

Observation of self-generation of dark envelope solitons for spin waves in ferromagnetic films

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We have performed experiments in which self-generation of dark envelope solitons for spin waves at microwave frequencies were obtained. Stable self-generation of dark solitons was observed in a ring consisting of tangentially magnetized yttrium iron garnet film and a microwave signal amplifier. © 1998 American Institute of Physics.
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It is well known that two types of envelope solitons can propagate in nonlinear waveguiding dispersive media — bright solitons and dark solitons (see, for example, Ref. 1). Most experimental works concern bright solitons. Here bright solitons in optical fibers² as well as solitons for spin waves in ferromagnetic films (see, for example, Refs. 3–6 and the literature cited there) are in the leading position. At the same time, the generation and propagation of dark optical solitons (detailed information about which can be found in the recent review Ref. 7) and spin-wave solitons (we know of only one work, Ref. 8) have clearly not been adequately investigated.

In the present letter we report the experimental observation of the generation of dark envelope solitons for spin waves at microwave frequencies. Just as in Ref. 6, where generation of bright solitons was obtained, a ring consisting of an yttrium iron garnet film (YIG) and a microwave signal amplifier was used for the experiment. We underscore that an external microwave signal was not introduced into the circuit. In other words, self-generation of dark microwave solitons was observed.

Previous experiments devoted to the investigation of bright envelope solitons of both weakly and strongly dispersive spin waves have found a good explanation in the nonlinear Schrödinger equation (NES) model. For this reason, this model was used to formulate the experiment described. According to the NES model,

$$i(\partial u / \partial t + V_g \partial u / \partial x) + (D/2) \partial^2 u / \partial x^2 - N|u|^2 u = 0, \quad (1)$$

dark envelope solitons can be observed in waveguiding media if the dispersion and nonlinear coefficients of the carrying wave have the same signs. A quasisurface spin wave propagating in tangentially magnetized ferromagnetic films in a direction perpen-

dicular to the bias magnetization field satisfies this requirement. In the case of single-crystal YIG films, which have free surface spins, such a wave has monotonic dispersion $\omega(k)$ in the long-wavelength region of the spectrum $kL \ll 1$.⁹ Its dispersion coefficient $D = \partial^2 \omega / \partial^2 k$ and nonlinear coefficient $N = \partial \omega / \partial |u|^2$ are negative.

The experiments were performed on samples in the form of narrow, 1.5 mm wide, strips of YIG films (spin-wave “waveguides”). The waveguides were cut from single-crystal YIG films of thickness $L = 5.2 \mu\text{m}$ grown on a (111) gadolinium-gallium garnet substrate. The spin waves were excited and detected with the standard “delay line” arrangement^{3,4} with short-circuited exciting and detecting microstrip antennas, each of width $50 \mu\text{m}$ and length equal to the width of the film waveguide. The distance between the antennas, formed photolithographically on mobile ceramic substrates, could be regulated. The spin-wave waveguides were placed on top of the antennas.

The spin-wave delay line described above was connected with a wideband microwave signal amplifier (the working frequency band of the amplifier was greater than 300 MHz) and a microwave signal modulator into a closed circuit — a ring. We underscore that for all microwave signal levels employed the amplifier always operated in a clearly linear regime. Therefore the nonlinear properties of the ring were determined by the nonlinearity of the spin system of the ferromagnetic film. The modulator was used for periodic “interruption” of the ring for short time intervals several to ten nanoseconds in duration. Having in mind a comparison with theory, it is important to note that the modulator employed could not give complete interruption of the ring. The attenuation introduced by the modulator relative to the constant (maximum) level of the circulating microwave signal was equal to 41 dB. In other words, in the existing terminology^{2,7} the modulator supported a generation regime for gray solitons.

An apparatus similar to that described in Ref. 6 was used for measurements. The experiments can be conventionally divided into two stages. At the first stage the waveguiding properties of the ring were investigated. Specifically, the spectrum of the resonance frequencies of the ring was measured with different gains of the circulating microwave signal. These measurements were performed without modulation of the ring. At the second stage generation processes, where the modulator provided modulation of the signal in the ring, were investigated.

Figure 1a shows the amplitude–frequency characteristic of the ring, measured with a gain slightly below the threshold for the appearance of microwave generation in the ring. This characteristic reflects the resonance properties of the ring in a regime with almost complete compensation of losses in it. The wave numbers k_n of the resonant spin waves can be found from the condition $k_n d + \phi = 2\pi n$, where d is the distance between the spin-wave antennas, ϕ is the phase shift of the signal due to the part of the circuit outside the ferromagnetic film, and n is an integer. This resonance condition makes it possible to determine the dispersion relation $\omega(k)$ of the spin waves according to the experimental peaks in Fig. 1a. Such an equation was found in the course of the work as the dispersion relation of the lowest quasisurface wave mode.⁹ A calculation using the obtained dispersion relation gave the following spin-wave parameters: group velocity $V_g = 2.9 \times 10^6$ cm/s, dispersion coefficient $D = -3310$ cm/rad·s, and nonlinear coefficient $N = -9.2 \times 10^9$ rad/s. (The values of the parameters V_g , D , and N are given for the central carrying frequency, which is determined below.)

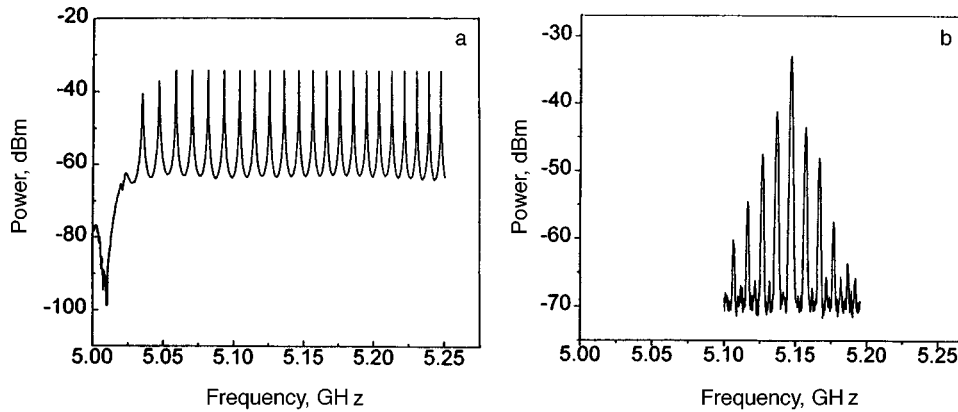


FIG. 1. Amplitude–frequency characteristic of the experimental ring (a) and frequency spectrum of the self-generated train of dark solitons (b).

At the second stage, experiments on self-generation of envelope solitons for spin waves were performed. The experiments were performed in a regime of periodic modulation of the ring by square “dark” pulses. In the experiments the envelope of the generated signal and its phase characteristic as well as the frequency spectrum of generation were measured simultaneously. To obtain stable self-generation several adjustments were made: 1. The distance d between the input and output antennas was adjusted to ensure that the circulation time t_0 of the microwave spin-wave pulses in the ring equals the external modulation period (here $t_0 = d/V_g + t_e$, where t_e is the propagation time of a microwave pulse outside the ferromagnetic film). 2. The ring gain was adjusted to compensate losses and achieve stable self-generation of dark microwave solitons. 3. The duration τ_{in} of the external pulses fed into the modulator was adjusted to obtain temporal profiles of the amplitude and phase of the envelope of the microwave signal that correspond to dark solitons.

It is important to note that in terms of frequencies the first condition corresponds to the condition that the spectral frequencies of the generated train of nonlinear pulses equal the characteristic frequencies of the ring. Satisfaction of this condition for a nonlinear propagation regime of spin-wave pulses was one of the main ideas of this experiment.

The results illustrating the regime of self-generation of dark solitons are presented in Fig. 2. The oscillograms shown in this figure were recorded with a periodic sequence of dark square pulses with duration $\tau_{in} = 22$ ns and clock rate 10 MHz fed to the modulator. The measurements were performed for the following parameters: distance between the input and output antennas $d = 2.3$ mm, total circulation time of the microwave pulses along the ring $t_0 = 100$ ns, and pulse propagation time outside the ferromagnetic film $t_e = 20$ ns. The power of the spin waves at the exit of the delay line was equal to 0.9 mW. Figure 2a shows a self-generated sequence of microwave pulses — dark spin-wave envelope solitons, while Fig. 2b shows its phase characteristic. (The measurements were performed with an HP70820A microwave transition analyzer.) The frequency spectrum of this sequence is displayed in Fig. 1b; the spectrum was obtained with a HP859E spectrum analyzer. As follows from the measurement results, in the case described self-

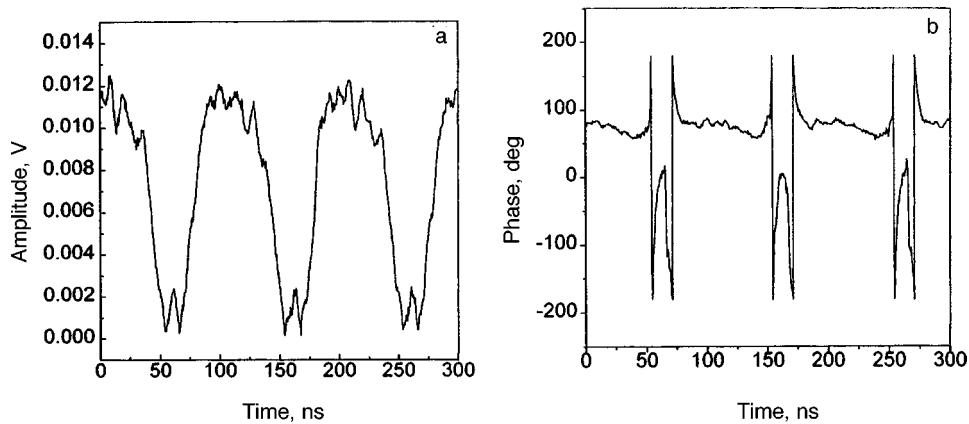


FIG. 2. Temporal profile of the envelope of a train of dark solitons (a) and its phase characteristic (b).

generation of dark solitons was observed with nonlinear self-synchronization of more than 10 ring modes.

We note that the phase characteristic was recorded with a 5146.6 MHz reference signal fed into the HP70820A. This frequency was set exactly equal to the central carrying frequency of the self-generating train of dark solitons (see Fig. 1b). The phase characteristic in Fig. 2b demonstrates two sharp changes in the phase of the carrying microwave signal (by 180° each), which occur “inside” the dark pulses; this is direct evidence of their soliton character. The propagation velocity of the dark solitons in a YIG film, within the limits of the measurement error which we estimate to be 10%, equals the group velocity of spin waves at the central frequency.

We shall now give a more detailed description of the data in Fig. 2. We note that each pulse of the self-generated sequence is always obtained with two minima in its profile (at the “bottom” of the pulse) (see Fig. 2a). Rapid changes in phase correspond to a change in the signal amplitude near these minima: one by $+180^\circ$ and the other by -180° . This behavior of the signal phase indicates that the observed nonlinear dark pulses can be interpreted as pairs of dark solitons. (We note that the abrupt 360° phase kicks, which correspond to the vertical lines in Fig. 2b, are purely instrumentation effects: They are due to a characteristic operational feature of the HP70820A and should be ignored.) On the whole, the two fast 180-degree phase changes occurring during a dark pulse compensate one another and the resulting phase of the carrying microwave signal does not change. This experimental fact corresponds to the theory of the generation of a pair of dark solitons from a square pulse.^{7,10,11}

We note in passing that the above-described behavior of the phase of a pair of dark solitons is fundamentally different from the case of bright solitons, where the phase of the carrying signal remains constant over the duration of the spin-wave soliton.⁶

In conclusion, we note that the obtained nonlinear pulsed spin-wave self-generation confirms theoretical ideas about dark envelope solitons. We believe that both the above-described experiments on self-generation of dark spin-wave solitons and the experiments

presented in Ref. 6 on self-generation of bright spin-wave solitons can be extended to diverse continuous and discrete waveguiding media.

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