

Formation of quasi-solitons in transverse confined ferromagnetic film media

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Abstract The formation of quasi-2D spin-wave waveforms in longitudinally magnetized stripes of ferrimagnetic film was observed by using time- and space-resolved Brillouin light scattering technique. In the linear regime it was found that the confinement decreases the amplitude of dynamic magnetization near the lateral stripe edges. Thus, the so-called effective dipolar pinning of dynamic magnetization takes place at the edges.

In the nonlinear regime a new stable spin wave packet propagating along a waveguide structure, for which both transversal instability and interaction with the side walls of the waveguide are important was observed. The experiments and a numerical simulation of the pulse evolution show that the shape of the formed waveforms and their behavior are strongly influenced by the confinement.

We report on the observation of a new type of a stable, two-dimensional nonlinear spin wave packet propagating in a magnetic waveguide structure and suggest a theoretical description of our experimental findings. Stable two-dimensional spin wave packets, so-called spin wave bullets, were previously observed, however solely in long and wide samples of a thin ferrimagnetic film of yttrium-iron-garnet (YIG) [1, 2, 3], that were practically un-

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bounded in both in-plane directions compared to the lateral size of the spin wave packets and the wavelength of the carrier spin wave. In a waveguide structure, where the transverse dimension is comparable to the wavelength, up to day only quasi one-dimensional nonlinear spin wave objects were observed, which are spin wave envelope solitons. Here a typical system is a narrow ($\simeq 1\text{-}2\text{mm}$) stripe of a YIG ferrite film [4, 5]. Both for solitons and bullets the spreading in dispersion is compensated by the longitudinal nonlinear compression. Concerning the transverse dimension, solitons have a cosine-like amplitude distribution due to the lateral confinement in the waveguide, whereas bullets show a transverse nonlinear instability compensating pulse widening due to diffraction and leading to transverse confinement.

Here we report on the observation of a new stable spin wave packet propagating along a waveguide structure, for which both transversal instability and interaction with the side walls of the waveguide are important.

The experiments were carried out using a longitudinally magnetized long YIG film stripe of 2.5mm width and $7\mu\text{m}$ thickness. The magnetizing field was 1831Oe . The spin waves were excited by a microwave magnetic field created with a microstrip antenna of $25\mu\text{m}$ width placed across the stripe and driven by electromagnetic pulses of 20ns duration at a carrier frequency of 7.125GHz . As is well known the backward volume magnetostatic spin wave (BVMSW) [6] excited in the given experimental configuration is able to form both envelope solitons and bullets [4], depending on the geometry. The spatio-temporal behavior of the traveling BVMSW packets was investigated by means of space- and time-resolved Brillouin light scattering spectroscopy [7].

The obtained results are demonstrated in Fig. 1 where the spatial distributions of the intensity of the spin wave packets are shown for given moments of time. The spin wave packets propagate here from left to right and decay in the course of their propagation along the waveguide because of magnetic loss. The left set of diagrams corresponds to the linear case. The power of the driving electromagnetic wave is 20mW . The right set of diagrams corresponding to the nonlinear case was collected for a driving power of 376mW .

Differences between these two cases are clearly observed. First of all the linear spin wave packet is characterized by a cosine-like lateral profile while the cross section of the nonlinear pulse is sharply modified relative to the linear case and has a pronounced bell-like shape. Second, the intensity of the linear packet decays monotonically with time while the intensity of the nonlinear packet initially increases because of its strong transversal compression (see the second diagram from the top in Fig. 1).

Both of these nonlinear features provide clear evidence for the develop-

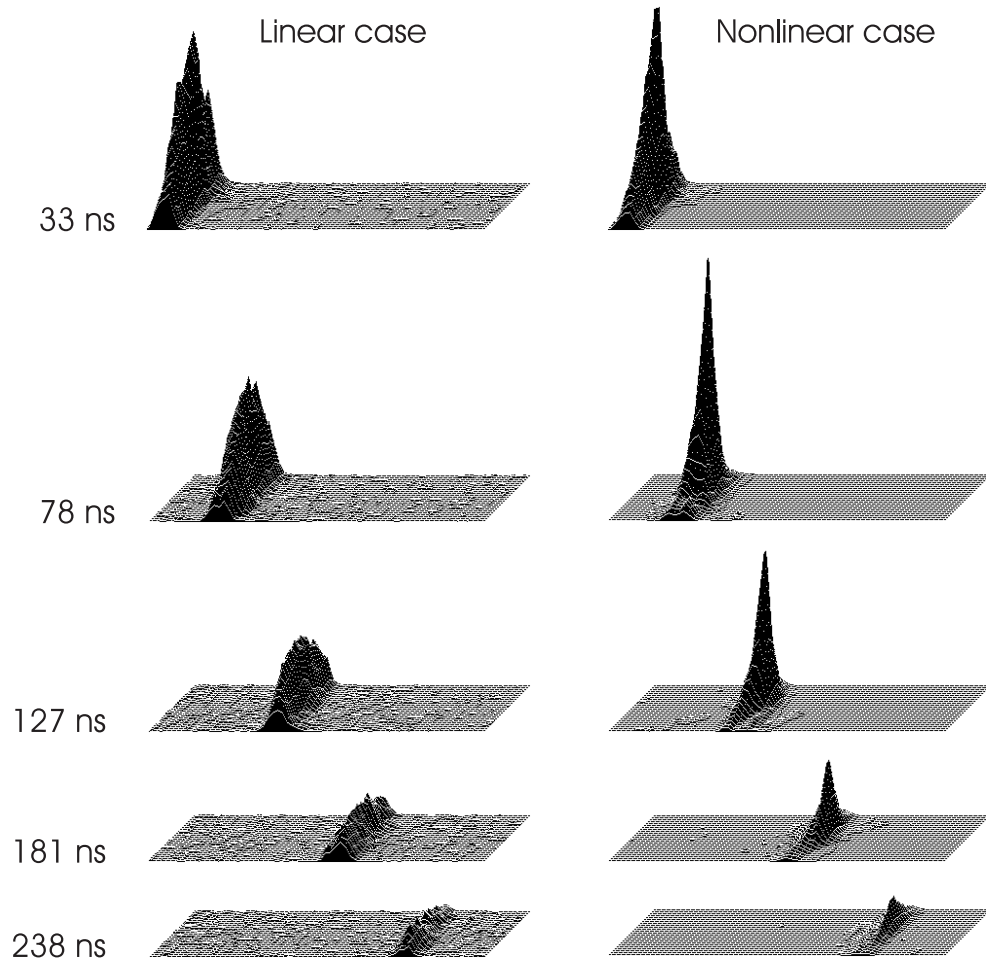


Figure 1: Bullet formation in the transversally confined yttrium-iron-garnet film.

ment of a transversal instability and bullet formation. It is interesting that the bell-like cross-section shape survives even at the end of the propagation distance when the pulse intensity decreases more than ten times and the nonlinear contribution to the spin wave dynamics should considerably diminish.

In order to interpret the experimental result we have assumed that the development of nonlinear instabilities in a laterally confined medium is strongly modified by a quantization of the spin wave spectrum. That is why we have transformed the two-dimensional Nonlinear Schrödinger Equation traditionally used for the analysis of bullet dynamics [4] into a system of coupled equations for amplitudes of the spin wave width modes. The specific form of the discrete set of these orthogonal modes is defined by the actual boundary conditions at the lateral edges of the stripe. We developed a two-dimensional theory of linear spin-wave dynamics in magnetic stripes. As an important outcome we found that the Guslienko-Slavins effective boundary condition [8] for dynamic magnetization at the stripe lateral edges, being initially derived for spin waves with vanishing longitudinal wavenumbers, is also valid in the case of propagating width modes with non-vanishing longitudinal wavenumbers [9]. The effective boundary condition shows that the magnetization vector at the lateral stripe edges is highly pinned, that means that the amplitude of dynamic magnetization practically vanishes at the edges. For simplicity it is even possible to consider the stripe width modes to be totally pinned at the stripe lateral edges. As seen from Fig. 1 this conclusion is in a good agreement with the experiment.

The analysis of the system of nonlinear equations derived from the Nonlinear Schrödinger Equation shows that the formation of the two-dimensional waveform can be considered as an enrichment of the spectrum of the width modes. The partial waveforms carried by the modes have the same carrier frequencies equal to that of the initial signal and the carrier wave numbers which satisfy the dispersion relations for the modes. In the linear regime all the modes are orthogonal to each other and do not interact. In the nonlinear (high amplitude) regime the width modes become intercoupled by the four-wave nonlinear interaction, resulting in an intermodal energy transfer and the mode spectrum enrichment.

As the spin wave input antenna effectively generates only the lowest width mode, the initial waveform launched in the stripe is determined by it solely. Therefore to understand the underlaying physics of quasi-bullet formation it is necessary to consider the nonlinear interaction of higherorder width modes with it.

Our theoretical analysis shows that the interaction of the lowest width mode ($n = 1$) with higherorder modes is different for odd and even higher or-

der modes. While interacting with even modes, the lowest width mode plays the role of the pumping wave. This parametrically transfers its energy to the higher width modes. The interaction is purely parametric and therefore a threshold process. It needs an initial signal to start the process. This signal usually is a thermally excited mode. Therefore the amplified waveform needs a large distance of propagation and a group velocity equal to the velocity of the lowest width mode in order to reach the soliton amplitude level. If there is a damping of the pumped wave, even modes will never reach an amplitude comparable with that of the lowest mode. As a result they can contribute to the nonlinear waveform profile only, if the amplitude of the initial waveform is far beyond the threshold of soliton formation.

Interaction of modes of the same type of symmetry are described by a parametric term as well as by an additional pseudo-linear (tri-linear) excitation term, playing the role of an external source of excitation. Such a pseudo-linear excitation is a threshold-free process. In contrast to parametric processes it does not need an initial amplitude value to start the process. The pseudo-linear excitation is possible only due to the effective dipolar pinning of the magnetization at the stripe edges. If the edge spins were unpinned, the interaction of all the width modes would be purely parametric.

The purely parametric mechanism of developing a transversal instability is typical for the process of bullet formation from a plane-wave waveform in an unconfined medium, which distinguishes it from the process of soliton and bullet formation in the waveguide structures.

In contrast, the transverse instability of a wave packet in a confined medium starts as a pseudolinear excitation of higher-order width modes. This mechanism ensures a rapid growth of the symmetric $n = 3$ mode up to the level where the parametric mechanism starts to work. After that the main mode together with the $n = 3$ mode are capable to rapidly generate a large set of yet higher modes through both pseudo-linear and parametric mechanisms.

Our theory shows that the efficiency of both nonlinear interaction mechanisms (parametric and tri-linear) strongly depends on the group velocity difference of modes and the initial length of the nonlinear pulse. In larger stripes the group velocities of modes are closer to each other. As a result the nonlinearly generated higher-order modes longer remain within the pump pulse. If the pulse is long enough, they reach significant amplitudes and a bullet-like waveform is formed. In narrower stripes the group velocity difference is larger, and consequently the nonlinearly generated highorder waveforms leave faster the pumping area. As a result, for the same pulse length, they do not reach significant amplitudes. The nonlinear steepening results

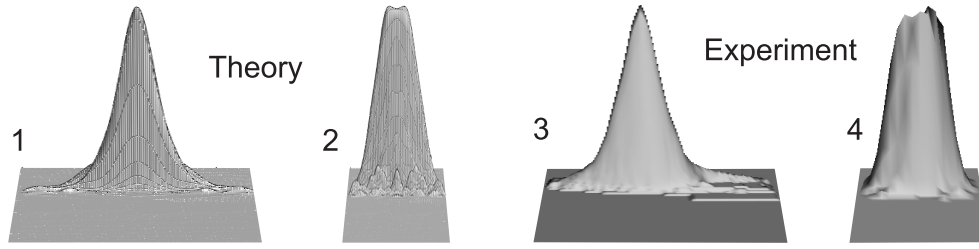


Figure 2: Lateral shapes of the nonlinear SW packets. 1 and 2 – theoretical results calculated for the ferrite stripes of width of 2.5mm and 1mm, respectively. 3 and 4 – experimental profiles observed in YIG waveguides of width of 2.5mm and 1mm, respectively. 1 and 3: bullets. 2 and 4: solitons.

in the transformation of the lowest mode into a soliton.

The results of our calculations of the lateral shapes of the nonlinear spin wave packets in wide (2.5mm) and narrow 1mm ferrite stripes are shown in Fig. 2. The excellent correspondence with the experimental data provides good evidence for the validity of the developed theory.

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