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Experimental observation of enhanced interaction of magnetic solitons with potential barriers and wells

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We have studied experimentally the interaction of nonlinear packets of spin waves with strongly localized nonuniformities of the static magnetic field representing magnetic potential barriers and wells. We have found that the nonlinearity in the system causes a noticeable modification of this interaction in comparison to the linear case. The strongest modification is observed under conditions where spin-wave envelope solitons are formed. Our findings show that for the case of potential barriers the solitons demonstrate an enhanced tunneling, whereas for potential wells they show an enhanced reflection. Moreover, the nonlinear enhancement of the interaction was found to be stronger for potential wells, which was associated with its resonant character.

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I. INTRODUCTION

The interaction of nonlinear waves with potential barriers and wells currently attracts enormous attention in connection with the recent progress in experimental investigations on the dynamics of matter waves in light induced potentials (see Refs. 1 and 2). The waves of atomic Bose-Einstein condensate have been experimentally found to demonstrate many nonlinear phenomena including dark,[3] bright,[4] and gap[5] solitons. It was also experimentally shown that the nonlinearity of the matter waves significantly influences the process of quantum-mechanical tunneling through a potential barrier leading to anharmonic oscillations and self-trapping.[6] Despite these impressive experimental advances, the intriguing problem of the interaction of matter wave solitons with potential barriers and wells still remains to be addressed only theoretically due to the evident complexity of such experiments. In particular, the numerous publications on the topic (see, e.g., Refs. 7–9 and references therein) predict anomalous transmission and reflection properties of the solitons, which differ significantly from those of linear waves.

Among systems especially attractive for experimental studying of universal nonlinear phenomena, spin waves in thin ferromagnetic films are uniquely positioned as a flexible and convenient model nonlinear system. Spin waves have been found to demonstrate large variety of nonlinear phenomena such as temporal and spatial instabilities, propagation of solitons and two-dimensional bullets, pattern formation, and deterministic chaos (see, e.g., Refs. 10–13). Besides, they allow experimental observation of nonlinear phenomena theoretically predicted for other nonlinear systems. As a striking example, one can mention the symmetry-breaking soliton eigenmodes, which were predicted for matter waves[14] but experimentally observed for spin waves only.[15] Recently it was demonstrated that spin waves are also well suited for experimental studying of the effect of tunneling through a potential barrier and interactions with complex nonuniform potentials.[16,17] These experiments are based on the unique controllability of spin waves by the applied magnetic field, which enables easy creation of potential barriers and wells by local application of an electric current.

Here we report on the experimental realization of transmission of spin-wave solitons through potential barriers and wells. We show that, in agreement with the theoretical predictions, the interaction of solitons with potentials differs noticeably from that of linear wave packets. In particular, the solitons demonstrate an enhanced tunneling through a potential barrier and an enhanced reflection from a potential well.

II. EXPERIMENT SETUP

The sketch of the experiment is shown in Fig. 1. As a medium for propagation of spin waves a 5-μm-thick film of yttrium iron garnet (YIG) was chosen. This material is characterized by very small magnetic losses and supports propagation of spin waves at distances up to several centimeters. The spin-wave waveguides were cut from the films in a form of narrow stripes with a length of 30 mm and a width of 2 mm. A uniform static magnetic field $H_0 = 700-2000$ Oe was applied in the plane of the film waveguide parallel to its axis. The excitation and detection of spin waves was performed with microstrip antennas with a width of 30 μm. The distance between the antennas was 7.5 mm. At a distance of 2.8 mm from the input antenna a gold wire conductor with a diameter of $d = 50$ μm was placed. This conductor was used for the local modification of the static magnetic field by transmission of an electric current $I = 0-1$ A. The experimental setup allowed the transmission of the current in both directions in order to realize local reduction or enhancement of the static magnetic field. The measurements were performed in the pulsed regime with the repetition rate of 20 kHz. The rectangular microwave pulses passing through the

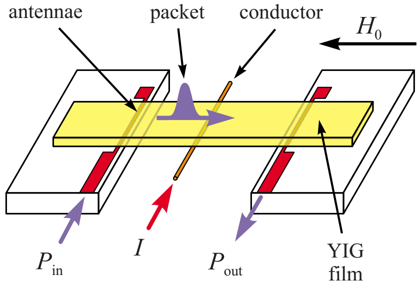

FIG. 1. (Color online) Sketch of the experiment.

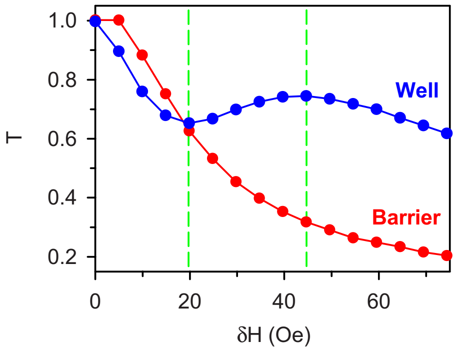

FIG. 2. (Color online) Transmission coefficient for a potential barrier and a well as a function of its height (depth) in the linear regime. $H_0=800$ Oe, $f=4.01$ GHz, and $P_{in}=1$ mW. Vertical dashed lines show the depths of the potential well corresponding to the resonant reflection and transmission.

input antenna for excitation of spin waves had a width of 40 ns and a peak power P_{in} in the range from 1 mW to 1 W. The pulses of current creating the inhomogeneous magnetic field had a width of 200 ns, covering the entire temporal interval, which the spin-wave packet needs to propagate between the antennas. The measured transmission coefficient of the spin-wave packets T was determined as the ratio between the peak powers in the spin-wave pulses P_{out} detected at the output antenna with and without the current in the wire conductor.

As was shown in Refs. 16 and 17, a local inhomogeneity of the static magnetic field can be considered as a potential barrier or well for spin waves depending on whether the field is reduced or enhanced. In particular, a reduction in the field leads to such a shift of the spin-wave spectrum, that the wave propagation is forbidden. Correspondingly, the local reduction in the field creates a potential barrier for spin waves in the region of the inhomogeneity. On the contrary, a local enhancement of the magnetic field corresponds to the case of a potential well. As a consequence, the shift of the spin-wave spectrum should result in a local decrease in the wavelength of the propagating spin wave only.

Figure 2 shows the measured transmission coefficient T for a barrier and a well as a function of its height (depth) expressed in terms of the maximum reduction (enhancement) in the static magnetic field δH in the area of the inhomogeneity. Since the thickness of the YIG film is much smaller than the diameter d of the conductor used to create a local magnetic inhomogeneity, δH was calculated for the given current I as the magnetic field on the surface of the conductor $\delta H=I/(\pi d)$. In fact, the spatial profile of the inhomogeneous magnetic field produced in this way has a bell-like shape and is characterized by a mean spatial width approximately equal to the diameter d.[16] The dependences shown in Fig. 2 were measured for $H_0=800$ Oe and the carrier frequency of the spin-wave packets $f=4.01$ GHz corresponding to the carrier wave number of 120 cm^{-1} for this field. They were recorded for the linear spin-wave propagation regime achieved by exciting spin waves at low power $P_{in}=1$ mW applied to the input antenna. As seen from Fig. 2, by increasing the height of the potential barrier T decreases monotonously from 1 to 0.2, whereas the transmission coefficient of the potential well shows a nonmonotonous variation with clearly defined minimum at $\delta H=20$ Oe and a maximum at $\delta H=45$ Oe. In Ref. 18 it was shown that this nonmonotonous behavior is associated with the resonant interaction of spin waves with a potential well, where, in contrast to a potential barrier, trapped spin-wave modes can exist. An exact calculation of the resonant conditions for a potential well is not trivial because of the spatially nonuniform magnetic field. For the case of continuous spin waves this effect was addressed theoretically in Ref. 18, whereas the theory for the case of short spin-wave packets is still missing. Nevertheless, the qualitative similarity between the dependences shown in Fig. 2 and those obtained in Ref. 18 allows one to associate the maximum at $\delta H=45$ Oe with the resonant transmission and the minimum at $\delta H=20$ Oe with the resonant reflection of spin-wave packets from the potential well.

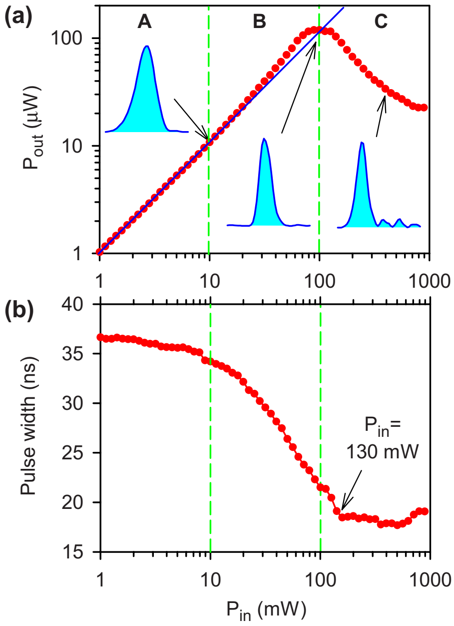

FIG. 3. (Color online) (a) Peak power of the spin-wave packet detected at the output antenna and (b) its width as a function of the peak power of the microwave pulse applied to the input antenna. The insets in (a) show temporal profiles of the pulses detected at the output antenna for different input powers. $H_0=800$ Oe, $I=0$, and $f=4.01$ GHz.

III. RESULTS AND DISCUSSION

As the first step, we studied the nonlinear spin-wave propagation between the antennas without any field inhomogeneity (no current applied to the conductor). The results of these measurements are presented in Fig. 3. Figure 3(a) shows a dependence of the peak power of the spin-wave packet P_{out} detected at the output antenna on the peak power P_{in} of the microwave pulse applied to the input antenna. The insets in Fig. 3(a) show temporal profiles of the output pulses for different input powers. The dependence clearly demonstrates three regions, which are typical for the propagation of nonlinear spin-wave packets in YIG films.[19,20] In the region A, corresponding to small input powers, the dependence is linear. Its slope is determined by the linear decay rate of a

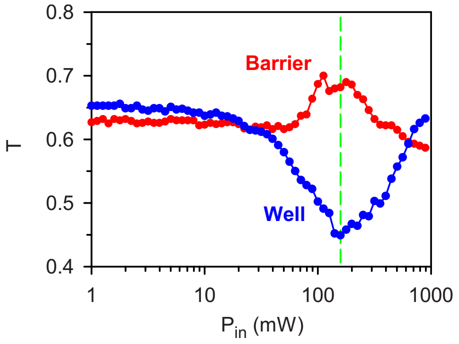

FIG. 4. (Color online) Dependence of the transmission coefficient for a barrier (well) with the height (depth) $\delta H = 20$ Oe on the excitation power. Vertical dashed line shows the threshold of the splitting of the spin-wave soliton into multiple pulses.

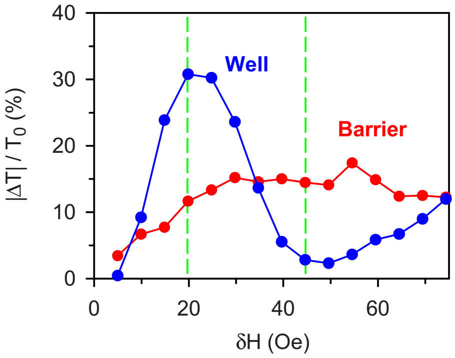

FIG. 5. (Color online) Dependence of the maximum relative variation of the transmission coefficient on the height (depth) of the potential barrier (well). Vertical dashed lines indicate the values of δH for which the resonant reflection and transmission were observed for the potential well in the linear regime.

spin-wave packet in the film and by the efficiency of spin-wave excitation by the antennas. Starting from a power of about 10 mW (region B) the dependence starts to deviate from the linear one, which is associated with an increase in the peak amplitude of the spin-wave packet due to its nonlinear compression and the beginning of the formation of a spin-wave soliton.[19,20] Finally, at powers of more than 100 mW (region C), P_{out} saturates and starts to decrease. As demonstrated by the corresponding inset, within this region the excessive energy pumped into the system leads to a splitting of the spin-wave soliton and the onset of the multisoliton effects studied in Ref. 21. Figure 3(b) showing a dependence of the temporal width of the output pulse on P_{in} further characterizes the nonlinear modifications of the spin-wave packet with the increase in the input power. As seen from the figure, in region B the width of the packet quickly decreases due to the nonlinear compression by about a factor of two and saturates in region C at the power $P_{in} = 130$ mW corresponding to the onset of the soliton splitting. These findings show that for our experimental system the propagation of a single soliton can be achieved in the range of P_{in} from 10 to 130 mW.

As the next step, we studied how the above nonlinear effects influence the transmission of the spin-wave packets through the potential barriers and wells. For this purpose we measured the transmission coefficient T as a function of the power of the input pulse for different heights (depths) δH of the potential barrier (well). Figure 4 shows the obtained dependences recorded for $\delta H = \pm 20$ Oe, corresponding in the case of the well to the resonant reflection (see Fig. 2). As seen from the figure, the transmission coefficient noticeably depends on the input power. In the case of a potential well, the transmission starts to decrease as the soliton formation threshold is reached. With increasing soliton energy this decrease continues until the input power $P_{in} = 130$ mW corresponding to the second threshold at which the soliton splits into multiple pulses. Then the transmission coefficient relaxes back to the value observed for the linear spin-wave packets. In the case of a potential barrier, the transmission coefficient shows similar behavior except that the nonlinearity leads to an enhancement of the transmission for input powers where a single soliton is formed. Therefore, one can conclude that the solitonic nature of the spin-wave packet interacting with a potential influences this interaction significantly. In particular, it leads to an enhancement of both the tunneling through a potential barrier and the reflection from a potential well. This enhancement becomes stronger, as the energy of the soliton increases and is limited by the splitting of the single soliton into multiple pulses at high excitation powers.

Qualitatively similar dependences of T on the excitation power were also observed for other heights (depths) δH of the barrier (well). Note that these dependences do not show any qualitative changes with varying δH even if δH passes the values corresponding to the resonant interaction with a potential well. Nevertheless, the quantitative characteristics of the nonlinear enhancement of the interaction with potentials have been found to change with δH in a way that is different for different types of potential and is significantly affected by the resonances in the potential well. Figure 5 presents dependences of the maximum relative variation of the transmission coefficient $|\Delta T|/T_0$ on δH for a potential barrier and a well. Here $|\Delta T|$ is the absolute value of the maximum deviation of the transmission coefficient from its value in the linear regime T_0. As seen from Fig. 5, the enhancement of the tunneling of a spin-wave soliton through a potential barrier monotonously increases with the barrier height and reaches its maximum value of about 15% for barriers higher than 30 Oe. In contrast, the enhancement of the soliton reflection from a potential well depends on its depth nonmonotonously. It exhibits a clear maximum of about 30% for $\delta H = 20-25$ Oe and a minimum for $\delta H = 45-50$ Oe. Note that the positions of the maximum and minimum enhancements are close to those found for the resonant reflection and transmission of a linear spin-wave packet through a potential well, which are shown in Fig. 5 by the vertical dashed lines. This fact allows the conclusion that the resonant properties of the interaction of spin-wave packets with potential wells also resonantly influence the enhancement of the soliton reflection. Note that the maximum value of the enhancement of the soliton reflection is by a factor of two larger than the maximum enhancement of the soliton tunneling through a potential barrier.

The obtained experimental results can be directly compared with the theoretical predictions made for matter wave solitons. Using the measured group velocity of the solitons (2×10^4 m/s), one can calculate their spatial width. For the temporal width in the range 18–36 ns [see Fig. 3(b)] the spatial width is equal to 360–720 μm. These values are significantly larger than the spatial width of the potential barriers (wells) created in the experiment, defined by the diameter of the wire conductor with current equal to 50 μm. Thus, the interaction of the solitons with the potential wells and barriers in our experiments is nonadiabatic. This situation was theoretically considered for matter wave solitons in Refs. 7 and 8. In particular, in Ref. 8 it was shown that a matter wave soliton should exhibit an enhanced tunneling through a potential barrier. The predicted enhancement is moderate and shows a maximum value of 15%, which agrees very well with our experimental findings. For the case of a potential well discussed in Ref. 7 an almost total reflection or transmission of a soliton was predicted, depending on its velocity with a sharp transition between these two regimes. Such results were associated with an interaction of the soliton with modes trapped in the well. Our experimental results also show a strong enhancement of the soliton reflection for the values of the depth of the well where the resonant interaction of spin-wave packets with the well is observed in the linear regime, which is in agreement with the above theoretical scenario. Further experiments on magnetic solitons can be connected with the studies of the influence of the soliton velocity on the observed phenomena. Such experiments can be realized by varying the thickness of the magnetic film, which mainly influences the group velocity of spin waves.

IV. CONCLUSIONS

In conclusion, using spin waves in ferromagnetic films as a model system we were able experimentally to observe an anomalous interaction of solitons with potential barriers and wells widely addressed theoretically for the case of solitons of atomic Bose-Einstein condensates. Our experimental findings show that magnetic solitons represent a superb object for the studies of nonlinear wave interactions with potential inhomogeneities. In accordance with the theoretical predictions, this interaction differs significantly from that of linear wave packets. These experimental results open a way for further experimental addressing of the nonlinear phenomena connected with interactions of wave packets with nonuniform potentials.

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