Self-focusing of spin waves in permalloy microstripes. Appl. Phys. Lett. 91(25), 252504

Article *in* Applied Physics Letters · December 2007

DOI: 10.1063/1.2825421

Patryk Krzysteczko
Physikalisch-Technische Bundesanstalt

Self-focusing of spin waves in Permalloy microstripes

Vladislav E. Demidov and Sergej O. Demokritov[a)]
Institute for Applied Physics and Center for Nonlinear Science, University of Muenster, Corrensstr. 2-4, 48149 Muenster, Germany

Karsten Rott, Patryk Krzysteczko, and Guenter Reiss
Department of Physics, Bielefeld University, P.O. Box 100131, 33501 Bielefeld, Germany

(Received 24 October 2007; accepted 27 November 2007; published online 20 December 2007)

Excitation and propagation of spin waves in Permalloy microstripes magnetized in their plane perpendicularly to the axis have been investigated by means of microfocus Brillouin light scattering spectroscopy with high spatial resolution. We show that the spatial profile of the spin-wave beam demonstrates a focusing at a certain distance from the excitation source depending on the stripe width. A model connecting the observed phenomenon with an interference of different spin-wave modes existing in the stripe due to the finite-size effect is proposed. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2825421]

In the last few decades, the spin dynamics in micrometer- and submicrometer-size laterally confined ferromagnetic elements has attracted a lot of attention (see recent reviews in Refs. 1 and 2, and references therein). The deep understanding of dynamic magnetic phenomena in such structures is of importance for both fundamental physics of magnetism on the nanometer scale and the technical applications of magnetic nanostructures in devices for information storage and sensing. Among small magnetic patterns, narrow ferromagnetic stripes play an exceptional role, since they represent a convenient model object for investigations of magnetization dynamics in quasi-one-dimensional approximation. It is worth noting that such widely addressed phenomena as spin-wave lateral quantization and spin-wave wells were discovered in narrow stripes.[3,4] From the point of view of technical applications, the ferromagnetic stripes are also of particular interest, since they can be used for information transport as waveguiding elements for spin waves. Such microwaveguides can be utilized, for example, to provide an efficient coupling and mutual phase locking between spin-torque-effect nano-oscillators.[5–7]

Up to now, spin dynamics in magnetic stripes has been experimentally addressed by means of Brillouin light scattering spectroscopy (BLS),[1] time-resolved Kerr microscopy,[8] microwave photovoltage technique,[9] and inductive probe technique.[10] These experimental techniques are characterized by a moderate spatial resolution, preventing spatially resolved measurements of the distributions of dynamic magnetization on the micrometer scale. Therefore, the processes of propagation and shaping of spin-wave beams in magnetic stripes were studied for millimeter-size samples of yttrium-iron-garnet only (see, e.g., Refs. 11–13). Very recently, the invention of the microfocus BLS technique with the spatial resolution down to 250 nm (Ref. 14) enabled addressing these phenomena for micrometer-size magnetic elements as well.[15]

In this letter, we report on space-resolved studies of spin-wave propagation in Permalloy microstripes. We show that the beam of spin waves propagating along a microstripe experiences a focusing at a certain distance from the excitation point depending on the stripe width. We connect the observed effect with the interference of several simultaneously excited spin-wave modes quantized in the transverse direction of the stripe. These findings can be used, for example, for the optimization of the spin-wave transfer between spin-torque nanooscillators.

The experimental samples are 300 μm long microstripes with the widths w=2.1, 5.1, and 10.2 μm patterned from a 20-nm-thick Permalloy ($Ni_{80}Fe_{20}$) film deposited onto a glass substrate and protected against oxidization with a 25-nm-thick SiO_2 layer. The separation between the stripes is 2 μm, which is enough for the stripes to be dynamically uncoupled. At the top of the stripes, 300-nm-thick and 1-μm-wide Au stripe antennae were manufactured. The antennae were oriented perpendicularly to the axes of the Permalloy microstripes and were used for the excitation of spin waves by a microwave-frequency current. The samples were placed into a static magnetic field H=930 Oe oriented in the plane of the stripe perpendicular to its axis. In this way, the so-called Damon-Eshbach geometry of spin waves[16] propagating along the microstripe perpendicularly to the direction of the static magnetic field was realized. The detection of local spin-wave intensity was done by means of microfocus BLS technique,[14] which is able to access spin waves with wave vectors up to 2×10^5 cm^{-1}.

First, the process of excitation of spin waves was characterized. For that the spectrum of spin waves excited by the microwave current was recorded in the middle of the microstripe at a distance of 3 μm from the edge of the antenna. The obtained spectrum was compared to that of the thermal spin waves existing in the microstripes due to thermal fluctuations. Both spectra for a 5.1-μm wide microstripe are shown in Fig. 1(a). As seen in the figure, the spectrum of thermally excited spin waves ranges from 8.2 to about 13 GHz and has its maximum intensity at a frequency which is close to the frequency of the uniform ferromagnetic resonance f_0 $\approx$8.9 GHz calculated for the conditions of the experiment. Spin waves with frequencies below and above f_0 correspond to the so-called backward volume wave modes and Damon-Eshbach (DE) wave mode,[16] respectively. Since the group velocity of the DE wave modes is much higher than that of

[a)]Author to whom correspondence should be addressed. Electronic mail: demokrit@uni-muenster.de.

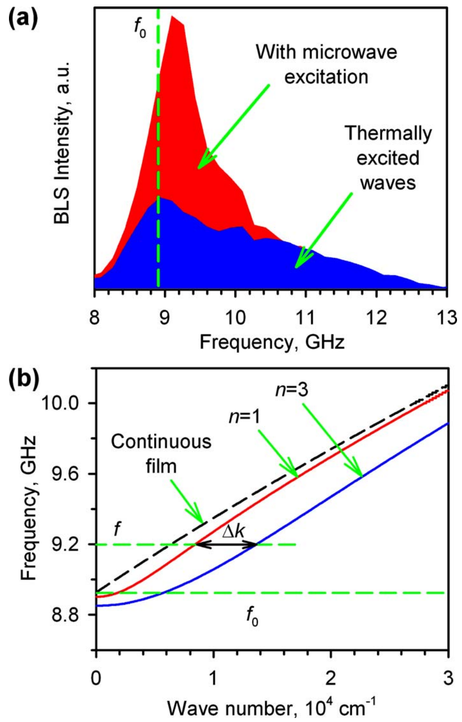

FIG. 1. (Color online) (a) BLS spectra for spin waves in a 5.1-μm-wide Permalloy stripe for H=930 Oe. Microwave excitation was performed with a current at a frequency swept from 8 to 13 GHz. (b) Dispersion characteristics for quantized spin-wave modes in a ferromagnetic stripe. n, transverse quantization number. f_0, frequency of the uniform ferromagnetic resonance of the stripe.

the backward volume wave modes, the spin-wave frequency range above f_0 is much larger than that below f_0.

The spectrum of excited spin waves was measured with the microwave current transmitted through the antenna. The frequency of the current was swept from 8 to 13 GHz. As seen from Fig. 1(a), the excitation of spin waves is efficient in a certain frequency range only. This range is defined by the maximum wave vector of spin waves that can be excited by a 1-μm-wide antenna and can be estimated[17] as 3×10^4 cm^{-1}. For DE modes, this maximum wave vector corresponds to the upper frequency of about 10 GHz, which is in agreement with experimental data shown in Fig. 1(a).

Note that neither the spectrum of thermal spin waves nor the spectrum of excited spin waves demonstrates any peaks, which could be associated with the effect of spin-wave quantization. This is due to the fact that the component of the wave vector parallel to the width of the microstripe is quantized, whereas the component of the wave vector along the stripe axis can change continuously. Since the microfocus technique does not select a certain longitudinal component of the wave vector by the strict definition of the scattering angle of photons, spin waves with all longitudinal wave vectors contribute to the BLS spectrum, and the spectrum appears to be continuous. In fact, the transverse quantization leads to a splitting of the dispersion curve of the DE waves into a series of curves corresponding to waves with different numbers of antinodes across the stripe width. This is illustrated by Fig. 1(b), where the dispersion of the spin waves calculated for the conditions of the experiment using the theory developed in Ref. 16 is shown. The dashed curve corresponds to the DE wave in a continuous ferromagnetic film. For the case of a microstripe, one obtains series of curves for different quantization numbers n determining the quantized components of the wave vector[18] $k_\perp=\pi n/w$. Two of these curves corresponding to n=1 and 3 are shown in Fig. 1(b). Due to the uniformity of the exciting microwave magnetic field across the width of the stripe, the modes corresponding to even n are not excited, whereas the efficiency of the excitation for odd modes decreases with n as $1/n^2$.[19] Therefore, the modes with $n>4$ will be neglected in the further analysis. Since the phase velocities of different modes differ, the copropagation of two modes with the same frequency leads to an interference pattern with the spatial period $l=2\pi/\Delta k$, where Δk is the separation between the curves [see Fig. 1(b)].

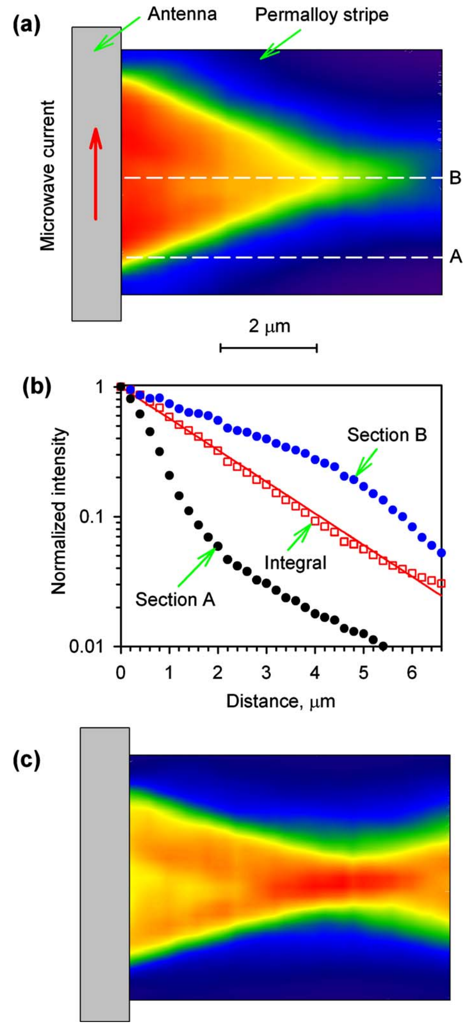

FIG. 2. (Color online) Propagation of spin waves with the frequency of 9.2 GHz in a Permalloy microstripe (w=5.1 μm). (a) Recorded two-dimensional map (5.2×6.6 μm^2) of the spin-wave intensity. (b) Sections of the intensity distribution along lines A and B (circles) and the spatial dependence of the integral of the spin-wave intensity across the stripe width (squares) characterizing the spatial decay of spin waves. The dependences are normalized at the edge of the antenna. Line: Fit of the experimental points by the decaying exponential function. (c) Distribution of the spin-wave intensity with compensated spatial decay due to the energy dissipation.

In the second step, spin waves were excited at a fixed frequency f and the distributions of the spin-wave intensities in the stripe were mapped with a step size of 0.2 μm. Figure 2(a) shows such a distribution for the 5.1-μm-wide stripe excited at the frequency f=9.2 GHz, corresponding to the maximum in the spectrum shown in Fig. 1(a). As seen from Fig. 2(a), the excited spin waves do not decay uniformly when traveling away from the antenna. Instead, they reveal a shaped beam demonstrating both the decay due to the energy dissipation and a focusing effect. In order to illustrate the effect of focusing, the normalized intensities of the spin-wave beam along the lines A and B of Fig. 2(a) and the intensity integrated over the stripe width are shown in Fig. 2(b).

As seen from this figure, the spatial decay along the line A close to the stripe edge is significantly stronger than that along the line B in the middle of the stripe. This difference can be explained by the interference of the spin-wave modes and does not allow the use of individual sections for the characterization of the energy dissipation, of the spin-wave beam. To characterize the energy dissipation, the dependence of the full integral of the spin-wave intensity across the stripe width as a function of the distance from the edge of the antenna was calculated, as shown in Fig. 2(b) by open squares. The fit of the obtained dependence by a decaying exponential function (see the corresponding line) gives the energy decay parameter $\gamma=0.5\ \mu\text{m}^{-1}$. This parameter can be recalculated into the Gilbert damping constant α using the mean group velocity of the DE modes of 2.3 μm/ns derived from the dispersion curves in Fig. 1(b). The result, $\alpha=0.011$, is quite close to the best values obtained for continuous Permalloy films $\alpha=0.007-0.008$.

The obtained energy decay parameter allows a deeper analysis of the mode interference pattern by means of compensation of the spatial decay of spin waves due to energy dissipation.[11] Figure 2(c) shows the same map of the spin-wave intensity as in Fig. 2(a) multiplied by the $\exp(\gamma z)$, where z is the propagation coordinate. This map is, therefore, free from the influence of the spin-wave dissipation and is governed by the mode interference only. As seen from Fig. 2(c), the mode interference leads to a focusing of spin-wave beam at a certain distance from the antenna. This focusing manifests itself in the increase of the spin-wave intensity at the middle line of the stripe, if the observation point moves away from the input antenna. Since the spin-wave energy concentrates at the middle line, the intensity close to the edges decays very quickly, as was already noted from Fig. 2(b).

If the proposed interference mechanism is responsible for this focusing effect, the focal length should be related to the spatial period of the mode interference pattern l defined by the separation between dispersion curves Δk [see Fig. 1(b)]. The calculation shows that in narrower stripes, the transverse quantization leads to larger mode separations and, consequently, to shorter spatial periods. In particular, for the stripe with $w=5.1\ \mu$m, the theory gives $l=11.9\ \mu$m, whereas for the stripe with $w=2.1\ \mu$m, $l=5.3\ \mu$m. Correspondingly, the focusing length in a 2.1-μm-wide stripe should be noticeably shorter than that in the 5.1-μm-wide stripe. This fact is illustrated in Fig. 3, where the profiles of the spin-wave intensity along the middle line of the stripe are shown for two stripe widths $w=2.1$ and 5.1 μm. The profiles are obtained from the two-dimensional intensity maps with compensated spatial decay and normalized at the edge of the antenna. It is clearly seen that the increase of the intensity due to the spin-wave focusing happens for a narrower stripe closer to the excitation source: the maximum intensity for $w=5.1\ \mu$m is observed at the distance of 4.4 μm, whereas for $w=2.1\ \mu$m, the maximum appears already at 1.4 μm.

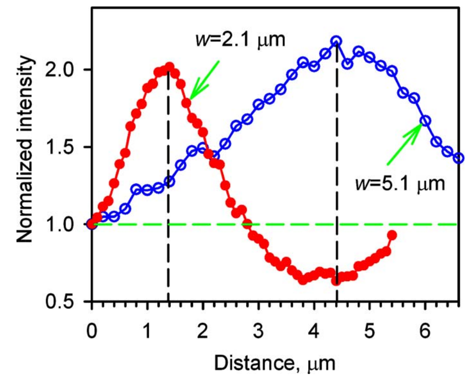

FIG. 3. (Color online) Sections of the intensity distributions with compensated spatial decay along the middle line of the stripe for different widths as indicated. The dependences are normalized at the edge of the antenna. The lines are guides for the eye.

In conclusion, we applied microfocus BLS technique to study the propagation of spin waves in narrow Permalloy microstripes. The analysis of the recorded two-dimensional maps of the spin-wave intensity clearly shows a focusing of the spin-wave beam, and the focal length is found to increase with increasing width of the stripes. A model connecting the observed effect with the interference of quantized spin-wave modes and describing the experimental findings is proposed.

This work was supported in part by the priority programme SPP1133 "Ultrafast magnetization processes" of the Deutsche Forschungsgemeinschaft.

[1]C. Bayer, J. Jorzick, S. O. Demokritov, A. N. Slavin, K. Y. Guslienko, D. V. Berkov, N. L. Gorn, M. P. Kostylev, and B. Hillebrands, Top. Appl. Phys. **101**, 57 (2006).
[2]C. H. Back, D. Pescia, and M. Buess, Top. Appl. Phys. **101**, 137 (2006).
[3]J. Jorzick, S. O. Demokritov, C. Mathieu, B. Hillebrands, B. Bartenlian, C. Chappert, F. Rousseaux, and A. N. Slavin, Phys. Rev. B **60**, 15194 (1999).
[4]J. Jorzick, S. O. Demokritov, B. Hillebrands, M. Bailleul, C. Fermon, K. Y. Guslienko, A. N. Slavin, D. V. Berkov, and N. L. Gorn, Phys. Rev. Lett. **88**, 047204 (2002).
[5]S. Kaka, M. R. Pufall, W. H. Rippard, T. J. Silva, S. E. Russek, and J. A. Katine, Nature (London) **437**, 389 (2005).
[6]F. B. Mancoff, N. D. Rizzo, B. N. Engel, and S. Tehrani, Nature (London) **437**, 393 (2005).
[7]M. R. Pufall, W. H. Rippard, S. E. Russek, S. Kaka, and J. A. Katine, Phys. Rev. Lett. **97**, 087206 (2006).
[8]C. Bayer, J. P. Park, H. Wang, M. Yan, C. E. Campbell, and P. A. Crowell, Phys. Rev. B **69**, 134401 (2004).
[9]Y. S. Gui, N. Mecking, and C.-M. Hu, Phys. Rev. Lett. **98**, 217603 (2007).
[10]M. M. Scott, B. A. Kalinikos, and C. E. Patton, J. Appl. Phys. **94**, 5877 (2003).
[11]M. Bauer, C. Mathieu, S. O. Demokritov, B. Hillebrands, P. A. Kolodin, S. Sure, H. Dötsch, V. Grimalsky, Yu. Rapoport, and A. N. Slavin, Phys. Rev. B **56**, R8483 (1997).
[12]C. Mathieu, V. T. Synogatch, and C. E. Patton, Phys. Rev. B **67**, 104402 (2003).
[13]V. E. Demidov, P. Rekers, B. Mahrov, and S. O. Demokritov, Appl. Phys. Lett. **89**, 212501 (2006).
[14]V. E. Demidov, S. O. Demokritov, B. Hillebrands, M. Laufenberg, and P. P. Freitas, Appl. Phys. Lett. **85**, 2866 (2004).
[15]K. Perzlmaier, M. Buess, C. H. Back, V. E. Demidov, B. Hillebrands, S. O. Demokritov, Phys. Rev. Lett. **94**, 057202 (2005).
[16]R. W. Damon and J. R. Eshbach, J. Phys. Chem. Solids **19**, 308 (1961).
[17]B. A. Kalinikos, IEE Proc., Part H: Microwaves, Opt. Antennas **127**, 4 (1980).
[18]K. Y. Guslienko, S. O. Demokritov, B. Hillebrands, and A. N. Slavin, Phys. Rev. B **66**, 132402 (2002).
[19]C. Kittel, Phys. Rev. **110**, 1295 (1958).