# Magnetostatic echo in ferrite films

V. V. Danilov and A. V. Tychinskiĭ
*T. G. Shevchenko Kiev State University*

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Signals corresponding to an electron spin echo have been detected and studied in epitaxial films of yttrium iron garnet. An echo method can be used to measure the relaxation parameters of long-wavelength magnetic-wave modes of ferrite films.

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We would hardly expect a uniformly magnetized sample of yttrium iron garnet (YIG) to be capable of generating echo signals at ferrimagnetic-resonance frequencies, primarily because the energy relaxation times of the spin system are short in YIG ($T \sim 10^{-7}$–$10^{-8}$ s), but also because inhomogeneous broadening ($1/T^*$) is negligible in the overall width ($\sim 1/T$) of the ferrimagnetic-resonance line in the absorption spectrum.

The first experimental attempts[1] to detect the electron spin echo in YIG were thus successful only when samples with a very nonuniform internal field were used. It was shown[2] that the echo process involves volume magnetostatic waves with a wave number $k \sim 10^3$ cm$^{-1}$ and a frequency $\omega_{\text{echo}} = \omega_L = \gamma H_i$, corresponding to the lower boundary of the spectrum. In Fig. 1, this region is ECHO$_1$.

In this letter we report an experimental study of the electron spin echo in another part of the spin-wave spectrum. The echo signal was generated through a two-pulse excitation of long ($k \sim 0$) magnetostatic waves with frequencies near $\omega_1$ (ECHO$_2$ in Fig. 1), where $\omega_1 = \gamma (H_i B_i)^{1/2}$; $\omega_U = \gamma (H_i + 2\pi M)$; $B_i = H_i + 4\pi M$; $\gamma$ is the gyromagnetic ratio; $H_i$ is the field in the sample; and $M$ is the saturation magnetization. The mechanism for the formation of the echo is the same in the two cases, so that the distinction between two types of echos is somewhat arbitrary.

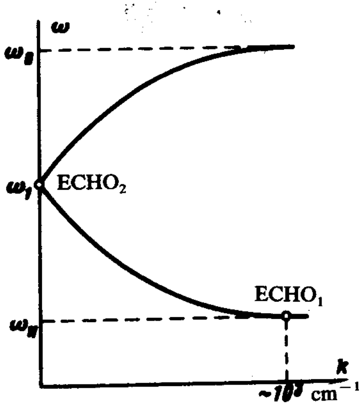


FIG. 1.

  

It was found possible to produce the echo at the frequency of the fundamental resonance ($\omega_1$) by using epitaxial YIG films. For such samples, the condition $T \gg T^*$ holds automatically because of structural inhomogeneities. The primary factors (the types of inhomogeneities) responsible for the spread of resonant frequencies and for the fact (in comparison with $T$) reversible phase relaxation are (a) a transition layer ($\sim$200–300 Å thick), in which the magnetization changes substantially,[3] (b) inhomogeneous elastic stresses resulting from the growth of the film on a substrate with a different lattice constant, and (c) variations of the anisotropy field over the film thickness.[4]

In the experiments we used single-crystal YIG films on [111] and [110] gadolinium-gallium garnet (GGG) substrates. The sample was irradiated with two short (30-ns) microwave pulses of equal height separated by a time interval $\tau$. The alternating magnetic field was directed perpendicular to the static magnetic field. The microwave pulses were launched from a miniature loop or a stripe antenna. Since the echo process in the system of ferrimagnetic spins is a temporal process, the echo signals were detected by the same antenna. The receiver was not overloaded because the echo appeared at a time $\tau$ after the application of the second pulse. The echo was reliably observed in all the YIG films with thicknesses from a few microns to tens of microns under a variety of magnetization conditions (with various directions of the external magnetic field $H_0$ with respect to the plane of the film). Experiments were carried out over the frequency range 1–2 GHz at room temperature. The echo was detected both in samples with dimensions comparable to those of the antenna and in "washers" ranging from 40 to 60 mm in diameter.

The insertion loss in this case is given by $\eta = 20\log(A_{\rm echo}/A_1)$, where $A_1$ and $A_{\rm echo}$ are the heights of the first pulse and of the echo, respectively. At a delay of $2\tau = 0.5\ \mu$s, this loss was $\sim$25 dB for several samples. By measuring the amplitude of the echo signal as a function of the delay between pulses we determined the temporal decay rate $\alpha$. Since the relaxation reduces the echo amplitude in accordance with $\exp(-2\tau/T)$, the relationship between $\alpha$ and the relaxation time is $\alpha = 20 \times \lg\{\exp(-2\tau/T)\}$. In most cases the values of $\alpha$ lie between 15 and 25 dB/$\mu$s.

The energy relaxation time of the spin system is determined directly from the dependence of the total loss $R = \eta + \alpha$ on the delay $\tau$. The dependence $R(\tau)$ is linear over a wide interval of delays (Fig. 2). The typical values of $T$ for most of the YIG films are 0.4–0.6 $\mu$s. Converting the results into the width of the resonance curve, $(2\Delta H)_h = 2/\gamma T$, we find 0.28–0.19 G, respectively. Here the subscript "$h$" refers to the homogeneous linewidth of the spin wave with $k \to 0$. Also shown in Fig. 2 are the total widths ($2\Delta H$) of the absorption line for the same samples, measured with an rf spectrometer. It follows from these results that the total linewidth is determined primarily by nonintrinsic relaxation processes caused by structural inhomogeneities of the film.

This method can thus be used to determine the relaxation parameters of long-wave magnetic-wave modes of ferrite films directly from the temporal decay of the echo signal. The results yield the contribution of intrinsic relaxation processes, undistorted by various types of inhomogeneities.

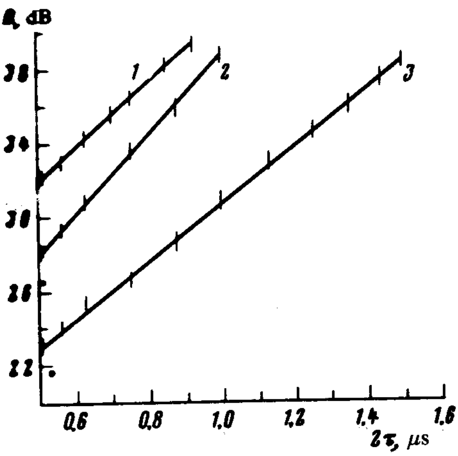


FIG. 2. Decay of the echo signal (with respect to the first pulse) over time. 1—Film thickness $S = 6.7$ $\mu$m, $\alpha = 18$ dB/$\mu$s, $T = 0.48$ $\mu$s, $(2\Delta H)_0 = 0.23$ G, $(2\Delta H) = 1.89$ G; 2—$S = 66$ $\mu$m, $\alpha = 21.2$ dB/s, $T = 0.4$ $\mu$s, $(2\Delta H)_0 = 0.27$ G, $(2\Delta H) = 1.54$ G; 3—$S = 30$ $\mu$m, $\alpha = 15.6$ dB/$\mu$s, $T = 0.55$ $\mu$s, $(2\Delta H)_0 = 0.2$ G, $(2\Delta H) = 0.8$ G.

The delay of the echo pulse in our experiments reached a maximum value of $2\tau = 2$ $\mu$s.

The echo is observed over a broad range of the external magnetic field $H_0$. The dependence of the echo amplitude on $H_0$ is oscillatory, as is particularly noticeable in the results from the thicker films (Fig. 3). This oscillation might be a consequence of a broad spectrum of magnetostatic wave modes, which are strongly coupled with the electromagnetic field. In the two-pulse excitation of each of these modes, echo genera-

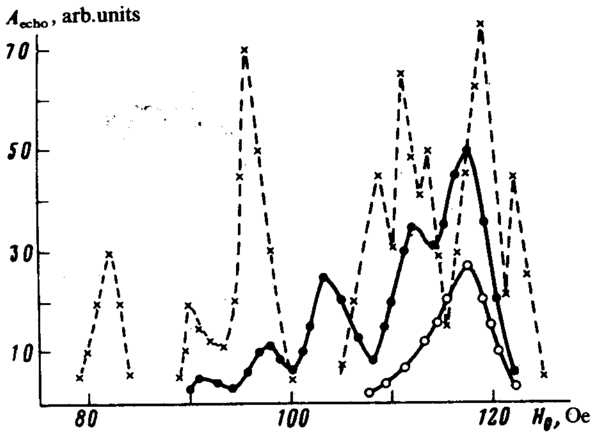


FIG. 3. Echo height vs the magnetic field for films of various thicknesses. Crosses—$S = 30$ $\mu$m; filled circles—$S = 8.33$ $\mu$m; open circles—$S = 1.07$ $\mu$m.

tion can occur. For thin films ($S \sim 1$ $\mu$m) the dependence $A_{echo}(H_0)$ is generally a smooth curve with a single maximum. The position of this maximum along the field scale corresponds to the fundamental resonance.

We also studied thin single-crystal YIG wafers (0.2–0.5 mm thick). In two-pulse excitation near the end of a longitudinally magnetized wafer (in a region of a nonuniform demagnetizing field) we observed an echo of the first type at the frequency $\omega_L$. We did not observe the echo of the second type in these samples. We then doped the surface of the wafers with gallium; i.e., we deliberately produced a magnetization nonuniformity of the nature of a (gallium iron ferrite)-to-GGG transition layer. When the sample was excited under conditions corresponding to a uniform internal field (at the middle of the wafer) in this case we detected an echo of the second type in the $\omega_1$ region. This experiment confirms suggestion regarding one of the factors responsible for echo generation in the films.

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