 6, 165 (1963); W. G. Nilsen, R. L. Comstock, and R. Walker, Phys. Rev. 139, A472 (1965).

<sup>2</sup>R. C. LeCraw, W. G. Nilsen, J. P. Remeika, and J. H. Van Vleck, Phys. Rev. Letters 11, 490 (1963).

<sup>3</sup>A. B. Smith, J. Appl. Phys. 34, 1283 (1963).

<sup>4</sup>R. F. Sekerka, unpublished thesis, Harvard University (1965).

$\text{Eu}^{3+}$ - $\text{Fe}^{3+}$  exchange interaction.<sup>5</sup> It is to be emphasized that the theory predicts the shifts vanish for an isotropic interaction. At zero strain, a general expression for the field of FMR at a given orientation may be written in the form

$$g_{\text{eff}}H_{\text{res}} = [(\hbar\omega/\beta)^2 + A^2]^{1/2} - g_{\text{Fe}}H_a - 4(M_{\text{Eu}}/M_{\text{Fe}})H_{\text{Eu}} + B, \quad (1)$$

where  $g_{\text{eff}} = g_{\text{Fe}}(M_{\text{EuIG}}/M_{\text{YIG}})$  and  $H_a$  is the YIG anisotropy field.  $H_{\text{Eu}}$  is the molecular field due to the  $\text{Eu}^{3+}$ - $\text{Eu}^{3+}$  exchange interaction and  $A$  and  $B$  represent the anisotropy of the  $\text{Eu}^{3+}$  ground state; each of these terms vary as the  $\text{Eu}^{3+}$  concentration ( $n_{\text{Eu}}$ ). Because of the requirements of overall cubic symmetry quadratic  $\text{Eu}^{3+}$  energy contributions vanish except for terms linear in the applied field and the  $\text{Eu}^{3+}$ - $\text{Eu}^{3+}$  exchange interaction. However, all quadratic terms are required to determine the magnetization of  $\text{EuIG}$ .<sup>6</sup>

With the application of a uniaxial stress the quadratic terms in the  $\text{Eu}^{3+}$ - $\text{Fe}^{3+}$  exchange re-enter and we obtain a general expression for the shift in the resonance field relative to the shift in pure YIG

$$g_{\text{eff}}\delta H_{\text{res}} - g_{\text{Fe}}\delta H_{\text{YIG}} = A\delta A [(\hbar\omega/\beta)^2 + A^2]^{-1/2} + \delta B, \quad (2)$$

where the terms  $\delta A$  and  $\delta B$  vary directly as  $n_{\text{Eu}}$ , the applied stress, and the square of the  $\text{Eu}^{3+}$ - $\text{Fe}^{3+}$  molecular field.  $\delta A$  and  $\delta B$  contain not only orientation-dependent terms but strain derivatives of the  $\text{Eu}^{3+}$ - $\text{Fe}^{3+}$  exchange parameters. These derivatives enter so that  $\delta A$  and  $\delta B$  vanish for isotropic exchange.

Our experiments were performed at  $Ku$  band using a standard transmission spectrometer with spherical samples oriented to permit resonance-shift measurements with the applied stress along  $[\bar{1}\bar{1}0]$  and the applied field in the  $(\bar{1}\bar{1}0)$  plane. With the stress values used it was verified that the shifts were linear in stress and that no appreciable inhomogeneous broadening was introduced.  $\text{Eu}^{3+}$  concentrations were estimated by linewidth comparisons<sup>2</sup> and these differed by at most 10% from the intended dopings.

Figure 1 gives resonance-field and shift data at 4.2°K as a function of  $\text{Eu}^{3+}$  concentration. The data has been fitted to Eqs. (1) and (2) using  $A$ ,  $B$ ,  $H_{\text{Eu}}$ ,  $\delta A$  and  $\delta B$  as parameters. The values obtained may be listed:  $B^{[110]} = A^{[111]} = 0$ ;  $A^{[110]} = 11.25$  kOe;  $B^{[111]} = 0.54$  kOe;  $H_{\text{Eu}} = -3.2$  kOe; for a stress  $= 2.1 \times 10^8$  dyn/cm<sup>2</sup>,  $\delta B^{[111]} = -42$  Oe,  $\delta B^{[110]} = -155$  Oe,  $\delta A^{[110]} = 772$  Oe. The  $H_{\text{Eu}}$  value implies an antiferromagnetic  $\text{Eu}^{3+}$ - $\text{Eu}^{3+}$

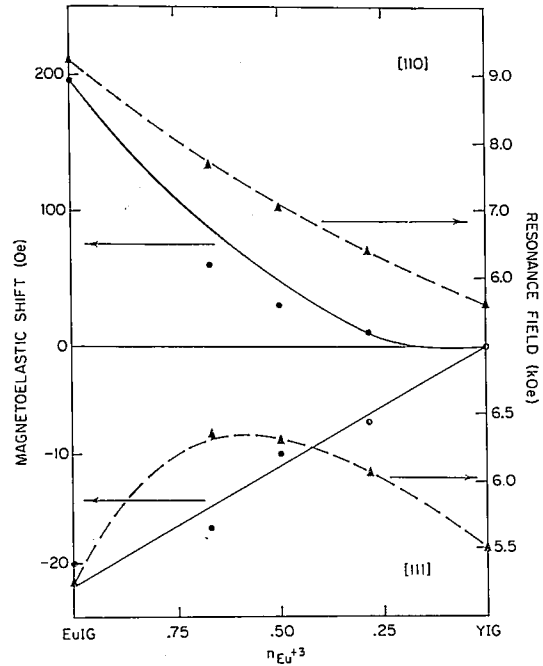


FIG. 1. Magnetoelastic shift and resonance field in  $\text{Eu}^{3+}$ -doped YIG vs  $\text{Eu}^{3+}$  concentration ( $n_{\text{Eu}^{3+}}$ ) for  $[110]$  and  $[111]$  orientations at  $T = 4.2^\circ\text{K}$ ,  $\nu = 16.0$  GHz and stress  $= 2.1 \times 10^8$  dyn/cm<sup>2</sup> applied along  $[\bar{1}\bar{1}0]$ . Stress-induced shift in resonance field is plotted as  $(g_{\text{eff}}/g_{\text{Fe}})\delta H_{\text{res}} - \delta H_{\text{YIG}}$ .

exchange constant of  $0.05$  cm<sup>-1</sup> in agreement with typical rare earth-rare earth couplings in garnets. The other constants are difficult to calculate exactly, but order of magnitude calculations agree with the results presented here. In fact, the general rule used in these estimates is that the strain variation of a given term is of order the term itself times the strain, since logarithmic derivatives are of near unity magnitude. The above parameters also account for the low-temperature behavior of the crystal system  $\text{Eu}_3\text{Fe}_{5-y}\text{Ga}_y\text{O}_{12}$ .

The magnetoelastic theory discussed involves only the ground state, and thus, is strictly applicable at low temperatures. However, the structure of the model allows us to infer the qualitative temperature-dependence of shifts. As we have shown, the stress-induced shift in the FMR may be attributed to a change of order  $\chi H_{\text{ex}}^2 (\partial/\partial \epsilon) (\ln H_{\text{ex}})$  in the  $\text{Eu}^{3+}$  ground-state energy. From Fig. 1, the linear compositional-dependence of the  $[111]$  shift indicates that measurements at this orientation characterize this intrinsic strain variation. As might be expected, then, measurements of the temperature-dependence of the  $[111]$  shift follow the  $\text{Eu}^{3+}$ -spin susceptibility.<sup>6</sup>

<sup>5</sup> P. M. Levy, Phys. Rev. 135, 155 (1964).

<sup>6</sup> W. P. Wolf and J. H. Van Vleck, Phys. Rev. 118, 1490 (1960).