Echo of magnetostatic modes in YIG films

A. A. Serga and A. V. Tychinskiĭ
Taras Shevchenko Kiev University, 252017 Kiev, The Ukraine

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Experimental results are reported on the observation of an echo in tangentially magnetized epitaxial films of yttrium iron garnet (YIG) during excitation of magnetostatic waves with fixed propagation directions with respect to the magnetizing field. The results support the suggestion that the echo process in YIG films is associated with slow surface magnetostatic waves which are propagating near critical angles.

Efficient echo generation in any physical system is known to require satisfaction of the conditions

$$\Delta t \ll T_1,\ T_2,\ T_2^*;\quad T_2 > \tau > T_2^*;\quad T_1 \gg T_2 \gg T_2^*,$$

where T_1 is the energy relaxation time, T_2 is the time scale of the irreversible phase relaxation, T_2^* is the time scale of the reversible phase relaxation, Δt is the length of the excitation pulses, and τ is the time interval between the excitation pulses.[1] For an echo of magnetostatic modes, the last of these conditions means that the magnetostatic oscillations must be excited in a frequency band $\Delta f \gg T_2^{-1}$, where $T_2 \simeq 0.3$ μs.

An echo in YIG films has been observed previously in the case of a high gradient ($\simeq 200$ Oe/mm) of the external magnetic field, at frequencies corresponding to surface magnetostatic waves with $k \simeq 70$ cm^{-1} (Ref. 2), or in a uniform field near the frequency of a ferrimagnetic resonance, ω_1 (Ref. 3). In Ref. 2, the spread in resonant frequencies required for echo generation was produced (as in bulk YIG samples) by a highly nonuniform magnetizing field. The attempt made in Ref. 3 to link this spread with a nonuniformity of the internal fields in the YIG film sounds somewhat dubious, since the dipole–dipole interaction is known[4] to cause an averaging of the resonant frequencies at different points in a sample, and no broadening of the ferrimagnetic-resonance occurs. A more likely explanation (in our opinion) can be found by taking into consideration the possibility of observing an echo by placing a small loop antenna (with a diameter $\leqslant 2$ mm), which doubles as receiver and transmitter, at the center of the samples, which would be "washers" with a diameter of 60 mm or more.[3] In this case, a resonator regime clearly does not occur for magnetostatic modes. This fact is evidence that the echo is generated by magnetostatic waves with low group velocities V_{gr}. Only under the condition

$$V_{gr} \leqslant L/2\tau, \tag{1}$$

where L is a length scale of the antenna, does the region of echo generation remain in the vicinity of the antenna for a time comparable to the delay time of the response signal. With $L = 2$ mm and with the time $2\tau \simeq 3$ μs, which is the longest time observed by us experimentally, we would have $V_{gr} \leqslant 0.1$ cm/μs. Under these conditions, there are both a spatial coincidence of the magnetostatic excitations from the two pulses and an efficient reception of the echo signal which is formed. We wish to emphasize that magnetostatic waves with a low group velocity and with wavelengths much shorter than the length scales of the sample do not sense the boundary conditions associated with the limited dimensions of the film; i.e., they have a continuous dispersion characteristic. Such waves can be excited over the entire frequency band corresponding to the spectrum of the microwave pulses; the frequency spread required for echo generation is set up automatically in this case. Curves of the amplitude of the two-pulse echo of magnetostatic modes in YIG films versus the angle between the plane of the sample and the direction of the external magnetic field were found in Refs. 5 and 6. They show that the echo is generated only if the angle between the plane of the film and the static internal magnetic field is small, i.e., only under conditions close to tangential magnetization. The forward bulk magnetostatic waves with the necessary group velocity which exist in the case of normal magnetization have wave numbers which are too large, and there is essentially no excitation of these waves.

In light of the discussion above it can be suggested that surface magnetostatic waves which are propagating near critical angles and which have, because of a narrowing of the band, arbitrarily low group velocities even at small wave numbers ($\simeq 150\ \mathrm{cm}^{-1}$), participate directly in the generation of an echo at the frequency ω_1. By "critical angle" here we mean that minimum value of the angle between the wave vector of the surface magnetostatic wave and the direction of the magnetizing field below which a wave of the given type does not exist.[7]

To test this suggestion, we carried out an experiment to observe an echo in tangentially magnetized YIG samples with diameters ranging from 20 to 60 mm. In the samples we excited magnetostatic waves, which propagated in specified directions with respect to the external magnetic field. These waves were excited by a microstrip line with a strip width $L \simeq 0.4$ mm, on which the YIG samples were positioned symmetrically. The maximum of the directional pattern in the system corresponds to the direction perpendicular to the axis of the strip. The angle (θ) between the mag-

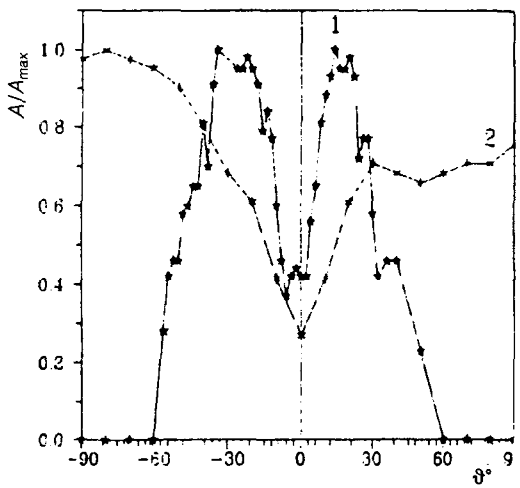

FIG. 1. Relative amplitude of the echo signal versus the angle θ. 1—The diameter of the sample is 60 mm, and the thickness of the YIG film is 6.11 μm; 2—25 mm, $\simeq 1$ μm.

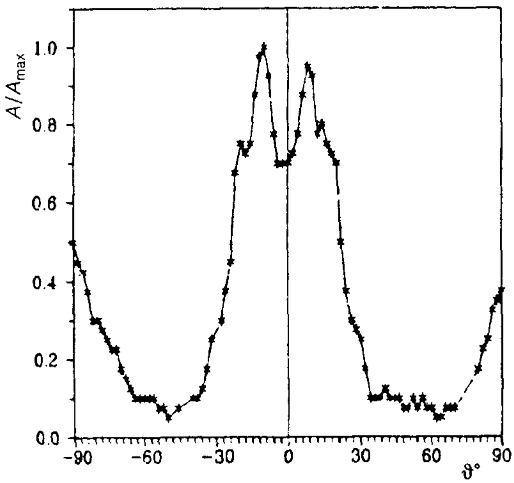

FIG. 2. Relative amplitude of the echo signal versus the angle θ for a sample 20 mm in diameter with a YIG film 12.89 μm thick.

netizing field and the wave propagation direction is changed by rotating the microstrip line with respect to the test sample, which is held fixed in the external magnetic field. In this system, the variable magnetization interacts primarily with the tangential component of the microwave magnetic field. The waves which are excited most efficiently are therefore those waves which propagate perpendicular to the external field. Consequently, as θ approaches zero, there is a decrease in the coupling of the microstrip antenna with the YIG film. To compensate for this effect, we varied the amplitude of the exciting pulses in the course of the measurements, in such a way that the power dissipated by the microstrip antenna remained constant.

Measurements were carried out at a frequency of 1300 MHz for a large number of (111) films with a saturation magnetization $\simeq 1750$ G. We studied films with thicknesses s ranging from 0.95 to 20 μm. An echo was observed near the frequency ω_1. The critical angle of the surface magnetostatic waves is on the order of 14° for the corresponding magnetizing fields. Some typical results are shown in Fig. 1. The decrease in the amplitude of the echo signal at small angles on curves 1 and 2 corresponds to directions at which surface magnetostatic waves cannot propagate, although the echo amplitude does not drop to zero here, because of the finite width of the directional pattern of the antenna. The wave numbers of the magnetostatic waves which are excited by the antenna can be estimated approximately from the expression $k \leqslant 2\pi/L$; their values are ≈ 150 cm^{-1}. For a surface magnetostatic wave with $k=150$ cm^{-1} in a film 6 μm thick, condition (1) holds at $\theta \simeq 20°$. This value of the angle θ corresponds quite accurately to the positions of the maxima on curve 1.

As the film thickness is increased, the maxima of the echo amplitude become progressively more prominent; for the thin films ($s \leqslant 1$ μm), in contrast, the maxima cannot be traced at all (curve 2 in Fig. 1). This tendency is explained on the basis of an inverse proportionality between V_{gr} and s, which leads to the satisfaction of condition (1) for thin films at much larger angles than for thick films.

For samples with diameters of 20 and 25 mm we observe an increase in the echo amplitude at $\theta=90°$ (Fig. 2). This increase may be due to a transformation of fast surface magnetostatic waves, which are excited efficiently, into slow waves at the edge of the film, followed by the generation of an echo.

In summary, these experimental results explain the mechanism for echo formation in the YIG films and show that it can be linked with specific types of magnetostatic excitations. This information is useful from the theoretical standpoint and also to guide the development of devices for processing microwave signals which would make use of this effect.

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