Observation of the amplification of spin-wave envelope solitons in ferromagnetic films by parallel magnetic pumping

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The propagation of envelope solitons of microwave-frequency spin waves in a spatially periodic field oriented parallel to the magnetic pump has been investigated experimentally. In a pulsed pumping regime with amplitude much greater than the threshold for parametric excitation of spin systems, amplification of spin-wave envelope solitons exceeding their natural damping was obtained. © *1997 American Institute of Physics.* [S0021-3640(97)01317-0]

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In recent years envelope solitons of both strongly (dipole-exchange) and weakly (dipole) dispersive microwave-frequency spin waves (SWs) propagating in ferromagnetic films (FFs) have been observed and investigated in a series of experiments (see, for example, Refs. 1–6 and the literature cited therein). Specifically, it has been established that magnetic dissipation greatly limits the lifetime and therefore the propagation path length of solitons. Even in the case of high-quality single-crystal yttrium iron garnet (YIG) films, which exhibit record low losses, the single-soliton path length does not exceed 1 cm (Ref. 6). To increase the lifetime of spin-wave solitons, it is necessary to find a method for compensating their natural damping.

It is known theoretically that the damping of spin waves can be compensated by three- and four-wave nonlinear interactions realized under conditions of parallel and transverse parametric pumping. Experimental investigations have shown that the intensification of linear spin waves in YIG films can be accomplished with parallel pumping.[7,8] The use of local longitudinal pumping to compensate damping of spin-wave envelope solitons was recently reported.[9] The maximum gain achieved in Ref. 9 was equal to 0.7 dB. Our objective in the present work was to study the propagation of spin-wave envelope solitons in a spatially periodic parallel magnetic pump field for the purpose of obtaining efficient amplification of solitons.

Theoretical investigations of the parametric intensification of spin-wave envelope solitons[10] show that of the possible types of spin-wave solitons in ferromagnetic films intensification is most easily accomplished in the case of the so-called backward volume spin waves (BVSWs). These waves propagate in the direction of a constant magnetic field in tangentially magnetized films and exhibit negative dispersion in the long-

wavelength region of the spectrum. As was shown earlier,[11] both theoretically and experimentally, long BVSWs possess a low parametric excitation threshold h_{th}, which makes their parametric regeneration a comparatively easy matter. Furthermore, on account of the characteristic dispersive and nonlinear properties of BVSWs, it is comparatively easy to produce envelope solitons of these waves.[3,4,6] This is the reason why in the present work the parametric amplification experiments were performed with BVSW solitons.

Specimens in the form of narrow film strips 2 mm wide (spin-wave ''waveguides'') were used for the experiments. These waveguides were cut from single-crystal YIG films with thickness $L=5.2$ μm, grown on a gadolinium–gallium garnet substrate with (111) orientation. Launching and receiving of the spin waves were accomplished with the standard construction,[1,6] using 50-μm wide short-circuited launching and receiving microstrip antennas whose length was equal to the width of the film waveguide. The distance between the antennas was equal to 6.1 mm. Two types of periodic microstrip structures were used to produce the microwave field parallel to the magnetic pump: in-phase (''grating'') and antiphase (''meander''). The grating structure has a period of 0.3 mm and consists of seven 0.1-mm wide elements. The meander structure has a period of 0.3 mm and consists of eleven 0.1-mm wide elements. Each pumping structure was placed alternately between the antennas. The distance from the input antenna to the edge of the first element of the structure was chosen to be 3 mm, which ensured the formation of a single envelope soliton when the wave packet approached the edge of the structure. (A discussion of the production of BVSW solitons can be found in Ref. 6.)

A pulsed pumping regime was used to obtain efficient amplification of the solitons. In this technique, the pump pulse was applied at the moment when the spin-wave soliton approached the edge of the pump structure. According to theory,[10] when the soliton and pump pulses are superposed in this manner, amplification can be effected in a nonstationary regime in which, even at large supercritical pumping $h/h_{\text{th}} \gg 1$, the parametric excitation of parasitic (thermal) spin waves has still not developed.

We shall now discuss the experimental data obtained using the grating microstrip structure as the pump element. In the absence of a pump field, the soliton excitation and propagation regime was similar to that described in detail in Ref. 6. The experiments were performed at the signal carrier frequency $f_s = 4669$ MHz, which was 50 MHz lower than the frequency of the homogeneous ferromagnetic resonance of the experimental film specimen. The computed value of the carrier wave vector was $k_s = 110$ rad/cm. The pump frequency f_p was varied in the region of twice the signal frequency. The best soliton amplification regime was obtained for $f_p/2 - f_s = 5$ MHz.

The experiments were performed in two stages. The power threshold P_{th} of the parametric instability of the spin system was measured at the first stage under practically stationary excitation conditions. For this, long (more than 50 μs) microwave pulses were applied to the microstrip pump structure. The threshold was fixed according to the appearance of parametrically generated BVSWs at the output antenna at frequency $f_p/2$. The amplification of linear spin-wave pulses and spin-wave solitons with simultaneous application of f_s and f_p was investigated at the second stage. In so doing, the pump power was chosen to be close to and higher than the threshold value P_{th}.

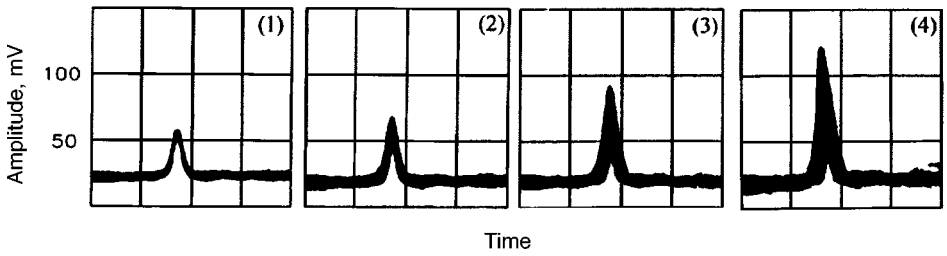

FIG. 1. Oscillograms of the envelope of a pulsed signal at the output antenna. The oscillograms were obtained for different pump powers: 1 — $P_p/P_{th}=2.5$, 2 — $P_p/P_{th}=128$, 3 — $P_p/P_{th}=155$, 4 — $P_p/P_{th}=251$.

Characteristic oscillograms illustrating the amplification of an BVSW envelope soliton are displayed in Fig. 1. The oscillograms were obtained with the following parameters: pump pulse duration — 100 ns, input signal pulse duration — 26 ns, soliton duration — 14 ns. The measured soliton delay time was equal to 237 ns, which gives a soliton velocity of 2.57×10^6 cm/s. This soliton velocity is close to the theoretically computed value of the group velocity of the carrier wave, equal to 2.4×10^6 cm/s.

It is clear from the oscillograms that the amplitude of the soliton increases with the pump power P_p, i.e., the soliton is amplified. We also note that the envelope of the amplified soliton pulses appears to be smeared in amplitude. This phenomenon is probably due to the asynchronicity of the signal and pump phases.

Figure 2 shows curves of the gain $G=f(P/P_{th})$ measured in the soliton regime and a regime which is linear in the input signal. We call attention to the fact that the gain for the linear pulse with the same pump powers P_p is much larger than the soliton gain.

The maximum soliton gain was equal to about 6 dB. The same gain was obtained using the meander pump structure.

Attempts to increase G by increasing P_p resulted in a change in the shape of the output pulse. Apparently, this corresponded to the onset of a transition into a two-soliton

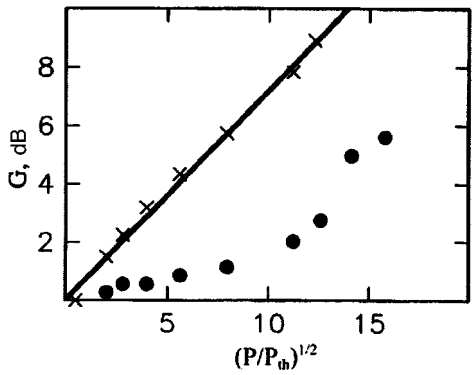

FIG. 2. Gain of linear spin-wave pulses (×) and spin-wave solitons (●) versus the normalized pump power. The solid line shows the computational result obtained from the numerical data.

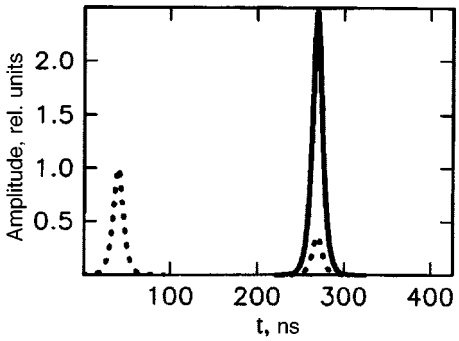

FIG. 3. Results of numerical simulation of the propagation of a spin-wave pulse in a YIG film. The dotted lines show the profiles of the input and output spin-wave pulses in the absence of a pump and the solid line shows the same profiles in the presence of a pump. The following parameters were used in the simulation: group velocity — 2.57×10^6 cm/s, input pulse duration — 14 ns, dissipation parameter — $\Delta H=0.25$ Oe, supercriticality — $(P_p/P_{\text{th}})^{1/2}=20$.

regime (according to the type described in Ref. 4). This last remark is tentative and requires a detailed experimental study. According to a theory in which the thresholds of the one- and many-soliton regimes are determined neglecting dissipation (see, for example, Ref. 12), the maximum gain in the one-soliton regime cannot exceed 9.6 dB.

A theory that would completely explain the experiments performed has not yet been developed. We performed a numerical simulation in order to determine the main features of the parametric amplification of the BVSW pulses by longitudinal-pump pulses. As the initial equations, we employed the evolutionary equations presented in Ref. 10. Two cases were simulated in order to clarify the physics of the process: co- and counterpropagation of the signal and idler waves. It was found that the experimental results obtained with linear-wave pulses find a good theoretical explanation when the signal and idler wave pulses propagate in the same direction. An example of the numerical results is shown in Fig. 3. For the numerical simulation, the profile of the signal wave was taken in the form $\text{sech}[a(t-t_0)]$. We underscore the fact that all other parameters were taken to be the same as in the experiment. The dotted lines in Fig. 3 show the profiles of the input and output signal pulses in the absence of a pump; the solid line shows the profile of the amplified spin-wave pulse. As is clear from the figure, the theoretical gain is greater than the natural damping of the spin-wave pulse.

The gain $G=f(P_p/P_{\text{th}})$ calculated from the numerical data is shown in Fig. 2 (solid line). It is easy to see that the experimental data are in good agreement with the calculations.

The codirectionality of the propagation of the signal and idler waves makes it possible to interpret their interaction in a pump field as a parametric process of the form $k_s+k_i=k_p$, where k_i and k_p are the wave numbers of the idler and pump waves. The latter relation gives $k_p=220$ rad/cm. This value of k_p gives $l=2\pi/k_p\cong0.029$ cm. These considerations were used to choose the period of the pump structures employed in the experiments.

A detailed description of the experimental results will be published later.

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