Observation of a collision of spin-wave envelope solitons in ferromagnetic films

B. A. Kalinikos and N. G. Kovshikov
St. Petersburg State Electrotechnical University, 197376 St. Petersburg, Russia

(Submitted 13 July 1994)
Pis'ma Zh. Eksp. Teor. Fiz. **60**, No. 4, 290–293 (25 August 1994)

First experiments have been carried out on the collision of counterpropagating envelope solitons of microwave spin waves in ferromagnetic films. The envelope solitons have essentially the same shape after a head-on collision.

Envelope solitons of high-dispersion (dipole–exchange) microwave spin waves and low-dispersion (dipole) microwave spin waves propagating in ferromagnetic films have been observed in numerous recent experiments (see, for example, Refs. 1–7 and the papers cited there). The wave phenomena which have been observed have been explained at both qualitative and quantitative levels on the basis of the nonlinear Schrödinger equation with a dissipative term.[1-6] Still, there has been no experimental study of one of the basic properties of solitons: their ability to retain their shape after a collision. In this letter we are reporting an experimental study of the collision of counterpropagating envelope solitons of microwave spin waves.

As has been shown in previous experiments, the competition between the dispersion and the nonlinearity of a spin system under the simultaneous effect of magnetic dissipation has the consequence that (for a given nonlinear level of the microwave input signal) there is a certain part of the path on which the spin-wave pulse formation behaves as an isolated envelope soliton. This part of the path is clearly defined during nonlinear pulsed excitation and propagation of low-dispersion spin waves in films of yttrium iron garnet (YIG) with free surface spins which have been subjected to perpendicular magnetization to the point of saturation.[4,5] Accordingly, films of this type were selected for the present experiments.

The test samples in the present experiments were narrow strips of films ("waveguides" for spin waves) 0.5–1 mm wide and more than 40 mm long. These strips were either prepared by chemical etching or cut from single-crystal YIG films with a thickness $L = 1-15$ μm and low magnetic losses (with a dissipation parameter $\Delta H_k = 0.2-0.4$ Oe). The films were grown epitaxially on substrates of gadolinium gallium garnet in the (111) orientation. One end of each waveguide (which served as a dispersion-free "reflector" of the spin waves) was oriented perpendicular to its axis. The spin waves were excited and received by a device of standard design,[1,6] which had short-circuited exciting and receiving microwave antennas, each 30 μm wide with a length equal to the width of the film waveguide. The antennas were fabricated by photolithography on moving ceramic substrates. The distance between the antennas, d, could be varied from 2 to 25 mm. The waveguides were placed on top of microstrip antennas. Their positions could be adjusted by changing the distance (l) from the receiving antenna to the reflector. The measurement apparatus described in detail in Ref. 1 was used for the experiments.

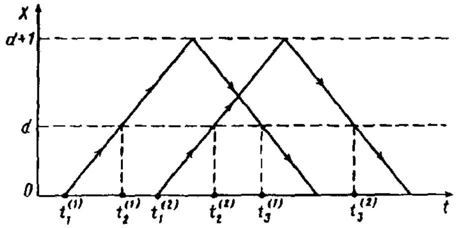

FIG. 1. Diagram used for a qualitative explanation of the position of a pair of spin-wave pulses as they propagate through a film waveguide.

The idea underlying the experiment is simple: To arrange conditions for a head-on collision of a forward spin-wave pulse (the incident pulse) and a reverse spin-wave pulse (the reflected pulse). The idea is illustrated in Fig. 1. Pulses with a microwave carrier frequency (of length τ_{in}) are applied in pairs to the input antenna at times $t_1^{(1)}$ and $t_1^{(2)}=t_1^{(1)}+T$. These pulses then propagate through the film waveguide and are received by the output antenna[1] at the times $t_2^{(1)}=t_1^{(1)}+\tau_d$ and $t_2^{(2)}=t_1^{(1)}+\tau_d+T$, i.e., after a delay time $\tau_d=d/v_g$, where d is the distance between antennas, and v_g is the group velocity of the carrier wave. After traversing the output antenna, the spin-wave pulses are then reflected from the end of the film waveguide[2] and are received a second time by the output antenna, at times $t_3^{(1)}=t_1^{(1)}+\tau_d+2\tau_r$ and $t_3^{(2)}=t_1^{(2)}+\tau_d+2\tau_r$, where $\tau_r=l/v_g$. By varying the distance l and the time $T=t_1^{(2)}-t_1^{(1)}$, one can easily adjust the position of the zone in which the incident and reflected pulses collide; i.e., one can move this zone along the film waveguide.

When a single input pulse is applied, or under the condition $T>2(\tau_d+\tau_r)$, the output antenna detects spin-wave pulses (incident and reflected) which have not undergone a collision. When a pair of pulses is applied, under the condition $T<\tau_d+\tau_r$, the first reflected pulse collides with the second incident pulse on the path between the output antenna and the "reflector." At the times $t_3^{(1)}$ and $t_3^{(2)}$, the output antenna thus detects the arrival of two reflected pulses, which have collided with each other.

A first series of experiments was carried out under collisionless conditions. In these experiments we studied the reflection of spin-wave pulses from the end of the film as a function of the level of the incident signal. The results of such experiments on the reflection of nonlinear spin-wave pulses are of interest in their own right, but a discussion of these results goes beyond the scope of the present letter. We would simply point out that we found an interval of the level of the microwave signal in which the nonlinear spin-wave pulse does not change shape upon reflection. It turns out that this interval corresponds to a soliton propagation regime for the spin waves.

A second series of experiments was carried out under collisional conditions. Here we studied the transformation of the shape of the spin-wave pulses as a function of their amplitude. Figure 2 shows some representative results of both series of experiments, carried out on a YIG film with a thickness $L=14.1$ μm. The position of the carrier frequency, $\omega/2\pi=3722$ MHz, with respect to the spin-wave spectrum is shown in Fig. 3, along with a theoretical plot of the group velocity of the spin waves for this particular sample. The crosses show the experimental values of $\omega=f(k)$, measured by the method of a two-element antenna under linear-excitation conditions. Incidentally, the measured soliton velocity 9.1×10^6 cm/s agrees within the measurement error, which we estimate to

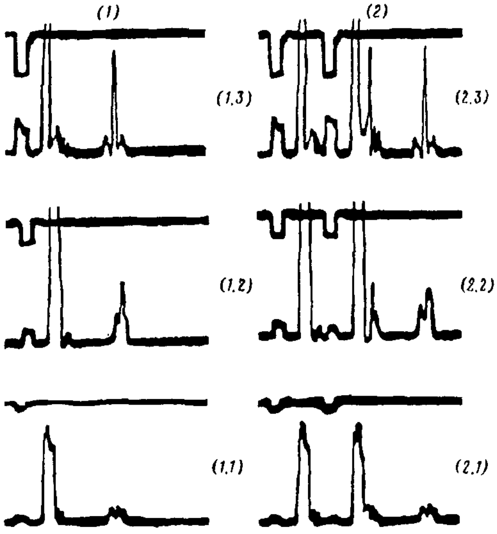

FIG. 2. Oscilloscope traces of the envelope of the magnetic signal at the input to the experimental prototype (upper traces) and at the output from this prototype (lower traces). These traces were recorded at various values of the input power in the collisionless regime (1) and in the collisional regime (2) of the propagation of the spin-wave pulses. The length of the input pulses in the experiments was $\tau_{\text{in}}=25$ ns. The microwave input power was 60 mW for (1.1) and (2.1), 250 mW for (1.2) and (2.2), and 520 mW for (1.3) and (2.3). $d=4.7$ mm, $l=6$ mm.

be 10%, with the theoretical value of the group velocity at the carrier frequency.

The upper traces on the oscillograms in Fig. 2 show the temporal position of the input pulses, $\tau_{\text{in}}=25$ ns. The sequence of pulses on the lower traces is explained by the diagram in Fig. 1. In addition to the pulses marked on the time diagram in Fig. 1, there

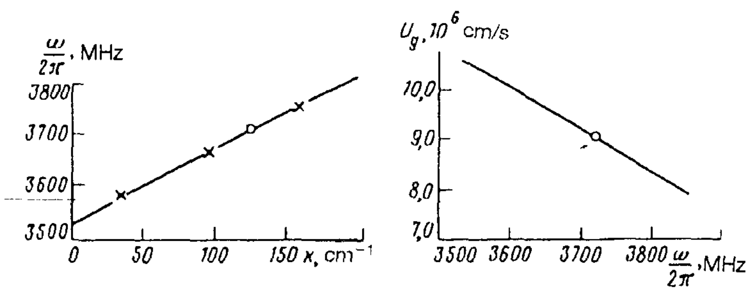

FIG. 3. Dispersion characteristics of a spin wave of the lower type of a test sample of a YIG film 14.1 μm thick. The calculations assumed a saturation magnetization $4\pi M_0 = 1750$ Oe and an external magnetizing field $H = 3010$ Oe. The surface spins were assumed to be free. Solid lines—Theoretical; crosses—experimental (the circles show the working frequency).

are some pickup pulses on the lower traces in Fig. 2 (corresponding to a "leakage" of the microwave signal between the input and output antennas). These pickup pulses have a zero delay time.

The results of the experiments carried out on all the YIG film samples show that it is possible to distinguish four intervals of the level of the microwave input power. We will refer to these intervals as the "linear," "slightly nonlinear," "soliton," and "highly nonlinear" intervals. In the linear regime, we naturally observe that the spin-wave pulses have the same shape after their collisions. In the slightly nonlinear regime, as can be seen from a comparison of the pairs of traces (1.1) and (2.1), and also (1.2) and (2.2), there is a perceptible distortion of the spin-wave pulses which have undergone a collision. In the soliton regime [compare traces (1.3) and (2.3)], the shape of the envelope of the spin-wave pulses remains essentially the same. As the level of the microwave input signal is increased further, we again observe a significant distortion of the pulses which have collided. (A detailed study of this distortion requires additional, detailed measurements.)

This retention of the envelope shape of the spin-wave pulses is typical of all the YIG film test samples in which a single-soliton propagation regime occurs for low-dispersion spin waves. Because of dissipation, the preservation of the shape of the nonlinear spin-wave pulses occurs in a comparatively narrow interval (a few decibels) of the microwave power.

As in our earlier studies,[2-5] the parameters of the solitons of low-dispersion spin waves which were observed can be explained on the basis of the nonlinear Schrödinger equation with a dissipative term. Some numerical calculations will be published later.

Preliminary results of this study were reported at the conference Intermag-93 (Ref. 8).

This study was supported by the Russian Fund for Fundamental Research (Project 93–02–2518).

[1)] There was a partial structural mismatch between the output antenna and the ferromagnetic film, so only a small fraction of the power of the incident signal was tapped.

[2)] Strictly speaking, according to existing theoretical ideas and experimental facts, the reflection of spin-wave pulses should occur not at the end of the film but at a "turning point," which arises because the static internal magnetic field is nonuniform near the edge of the film. However, numerical estimates show that the turning point and the end of the film waveguide can be assumed to coincide, within the error of the delay-time measurements because of the small film thickness.

---

[1] B. A. Kalinikos *et al.*, Zh. Eksp. Teor. Fiz. **94**, 159 (1983) [Sov. Phys. JETP **67**, 89 (1988)].

[2] B. A. Kalinikos *et al.*, Phys. Rev. B **42**, 8658 (1990).

[3] B. A. Kalinikos *et al.*, J. Appl. Phys. **67**, 5633 (1990).

[4] B. A. Kalinikos *et al.*, J. Appl. Phys. **68**, 5712 (1991).

[5] B. A. Kalinikos *et al.*, IEEE Trans. MAG **28**, 3207 (1992).

[6] M. Chen *et al.*, Phys. Rev. B **45**, 2773 (1993).

[7] M. Chen *et al.*, Phys. Rev. Lett. **70**, 1707 (1993).

[8] B. A. Kalinikos *et al.*, *Digests of International Magnetics Conference* (Stockholm, Sweden, April 13–16, 1993, p. AE–03.

Translated by D. Parsons