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D. Craik, A. Kitto, D. Ross. MAGNETIZATION PRECESSION IN SPINELS AND GARNETS. Journal de Physique Colloques, 1971, 32 (C1), pp.C1-771-C1-773. 10.1051/jphyscol:19711269 . jpa-00214100

HAL Id: jpa-00214100
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Submitted on 4 Feb 2008

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MAGNETIZATION PRECESSION IN SPINELS AND GARNETS

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Résumé. — Une large étude de la précession dans des champs pulsés a vérifié la variation attendue de la fréquence de précession en fonction du champ total effectif (englobant le champ appliqué, M_s et la forme de l'échantillon) et montré comment l'amortissement de la précession dépend à la fois de la microstructure, des impuretés, et des amplitudes des champs appliqués.

Abstract. — An extensive study of precession in pulsed fields has verified the expected dependence of the precessional frequency on the total effective field (involving applied fields, M_s and specimen shape) and shown how the damping of the precession depends on both microstructure, impurities, and the magnitudes of the applied fields.

Introduction. — Due to the association of angular momentum with a magnetic moment the basic response of the magnetization to an applied field consists of precession. In practice this may be damped away quite rapidly and if fields are applied slowly the magnetization appears to approach the field direction directly. Precession can be observed by applying field pulse with a rise time less than the expected precessional period and observing the response with good time resolution, but only few results have been reported [1, 2]. Apart from its intrinsic interest, precession represents a basic limitation to fast switching and thus a systematic quantitative study was made.

With complete neglect of damping, or relaxation of the magnetization, the torque equation $\dot{\mathbf{M}} = \gamma \mathbf{M} \times \mathbf{H}$ is readily solved to indicate that M_z is constant (assuming $\mathbf{H}//oz$) whereas M_x and M_y vary sinusoidally with constant amplitude, and with angular frequency $\omega = \gamma H$. This is simple precession and the voltage induced in a conductor near the specimen and parallel to $\mathbf{H}$ should have the form of an undamped sine wave. Damping of the motion, connected with various relaxation processes, must always exist in real specimens or the magnetization would not be observed to reach an equilibrium orientation. If it is assumed that the magnitude of the magnetization vector remains constant and that only the relaxation of the transverse components need be taken into account the process can be represented by a single relaxation time, T. The solutions of the damped equation of motion

$$\mathbf{M} = \gamma(\mathbf{M} \times \mathbf{H}) - (\lambda/M^2)\,\mathbf{M} \times (\mathbf{M} \times \mathbf{H}) \qquad (1)$$

in which λ is the damping constant, are

$$\begin{aligned} M_x &= M_t\, e^{-t/T} \cos(\gamma H t + \varepsilon) \\ M_y &= M_t\, e^{-t/T} \sin(\gamma H t + \varepsilon) \\ M_z &= M_s \{ 1 - (M_t/M_s)^2\, e^{-2t/T} \}^{1/2} \end{aligned} \qquad (2)$$

where M_t is the initial value of the transverse magnetization and $T = M_s/\lambda H$ for a spherical specimen. For a disc shaped specimen with fields applied in the plane of the disc

$$T = M_s/\lambda \{ H + M_s(N_t - N_z)/2 \}. \qquad (3)$$

The precessional frequency is unchanged but the magnetization spinals towards the field direction at a rate indicated by T or λ.

As in the more familiar field of ferromagnetic resonance the effects of specimen shape and crystalline anisotropy can be accounted for by replacing H by an effective field, H_e.

Methods and Materials. — To preclude complexities due to domain structures and define an initial direction a saturating bias field was applied and precession observed in a field which is the resultant of this and a pulse field normal to it. Disc-shaped specimens (of polycrystalline materials) were chosen to facilitate saturation, with fields applied in the plane of the disc. The precessional frequency is expected to be

$$\omega = \gamma H_e = \gamma \{ H[H + (N_t - N_z)\, M_s] \}^{1/2} \qquad (4)$$

where $(N_t - N_z) \sim 4\pi$. Since H is controlled largely by M_s, for saturation to be achieved, it is essential that M_s should be low in order to give precessional half periods $\tau/2 \sim 1$ ns, which can be readily observed by using sampling oscilloscopes. Thus Al substituted YIG specimens were mainly used, i. e. $Y_3Al_xFe_{3-x}O_{12}$: $x = 0.8, 1.0, 1.25, 1.5, 1.6$. M_s is also subject to control by thermal treatment in this material [3].

Having predicted an approximate range for τ it is necessary to apply pulses with a rise-time substantially less than this : 200 ps rise-time pulses were generated by a mercury wetted relay and transmitted along a strip-line close to the specimen to give fields of the order of 10 Oe. The precession was detected by the voltage pulses induced in an orthogonal strip line, the treatment and recording of the pulses being as described by Craik, Mc Quillan and Ross [4, 5, 6].

Results : Precessional Frequency. — The two most apparent objectives were to substantiate the relation $\omega = H_e$ for the conditions of free precession and to investigate the damping of the precession.

Figure 1 shows the effect of changing M_s in $Al_{1.6}$YIG by quenching from different temperatures so that the microstructure was identical. The effect of the change in M_s indicated is clearly resolved, particularly at the lower values of H where demagnetizing effects make the greater relative contribution to H_e. Curves of this type have been obtained repeatedly : for example for differing Al substitutions, heat treatments and silicon

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Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/jphyscol:19711269

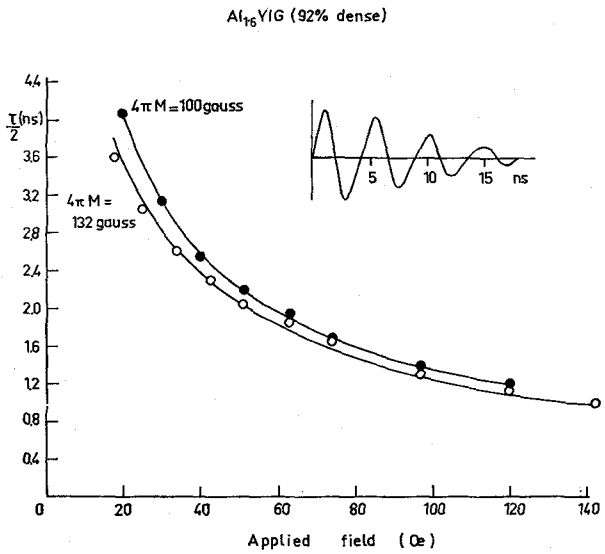

FIG. 1. — The dependence of precessional half $\tau/2$ on the applied field magnitude, and the effect of changing M_e by heat treatment.

doping (which affects M_s and the anisotropy). That they are of the expected form is shown by transforming to plots of $\tau/2$ vs. $1/H_e$ as in figure 2.

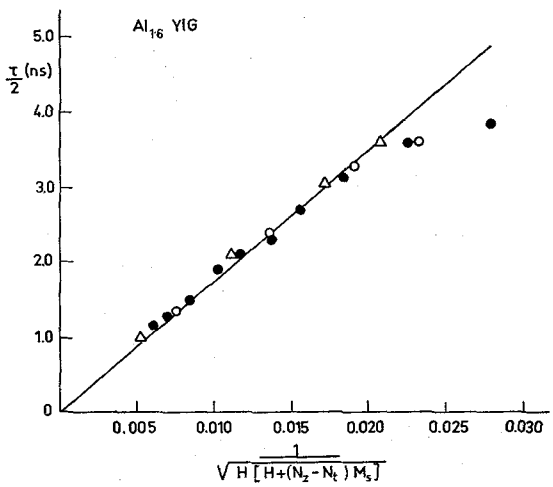

FIG. 2. — $\tau/2$ (as in Fig. 1) against $1/H_e$, including demagnetizing effects.

The deviations of $(N_z - N_t)$ from the value of 4π, for discs with a width to thickness ratio around 10, have a small but significant effect on the data and are taken into account in H_e.

It was confirmed, with an accuracy of better than 10 %, that for a constant effective field the period was independent of the magnitude of the pulse field, i. e. of the angle of precession between 0.5° and 10°.

Significant deviations from the theory occur for the lower effective fields. Referring back to the data it is seen that these deviations are associated principally with low values of H rather than of M_s : generally the lower M_s the better the fit. Thus the deviations are assigned to lack of saturation. All the meaningful results were obtained on specimens with quite low values of M_s (and low damping so that several oscillations occurred). Results of some interest have been obtained for pure YIG and spinels with high M_s, but due to certain lack of saturation in the fields available their analysis is complex and will not be pursued in detail. Exceptionally slow precession, or switching, was observed for a nickel-zinc ferrite specimen as compared with expectations for a saturated specimen, and extremely high apparent damping and *increase* of the precessional period with increase of bias field (pulse field constant) were observed for YIG.

To a first approximation the contribution of crystal anisotropy can be ignored, particularly for applied fields $H > H_K$. For low values of H the anisotropy can increase H_e substantially as suggested by Okamura and Kojima [7], and this effect was confirmed by doping $Al_{1.5}YIG$ with silicon to reduce the dynamic crystal anisotropy [8, 9]. It appears that the effect of anisotropy becomes insignificant for $x = 0.1$ in $Fe_{3.5-2x}(Si^{4+}Fe^{2+})_xO_{12}$, in line with resonance work on YIG (10).

Damping. — By analogy with resonance studies one expects to associate damping of the precession with microstructure and with impurities such as rare earths with large unquenched orbital angular momentum, or silicon which generates ferrous ions. Logarithmic plots of signal pulse height against time were linear for $Al_{1.6}YIG$ specimens for example (Fig. 3) and effective

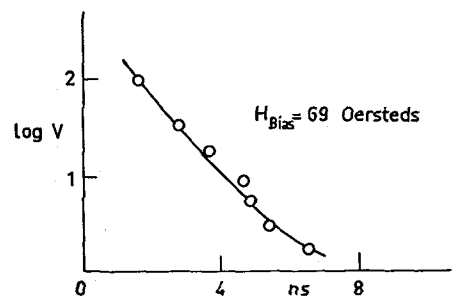

FIG. 3. — Log pulse height vs. time for $Al_{1.5}YIG$.

inverse relaxation times $\eta = 1/T$ were measured on the assumption that $M(t) = M(0)_{x,y} \exp(i\omega t) \exp(-\eta t)$.

The effect of porosity is indeed very marked and η was found to be directly proportional to the porosity up to 20 % for $Al_{1.6}YIG$, as described in a previous publication [6]. A change in the relation at about 20 % porosity suggests that the independent grain approximation [11] rather than the dipole narrowed treatment [12, 13] may apply above that value.

The effect of holmium doping on η was studied for four values of x in $Y_{3-x}Ho_xAl_{1.5}Fe_{3.5}O_{12}$. The densities of the specimens are indicated in figure 4. The measured values of $4\pi M_s$ were 142, 132, 138 and 130 gauss for $x = 0.1$, 0.2, 0.3 and 0.4. η depended on the effective field, as shown in figure 4, for the higher values of x. The gradients increase with x. An increase of η with H_e is expected from equation 3, in which the damping factor λ includes contributions from crystal anisotropy and porosity as well as the spin-lattice relaxation due to the holmium. For the specimen with $x = 0.4$, λ may be obtained from the slope of η vs. H_e as 6×10^7 s^{-1}. The plots cross and the extrapolated values of η for $x = 0.4$ at low effective fields would appear to be less than that for undoped

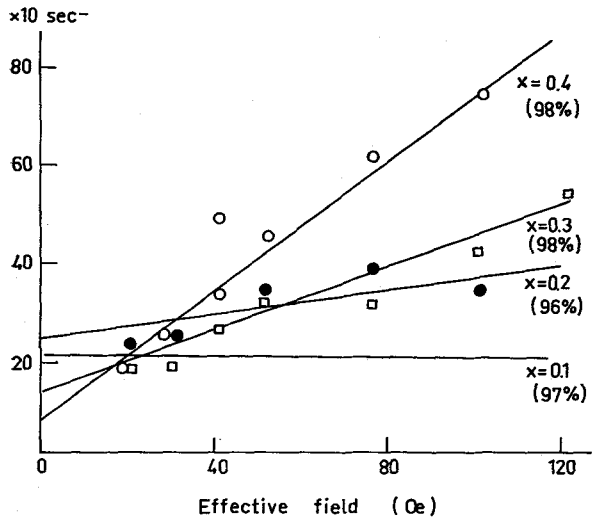

FIG. 4. — The variation of η with effective field.

$Al_{1.5}$YIG. It should be stressed that measurements of η are only made with good accuracy when the damping is light and a considerable number of oscillations can be observed.

A similar though less strong dependence of η upon Si doping and applied field was observed for $x = 0$, 0.05, and 0.1 in $Si_xAl_{1.5}$YIG, and this may be attributed to valence exchange relaxation [8].

Conclusions. — The frequency of precession in pulsed fields is found to conform to the expected relation, $\omega = \gamma H_e$, in which H_e includes the effects of specimen shape and M_s, so long as M_s is low. For materials with high M_s and H_K the simple treatment is inappropriate. Relaxation frequencies measured from the decrement of the signal oscillations are strongly dependent upon porosity, and doping with holmium or silicon, in accordance with spin-lattice and valence exchange relaxations.

The authors wish to thank the Ministry of Technology for supporting this work, and Mr J. D. R. McQuillin for his invaluable advice.

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