Direct Brillouin light scattering observation of dark spin-wave envelope solitons in magnetic films

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The formation and evolution of dark spin-wave envelope solitons have been studied in a yttrium iron garnet (YIG) film. The Brillouin light scattering (BLS) technique has been used to map the propagation and evolution of the excited dark solitons. Experiments have been carried out using (1) a YIG-film delay-line structure supporting propagation of backward volume spin waves, (2) time- and space-resolved forward-scattering BLS, (3) a fixed magnetic field of 1000 Oe applied along the propagation direction, and (4) a soliton excitation technique based on the nonlinear interaction of two large amplitude cw input signals with fixed frequency enabling an induced modulation instability. Theoretical interpretation of the experiments based on numerical solution of the Ginzburg-Landau equation taking into account the conditions of nonlinear spin-wave dissipation is given. It is found that the dark soliton formation process involves competition between effects of nonlinearity and dispersion, and that nonlinear damping effects play an important role.

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I. INTRODUCTION

Solitons are localized waves arising from nonlinear and dispersive properties of matter and are among the key objects of nonlinear science. In recent decades, soliton excitations have been realized in a large variety of waveguiding media including deep water, plasmas, optical fibers, electrical transmission lines, and magnetic films. From an experimental point of view, spin waves (SWs) in thin magnetic films such as yttrium iron garnet (YIG) provide an exceptional test ground for the study of nonlinear phenomena. Valuable features of SWs in magnetic films (MFs) arise from their nonlinearity and rich dispersive properties, which are easily tuned by changing such simple experimental parameters as the bias magnetic field and film thickness. Spin-wave nonlinear effects in magnetic films manifest themselves at room temperature and at rather moderate microwave power levels. As a result, one of the fundamental solitonic effects, namely, self-modulation instability (SMI), was clearly observed for microwave spin waves excited in a YIG film years ago. Note that this was the first observation of SMI in solid-state media.

In recent decades, different types of spin-wave envelope solitons and modulation instabilities have been observed and studied in thin YIG films. Some remarkable demonstrations of such effects include the observation of dark and bright solitons in the time domain, nonlinear soliton amplification, “Mobius” solitons that break the usual $2\pi$ symmetry, spatially resolved phase sensitive measurements, and controlled modulation instability effects. Notable effects have also been observed in metal films, such as nonlinear spin-wave instabilities in Permalloy, nonlinear spatial self-modulation of spin waves, nonlinear ferromagnetic resonance effects, and nano-oscillators. Microwave spectroscopy has been the key technique enabling these studies, which in fact gave birth to the field of solitons in magnetic films.

One of the disadvantages of this technique is that it gives a resultant nonlinear wave form solely at the output of the experimental device structure without giving any information on the forming process within the magnetic medium. A technique that enables one to study nonlinear spin-wave phenomena with spatial and temporal resolution within the soliton medium is Brillouin light scattering (BLS). This is a spectroscopic technique based on a high-quality interferometer that measures small frequency changes of photons due to an inelastic interaction with magnons in a magnetic sample. This has enabled visualization of one- and two-dimensional nonlinear wave forms as they propagate in ferrite films. It has also been used to study nonlinear parametric spin-wave processes.

Many initial experiments on spin-wave envelope solitons found a reasonable interpretation in terms of the nonlinear Schrödinger equation. More recently, it was realized that the nonlinear damping of the carrier spin waves may play a very important role in the formation and propagation of solitons in thin magnetic films and that one can actually take advantage of this to control the formation of dark or bright solitons by manipulating excitation power levels. This work builds on this suggestion.

Here we report on an experimental observation of dark spin-wave spatial envelope solitons, trace their spatial evolution, and suggest a theoretical model based on the Ginzburg-Landau equation to explain the observed phenomena. The data show that spin-wave nonlinear damping plays a significant role in the observed effects.

Section II describes the BLS/microwave experimental setup. In Sec. III we present experimental results of the microwave characterization of the dark solitons together with time- and space-resolved BLS measurements. Section IV provides a theoretical model applicable to the experimental results and Sec. V provides a summary and conclusions.

II. MICROWAVE AND BRILLOUIN LIGHT SCATTERING SETUP

The experiments reported here utilized a spin-wave “waveguide” comprised of a long and narrow YIG film strip in a
standard magnetostatic backward volume wave (MSBVW) spin-wave delay-line configuration.\textsuperscript{21} The open-design microstrip transducer structure allowed for microwave excitation and optical detection in the forward-scattering BLS configuration\textsuperscript{21} as shown in Fig. 1. The YIG strip sample was 20 mm long, 2 mm wide, and 6.3 μm thick. The low loss YIG film was grown by standard liquid phase epitaxy techniques. The 5 GHz ferromagnetic resonance half power line width was about 0.5 Oe. A pair of 50-μm-wide and 2-mm-long microstrip transducers with a separation of 7 mm were used to excite and detect the propagating spin waves. For propagation in the MSBVW configuration, the static external field \( H_0 \) was applied parallel to the long dimension of the strip and the spin-wave propagation direction. The field was set at a nominal value of 1000 Oe for all measurements and yielded a MSBVW band-edge frequency \( f_B = \omega_B / 2\pi = 4560 \text{ MHz} \).

The microwave/BLS experiments were carried out in stages. In the first stage, linear dispersion characteristics, as well as linear and nonlinear damping parameters of the YIG-film waveguide, were measured following the same protocol as in Ref. 23. This involved the following: (a) By measuring the phase-frequency characteristic over a fixed propagation distance between the microstrip antennas, the dispersion relation \( \omega(k) \) was determined. (b) The low power linear signal decay rates were determined at a fixed frequency by comparing the input vs output power for two different propagation lengths. The value of the linear relaxation frequency was \( 5.3 \times 10^8 \text{ rad/s} \). (c) The nonlinear damping parameter \( \nu \) was obtained from the measured output power vs input power characteristics by using the full available power range. The value of \( \nu \) was found to be \( 1.8 \times 10^{12} \text{ rad/s} \). These data were used to calculate the group velocity, dispersion, and nonlinear coefficients.

In the second stage, microwave measurements aiming to determine the optimal regime for the formation of dark solitons were performed. The two main experimental techniques to generate dark solitons are (i) the excitation of individual envelope solitons applying as an input signal a sequence of two microwave pulses with a controlled time delay and phase shift between them,\textsuperscript{24} and (ii) the formation of envelope soliton trains through nonlinear interaction of two large-amplitude cw input signals.\textsuperscript{25} The second technique is also known as induced modulation instability (IMI).\textsuperscript{1} In this process, solitons arise from the mode beating of two copropagating input spin waves. From an electronics point of view, this technique is easier to implement for a stable dark soliton excitation than the pulsed technique and was thus utilized in our measurements.

The input microwave signals were provided by synchronized stable frequency sources. The signals at the input and output antennas were analyzed in the time and frequency domains with a fast oscilloscope and a microwave spectrum analyzer, respectively. The particular combination of equal \( P_1 \) and \( P_2 \) and the correct choice of frequency interval \( \Delta f = (f_2 - f_1) \) provides the conditions to generate a stable train of dark solitons.\textsuperscript{22} The value of the higher carrier frequency was kept approximately 50 MHz below the upper MSBVW frequency limit \( f_B \).\textsuperscript{25} For smaller values of \( \Delta f \) (e.g., 3 MHz) and for values above 30 MHz, there was no identifiable soliton response with the available power levels (up to 18 dBm). As for power levels, a nonlinear response was found at input powers above 6 dBm. When the two power levels were unequal, the nonlinear response was in the form of cnoidal waves or bright soliton waves. When the two power levels were balanced, the nonlinear response was in the form of dark soliton trains. The value of \( \Delta f \) necessary to generate stable and easily identifiable dark soliton trains in the form of characteristic dips in the time trace was found to be in the range of 6 to 10 MHz. The frequencies of the input signals were set to \( f_1 = 4500 \text{ MHz} \) and \( f_2 = 4490 \text{ MHz} \).

In the third stage, an implementation of the BLS technique based on a multi-pass tandem Fabry-Pérot interferometer in the forward-scattering configuration\textsuperscript{21} was used to map the propagation and evolution of the nonlinear wave forms. This high-speed implementation responds to the need to perform a photon-counting frequency scan at each pixel. For this experiment, a 514.5-nm-wavelength linearly polarized argon ion laser was focused onto the YIG film by a 12-cm-focal-length lens at normal incidence with 10 mW incident power. The directly transmitted and scattered light was collected by a 50-mm-focal-length and 30-mm-diameter F1.4 camera lens. A polarization filter set perpendicular to the incident light polarization was used to reduce substantially the intensity of the directly transmitted beam. Magnon scattered light generally experiences a 90° rotation in polarization from the incident beam and this is what the interferometer detects.

BLS space-resolved enhancement was achieved by attaching the standard YIG-based delay-line structure on a two-axis motorized submicrometric translation stage controlled by a computer and synchronized with the main BLS control software. The time-resolved subsystem was based on a 250-ps-time-resolution multichannel analyzer, which was constantly synchronized by the BLS main control software and triggered by the modulated cw microwave signal at the input of the YIG-based delay-line structure. The scanned area was defined to include a 7-mm-long propagation path between the input and output antennas with 100-μm-sized square pixels. The time-resolved data were measured using time channels of 0.7 ns.
First, the form in the time domain of a dark soliton must show sharp dips that fall to zero level.\(^1\) Second, there must be a 180° phase jump where the signal amplitude reaches zero. Third, the spectrum of the signal must show a multiharmonic form. To this end, we performed a series of microwave measurements in the time and frequency domain. Figure 2 shows data measured at the output microstrip antenna. Graph 2(a) shows the time trace of the signal recorded with a microwave power detector and an oscilloscope. This graph also shows the time trace of a simulated signal that will be discussed in the next section. Graph 2(b) shows the phase profile of the microwave signal. Here, the output signal was measured at the GHz time scale with a fast oscilloscope and the time evolution of its phase was determined mathematically using as reference the precisely known input frequencies. Graph 2(c) shows the frequency spectrum of the signal measured with a spectrum analyzer.

From Fig. 2 we observed the well-known signatures of dark solitons.\(^1\) The signal that corresponds to the envelope of the dark soliton train, with the characteristic dips, consistent with previous observations,\(^2\) is shown in graph 2(a). The characteristic phase jumps coinciding with minima in the envelope trace are shown in graph 2(b). The expected multiharmonic enriched spectrum, indicating that induced modulation instability is taking place as a result of the nonlinear beating of the two cw input signals, is manifest in graph 2(c). This indicates clearly that dark solitons are being generated and propagate along the YIG strip which acts as a soliton “waveguide.”

The characterization of the spatial evolution of the dark soliton trains in the YIG film is the main result of this paper. Synchronized with a stable train of dark solitons, time- and space-resolved BLS measurements were carried out. Figure 3 shows data of the spatial evolution of a train of dark solitons along the YIG-film strip. The experimental points represent a snapshot of the normalized space-resolved BLS data. The solid line represents the corresponding results of the simulations to be discussed in the next section. The vertical dashed line is meant to divide two zones of qualitatively different behavior. The experimental curve was formed by combining the BLS intensity measured at every pixel along the propagation path at a specific time after excitation. Given the symmetry of the system, a trace in one spatial dimension was sufficient to characterize the propagation.

Within the two zones marked in Fig. 3, we suggest the following interpretation: (a) In zone one, solitons cannot be identified since the characteristic form of a sharp dip between two crests is not observable. Here the fast amplitude decay could be due to the presence of nonlinear and linear damping. (b) In zone two, the characteristic shape of a dark soliton can be identified and the smooth and apparently exponential amplitude decay suggest the presence of only linear damping.

### III. MICROWAVE AND BLS MEASUREMENTS

In order to be certain of the existence of dark solitons in our configuration, characteristic signatures must be observed. First, the form in the time domain of a dark soliton must show sharp dips that fall to zero level.\(^1\) Second, there must be a 180° phase jump where the signal amplitude reaches zero. Third, the spectrum of the signal must show a multiharmonic form. To this end, we performed a series of microwave measurements in the time and frequency domain. Figure 2 shows data measured at the output microstrip antenna. Graph 2(a) shows the time trace of the signal recorded with a microwave power detector and an oscilloscope. This graph also shows the time trace of a simulated signal that will be discussed in the next section. Graph 2(b) shows the phase profile of the microwave signal. Here, the output signal was measured at the GHz time scale with a fast oscilloscope and the time evolution of its phase was determined mathematically using as reference the precisely known input frequencies. Graph 2(c) shows the frequency spectrum of the signal measured with a spectrum analyzer.

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### IV. NUMERICAL MODELING

Numerical modeling was carried out using the Ginzburg-Landau equation, as in previous works. The main reason is that this model allows the inclusion of nonlinear damping. The Ginzburg-Landau equation can be written as

\[
i \left( \frac{\partial u}{\partial t} + V_s \frac{\partial u}{\partial x} + \omega_r u \right) + \frac{D}{2} \frac{\partial^2 u}{\partial x^2} - (N - i\nu)|u|^2u = 0,
\]

where \(\omega_r, V_s, D, N,\) and \(\nu\) denote, respectively, the linear relaxation frequency, the group velocity, the dispersion \(\partial^2 \omega / \partial k^2\), the nonlinear response coefficient \(\partial \omega / \partial |u|^2\), and the nonlinear damping.\(^2\) Although two-frequency excitation was utilized in the experiment, the equation coefficients were calculated at the central frequency \(f_c = (f_1 + f_2)/2\) because \(\Delta f \ll f_1, f_2\). To determine the values of the coefficients in the equation for the nonlinear backward volume spin wave (BVSW) spectrum, the experimental data were used. In doing so, we found that \(V_2 = 2.36 \times 10^9\) cm/s, \(D = 580\) cm\(^2\)/rad·s, and \(N = -8.1 \times 10^6\) rad/s. Initial conditions for numerical modeling corresponded to the
two-frequency excitation and were defined as

\[ u = u_0 \left[ \cos(2\pi f_1 t) + \cos(2\pi f_2 t) \right]. \]

The value of the initial amplitude \( u_0 \) was used as an adjustable parameter and the best coincidence between experimentally measured and computed spatial solitonic profiles was obtained for \( u_0 = 10^{-3} \).

In addition to the experimental data, Fig. 2(a) shows the numerical results for a train of dark solitons in the time domain. The characteristic form of sharp dips reaching zero level is well reproduced and fits qualitatively with the data. In the spatial domain, Fig. 3 presents the result of the numerical modeling. Both the fast initial decay (zone 1) and the lower rate decay (zone 2) are well reproduced and show very good agreement with the experiment. In both cases, the good agreement between the numerical model and the experiment is highly dependent on the introduction of nonlinear damping in the model through the use of the Ginzburg-Landau equation. Consequently, the nonlinear Schrodinger equation, which was commonly used to describe solitons, cannot be employed to explain dark soliton formation for the case of attractive nonlinearity \( DN < 0 \), which is characteristic of the BVSW.

Some conclusions can be drawn. (a) The Lighthill criterion, \( DN < 0 \), does not always lead to bright soliton formation. Our data confirm this because in spite of the experimental condition \( DN < 0 \), a stable train of dark envelope solitons is generated. (b) Nonlinear damping plays an important role in the dark soliton excitation process. As is observable in Fig. 3, the amplitude decay in zone 1 is much faster than in zone 2. In other words, the signal decays more than 60% in the first two millimeters, and then decays by a much smaller proportion in subsequent 2 mm intervals, indicating two very different decay rates. This is mainly due to the influence of nonlinear damping which is dominant in the first zone. (c) It is well known that at higher amplitudes of the spin waves near the input antenna, the spectrum will present a dense multiharmonic characteristic facilitating the process of soliton formation.

The experimental data and computer modeling provide evidence that there are two distinctive zones in the nonlinear propagation path. The first zone is characterized by decreasing spin-wave amplitude mainly due to nonlinear damping and “phase adjustment,” which is necessary for dark envelope soliton formation. There are no solitons visible in this zone (we cannot identify a sharp dip between two maxima) because phases of the carrier spectral harmonics are not “synchronized.” The medium is “seeking” to create solitons from an initial excitation. In the concrete experimental situation, the length of the phase adjustment path, as follows from the modeling, is 1.8 mm. The next zone is a “soliton life length.” In this zone, the dark soliton shapes are characterized by dips in the form of hyperbolic tangents and \( \pi \)-phase jumps at amplitude minima, as one would expect. Note that physically, the lengths of the intervals depend on the dispersion properties, operating frequencies, and relaxation parameters.

V. CONCLUSIONS

In summary, this paper describes the observation of the formation and spatial evolution of dark spin-wave solitons in a magnetic film. Dark envelope solitons were obtained through the induced modulation instability. In order to describe their propagation and evolution, time- and space-resolved Brillouin light scattering was used in combination with microwave excitation. It is shown that the observed nonlinear solitonic wave forms are influenced by nonlinear damping. The experimental data can be modeled using the Ginzburg-Landau equation. The agreement between the theoretical and experimental traces confirms that dark soliton formation involves a competition not only between nonlinearity and dispersion, but also involves strong nonlinear damping effects.

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