Nonlinear Propagation of Spin Waves in Microscopic Magnetic Stripes

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We have studied experimentally with high spatial and temporal resolution propagation of intense spin waves in microscopic Permalloy stripes. We show that the nonlinearity of the spin system of metallic magnetic films together with microscopic-scale confinement effects lead to an anomalous nonlinear magnetic dynamics, such as a nonlinear spatial self-modulation of spin waves characterized by the repulsive nonlinearity. This phenomenon appears to be densely connected with the nonlinear damping in the system. We find that both of these effects develop synchronously on the nanosecond temporal scale.

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Spin waves (SWs) in macroscopic samples of epitaxial dielectric ferrite films have been considered for many years as a unique model system demonstrating a large number of universal nonlinear phenomena including solitons, modulation instabilities, dynamic chaos, etc. [1–5]. Among these nonlinear phenomena, two-dimensional bullets [4] and symmetry-breaking soliton eigenmodes [5] can be separately mentioned as those experimentally found in magnetic films earlier than in other nonlinear systems. Moreover, it has been recently found that strong nonlinearities in the magnon system in ferrite films can result in Bose-Einstein condensation of magnons at room temperature [6], which further proves the large potential of magnetic systems for investigations of basic physical phenomena.

Because of recent progress in the preparation of magnetic nanostructures and the development of novel methods for their experimental study, the main attention in the area of magnetic dynamics has been focused in the last years on microscopic structures lithographically patterned from metallic ferromagnetic films. The wide interest in such systems originates from their large potential for technical applications [7,8] and from the fact that they demonstrate physical phenomena, which do not appear on the macroscopic scale. Despite the enormous amount of attention paid to magnetization dynamics in microscopic structures, the nonlinear magnetic phenomena in these systems were not sufficiently addressed up to very recently. In fact, numerous theoretical works (see, e.g., [9–11]) predicted a series of interesting nonlinear effects, but the only nonlinear phenomena experimentally observed in magnetic nanostructures were nonlinear ferromagnetic resonance and accompanying magnetization switching [12–14], as well as spin-torque excitation of magnetic dynamics and phase locking of spin-torque oscillators [15,16].

In this Letter we report on the experimental investigation of nonlinear SWs in microscopic Permalloy stripes with the help of space- and time-resolved microfocus Brillouin light scattering (BLS) spectroscopy. We find that at increased amplitudes the SWs demonstrate a spatial self-modulation effect, which is not allowed in macroscopic samples due to the repulsive type of nonlinearity known for the studied propagation geometry. We associate this anomalous nonlinear behavior with a dominant action in metallic magnetic films of nonlinear magnetic damping, which appears to be especially important on the microscopic scale. This conclusion is supported by an observation in the experiments of nonlinear damping having the same threshold and the same temporal development as the self-modulation effect.

The sketch of samples used in the experiments is shown in Fig. 1. The samples are 2.4 μm wide stripes patterned by electron-beam lithography from Permalloy film with the thickness of 36 nm. The stripes were prepared on a glass substrate and covered by a protective 25 nm thick SiO_2 layer. For excitation of SWs we used lithographically prepared 300 nm thick and 1.5 μm wide Au antennas oriented perpendicularly to the Permalloy stripes. The microwave electric current at a frequency $F = 8.5$–10 GHz transmitted through the antennas created a dynamic magnetic field coupled to the dynamic magnetization. As a

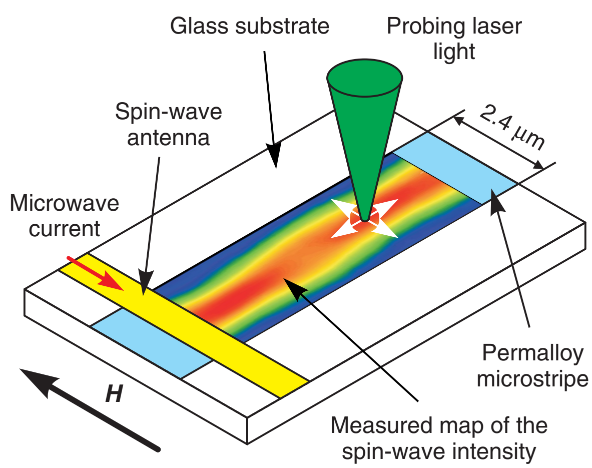

FIG. 1 (color online). Sketch of the experiment.

result, a SW with a well-defined frequency was excited and propagated along the Permalloy stripe. The intensity of the SW was varied by the variation of the microwave power P applied to the antennas in the range from 1 to 400 mW. The continuous-wave and the short-pulse excitation regimes were used providing high signal-to-noise ratio and the possibility of observation of temporal development, respectively. The detection of SWs was performed with the help of spatially and temporally resolved micro-focus BLS spectroscopy described in detail elsewhere [17]. The temporal resolution of the setup was about 1 ns and the spatial resolution was about 250 nm. As shown in Fig. 1, scanning the probing laser light across the surface of the Permalloy stripe, we recorded two-dimensional maps of the SW intensity. By employing the time-of-flight analysis to inelastically scattered photons [18], the maps were measured with temporal resolution with respect to the start of the microwave pulse applied to the antenna without the use of modulation of the probing light. The samples were placed into a uniform static magnetic field $H = 830$ Oe applied perpendicularly to the axes of Permalloy stripes, which corresponds to the propagation geometry of Damon-Eshbach waves [19].

In the first step we used the continuous-wave excitation and studied propagation of SWs for different F and P. Figure 2 shows an example of the recorded SW intensity maps corresponding to $F = 8.8$ GHz (wave number $k \approx 1.2\ \mu\text{m}^{-1}$) and different values of P, as indicated. The maps were recorded by scanning the area with dimensions of 2.4 by 7 μm with spatial step sizes of 100 and 250 nm in the directions perpendicular and parallel to the axis of the Permalloy stripe, respectively. In order to see the intrinsic structure of the SW beam, the spatial decay was numerically compensated by normalizing the integral intensity over transverse sections of the maps I. As seen from Fig. 2, with the increase of P the spatial structure of the SW beam experiences nonlinear modifications, which can be described as a transverse self-modulation. In fact, the map recorded for $P = 10$ mW, corresponding to the linear propagation regime, shows a weak modulation of the width of the SW beam accompanied by a periodic concentration of the energy in the middle of the stripe—SW focusing. This phenomenon was experimentally and theoretically addressed in Ref. [20] and was found to originate from the simultaneous propagation of several quantized SW modes. It was shown that the depth of this modulation is determined by the ratio of the intensities of different modes and cannot be changed in the linear case. Nevertheless, if the spatial SW modes, independent of each other in the linear regime, have sufficiently large intensities, the nonlinearity can potentially lead to their coupling and the energy transfer between them. Note that nonlinear dynamics usually depends on the interplay between the nonlinear frequency shift and the dispersion. For the studied Damon-Eshbach waves this interplay results in the repulsive type

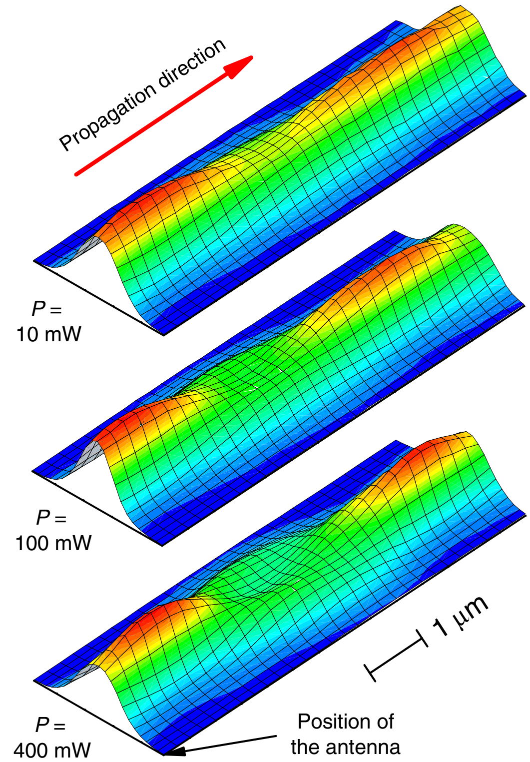

FIG. 2 (color online). Measured maps of SW intensity in the continuous-wave excitation regime for different powers P applied to the antenna. The maps have dimensions of 2.4 by 7 μm. Spatial decay is numerically compensated. $F = 8.8$ GHz. $H = 830$ Oe.

of nonlinearity, which should lead to a nonlinear suppression of the transverse modulation and a stabilization of the SW beam at increased intensities, as was observed for macroscopic samples [21]. However, as one can see from Fig. 2, in microscopic samples the nonlinearity leads to an opposite effect. As P is increased, the modulation of the SW beam strengthens and the periodic SW focusing (defocusing) becomes much better pronounced. Such an anomalous nonlinear behavior can be associated with a competitive action of the nonlinear frequency shift and the nonlinear damping caused by the four-magnon scattering processes. As was found for macroscopic magnetic samples [22], the presence of the nonlinear damping can reverse the action of the nonlinearity in such a way that phenomena typical for repulsive nonlinearity appear in magnetic systems characterized by the attractive one. Note here, that such a reversed action was observed for the attractive nonlinearity only, whereas the action of the repulsive nonlinearity was found not to be strongly affected by the nonlinear damping [21].

To clarify the connection between the nonlinear self-modulation and the nonlinear damping, we analyzed the quantitative characteristics of these two phenomena. Figure 3(a) shows the width of the SW beam w as a function of the propagation distance d. The shown depen-

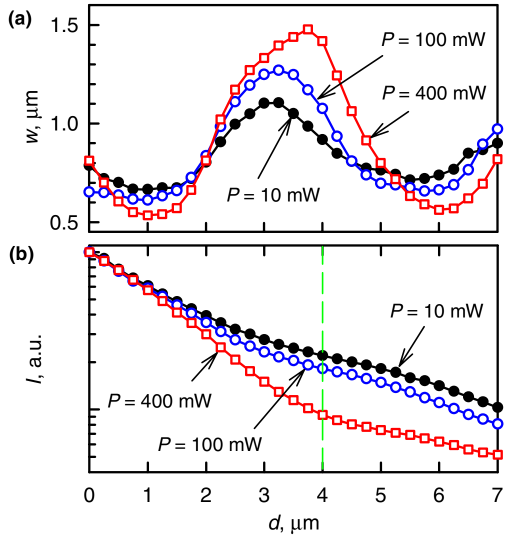

FIG. 3 (color online). (a) width of SW beam w as a function of the propagation distance d for different excitation powers P. (b) spatial variation of the integral of SW intensity over transverse sections I, characterizing the spatial decay of SWs at different P. The data are normalized at $d = 0$. Note the logarithmic scale of the vertical axis. $F = 8.8$ GHz. $H = 830$ Oe.

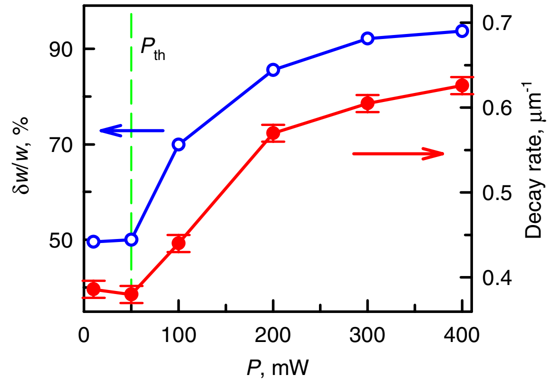

FIG. 4 (color online). Dependences of the modulation depth of SW beam $\delta w/w$ and the mean decay rate of SW intensity on the excitation power P. P_{th} denotes the threshold power necessary for the appearance of the self-modulation and the nonlinear damping phenomena.

dences prove the above qualitative conclusion about the nonlinear self-modulation of the SW beam. As seen from Fig. 3(a), the initial weak modulation increases noticeably, as P is increased from 10 to 400 mW, so that the beam experiences an additional nonlinear compression in the focusing regions and an additional nonlinear widening in the defocusing regions. Figure 3(b) demonstrates the changes in the spatial decay appearing within the same range of P. As a quantitative characteristic for this decay we have chosen a spatial variation of the integral of the SW intensity over transverse sections I, reflecting the energy transferred by the wave through the stripe at a given distance from the antenna. Figure 3(b) clearly shows that the self-modulation is accompanied by an increase of the spatial decay rate, which should be associated with additional damping mechanisms connected with parametric excitation of short-wavelength SWs [11]. Note here, that for high-power excitation ($P = 400$ mW) the spatial decay rate appears to be dependent on d. The corresponding curve in Fig. 3(b) clearly exhibits an abrupt decrease of the decay rate at $d > 4$ μm, which is also consistent with the concept of the nonlinear damping caused by parametric processes having a certain threshold with respect to the intensity of the initial SW. Figure 4 summarizes the above results. It shows in the same graph the power dependences of the modulation depth of the SW beam $\delta w/w = 2(w_{max} - w_{min})/(w_{max} + w_{min})$ and the decay rate of the SW intensity averaged over $d = 0$–4 μm. As seen from Fig. 4, both the nonlinear increase of the modulation depth and the nonlinear increase of the decay rate have the same threshold $P_{th} \approx 50$ mW and show very similar saturating behavior at P approaching 400 mW. Qualitatively similar dependences were observed over the entire range of frequencies $F = 8.5$–9.4 GHz, where the SWs can be efficiently excited. With the increase of F, P_{th} was found to shift towards larger values, which can be associated with the decreasing coupling of short-wavelength SWs to the dynamic magnetic field of the antenna [20].

Finally, we analyzed the temporal characteristics of the observed nonlinear phenomena. For this we used a short-pulse excitation regime with the duration of the microwave pulses of 50 ns and the repetition rate of 1 MHz. The main results of these measurements are summarized in Fig. 5. The inset in Fig. 5(a) shows typical waveforms reflecting the shape of the strongly nonlinear SW pulse detected close to the antenna ($d = 0$) and at $d = 6$ μm. As seen from the inset, at $d = 0$ this shape is close to the rectangular one of the microwave pulse used for excitation, whereas at $d = 6$ μm the pulse exhibits a narrow peak at its leading edge and a plateau over the rest of its duration. These features are typical manifestation of the nonlinear damping associated with parametric processes, which need certain time for their development [11]. In fact, the leading part of the pulse does not experience any nonlinear damping because within the first several nanoseconds after application of the excitation, the parametric processes have not enough time to develop. As the amplitudes of parametrically excited waves grow with time, the decay of the initial SW increases and the rest of the pulse decays in space faster, which leads to the reduction of the SW intensity in the region of the plateau. Correspondingly, with a good accuracy one can take the duration of the peak at the leading edge of the pulse as the characteristic time of the development of the nonlinear damping.

Figure 5(a) shows waveforms of the leading part of the SW pulse detected at $d = 6$ μm for the linear ($P = 10$ mW) and the strongly nonlinear ($P = 400$ mW) cases.

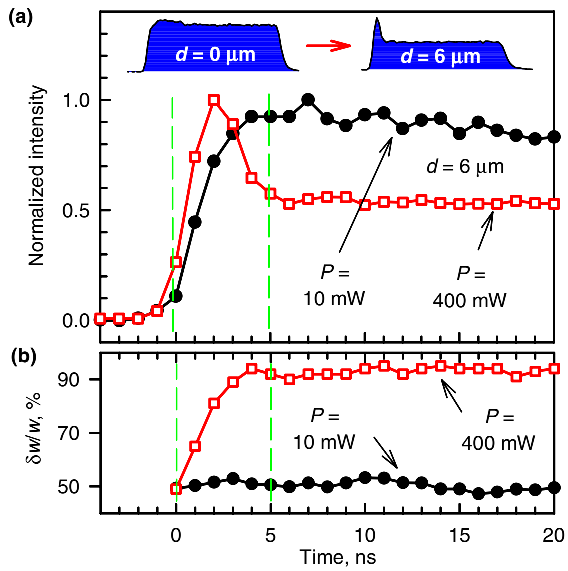

FIG. 5 (color online). (a) Waveforms of the leading part of SW pulse detected at $d = 6\ \mu$m for the linear ($P = 10$ mW) and the strongly nonlinear ($P = 400$ mW) cases. Inset—waveforms of the nonlinear ($P = 400$ mW) SW pulse detected $d = 0$ and 6 μm. (b) Temporal dependences of the modulation depth $\delta w/w$ for the linear and the strongly nonlinear cases.

In the linear case, the SW pulse does not demonstrate any peaks and its shape is very close to that detected in the proximity of the antenna, whereas for the strongly nonlinear case, the pulse shows a peak with the duration of about 5 ns, which we assume to be the time of development of the nonlinear damping. In order to get information about the temporal development of the self-modulation effect we measured two-dimensional maps of the SW intensity with a temporal step of 1 ns and obtained the temporal dependence of the modulation depth $\delta w/w$ shown in Fig. 5(b). One can see from the figure, that at $P = 10$ mW $\delta w/w$ does not change with time and stays at a value of about 50%, typical for the linear case (see Fig. 4), whereas at $P = 400$ mW $\delta w/w$ quickly increases from 50 to more than 90% within the same 5 ns, as needed for the development of the nonlinear damping. This fact represents the clear evidence that the nonlinear self-modulation and the nonlinear damping are intimately correlated and allows one to associate the anomalous spatial nonlinear modifications of SW beams with the influence of the nonlinear damping. For the deep understanding of the observed phenomena a self-consistent theory is needed, which could be based on the numerical analysis of the nonlinear Ginzburg-Landau equation phenomenologically taking into account the nonlinear magnon-magnon scattering processes [10,22]. In order to be able to describe properly the microscopic magnetic structures, the theory should also take into account finite-size and edge effects, as well as the nonuniformity of the internal magnetic field.

In conclusion, we have experimentally studied propagation of nonlinear SWs in microscopic magnetic stripes. Our results show that this system demonstrates nonlinear effects, which do not appear on the macroscopic scale and result from the strong influence on the nonlinear wave dynamics of the nonlinear magnetic damping in thin metallic ferromagnetic films. Our findings contribute to the area of general physics of strongly dissipative nonlinear systems, as well as to the recently established scientific field of SW nano-optics [8]. We believe that they will stimulate further theoretical studies in the nonlinear physics and bring new ideas for technical applications of high-frequency magnetization dynamics in magnetic nanostructures.

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