Spin-Wave Eigenmodes of Permalloy Squares with a Closure Domain Structure

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Quantized spin-wave eigenmodes in single, 16 nm thick and 0.75 to 4 μm wide square permalloy islands with a fourfold closure domain structure have been investigated by microfocus Brillouin light scattering spectroscopy and time resolved scanning magneto-optical Kerr microscopy. Up to six eigenmodes were detected and classified. The main direction of the spin-wave quantization in the domains was found to be perpendicular to the local static magnetization. An additional less pronounced quantization along the direction parallel to the static magnetization was also observed.

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Substantial effort has recently been put towards understanding the excitation spectrum of small ferromagnetic elements [1–18]. These excitations determine the response of small magnetic elements subject to ultrashort magnetic field pulses. This is of great importance for advanced magnetic recording technology, as switching time is further reduced and pushed well into the precessional regime. The same excitations cause the high-frequency magnetic thermal noise in the elements which limits the figure of merit of magnetic sensors and read heads. On the other hand, the dynamics of magnetic elements of micrometer and submicrometer sizes is of special interest from the fundamental point of view, since both the exchange and the magnetic dipolar interactions essentially contribute to magnetic confinement phenomena in such elements. In the past several years high-frequency confined spin-wave eigenmodes of micrometer-sized magnetic elements have been systematically studied for the straightforward case of elements possessing an almost monodomain state [1,2,4–7,11–13].

Significantly less is known about the magnetization dynamics in mesoscopic systems with inhomogeneous distribution of the static magnetization. The simplest of these systems is a magnetic disk in the vortex state characterized by an axial symmetry. The corresponding confined spin-wave modes are now intensively studied both theoretically and experimentally [8–10,14,18] and seem to be well understood. Another, more complex magnetic structure with reduced symmetry is a square in the flux closure Landau state with fourfold symmetry in the magnetization distribution [19]. Regarding the dynamic mode spectrum, no reliable theoretical prediction and only a few experimental findings have been reported up to now, although such a state has been known for almost 70 years. The only publications reporting experimental results are Refs. [10,15] where two low-frequency quantized modes were observed.

Because of the finite size of each of the four triangular domains in the given Landau state, confinement effects for the spin-wave excitations are likely. It is the subject of this Letter to report on the discovery and the properties of these eigenmodes. In single permalloy squares of 16 nm thickness with a lateral width L between 0.75 and 4 μm up to six eigenmodes are identified and their mode profiles are determined. The use of two novel complementary experimental techniques such as microfocus Brillouin light scattering (BLS) spectroscopy and time resolved scanning Kerr microscopy (TRSKEM) allowed us to perform the investigations in a wide frequency interval. While TRSKEM is more sensitive to low-frequency modes, BLS is potentially capable of observing the mode spectrum in the frequency range up to several 100 GHz.

Single permalloy ($Ni_{80}Fe_{20}$) squares were produced by e-beam evaporation on a Si substrate and capped with 2 nm Al for corrosion protection. Each square was placed inside a single turn Au loop of 300 nm thickness connected to a 50 Ω microstrip transmission line. The loop has inner and outer diameters of 8 and 12 μm, respectively. For a sketch of the sample, see Fig. 1(a). Using nonpatterned films evaporated in the same batch as the samples under investigation, the sample thickness d and its saturation magnetization M_s were measured by means of x-ray fluorescence and a superconducting quantum interference device magnetometer. The values obtained are 16 nm and 800 G, respectively. Before each measurement the samples were demagnetized using a gradually decreasing ac magnetic field applied perpendicular to the plane of the samples. The presence of a fourfold closure domain structure was

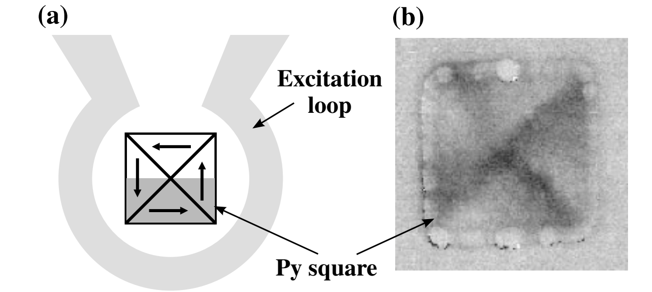

FIG. 1. (a) Schematic layout of a sample: a magnetic permalloy square with a closure domain fourfold Landau structure is surrounded by a gold excitation loop. The solid lines show the domain walls, whereas the arrows indicate the directions of the static magnetization in each domain. The shadowed area has been imaged using microfocus BLS. (b) A typical MFM image for the square with a lateral width of 1 μm.

checked for each sample by means of magnetic force microscopy (MFM). A typical MFM image is shown in Fig. 1(b).

First, spectra of thermally excited quantized spin waves were studied using the microfocus Brillouin light scattering setup described elsewhere [20]. The setup is characterized by a diameter of the probing laser spot less than 300 nm and allows for simultaneous detection of spin-wave excitations in a wide range of wave vectors of up to 2×10^5 cm^{-1}. The results of these measurements are presented in Fig. 2. For the measurements the probing laser spot was positioned in the middle of one of the four triangular domains of the closure domain structure. The accumulation time of each spectrum was 2 h. The lower frequency limit (2 GHz) was determined by the influence of the elastically scattered light, nonfiltered by the Brillouin spectrometer due to its finite finesse for the given free spectral range of 72 GHz.

As seen from Fig. 2, up to six peaks can be clearly distinguished in the spectrum of the square with $L = 0.75$ μm. With increasing size the frequencies corresponding to the peaks decrease and the spectrum becomes denser. The broad spectrum for $L = 4$ μm appears to be continuous. Such an evolution can be associated with the fact that the finite decay length of spin waves becomes smaller than the size of the square. This length can be estimated for our samples as 1–2 μm. As a result, in larger squares ($L = 2$–4 μm) spin-wave modes are only weakly resonant and the spectrum comprises several broad, strongly overlapping peaks.

To study the low-frequency part of the spin-wave mode spectrum, TRSKEM measurements on the $L = 4$ μm square have been performed. Details of the experimental setup are described elsewhere [14]. In order to excite the magnetization inside the square, a current pulse has been sent through the loop producing a perpendicular magnetic tipping field of 300 ps duration. Two-dimensional snapshots of the amplitude of the dynamic magnetization excited by the pulse have been recorded with a 10 ps time

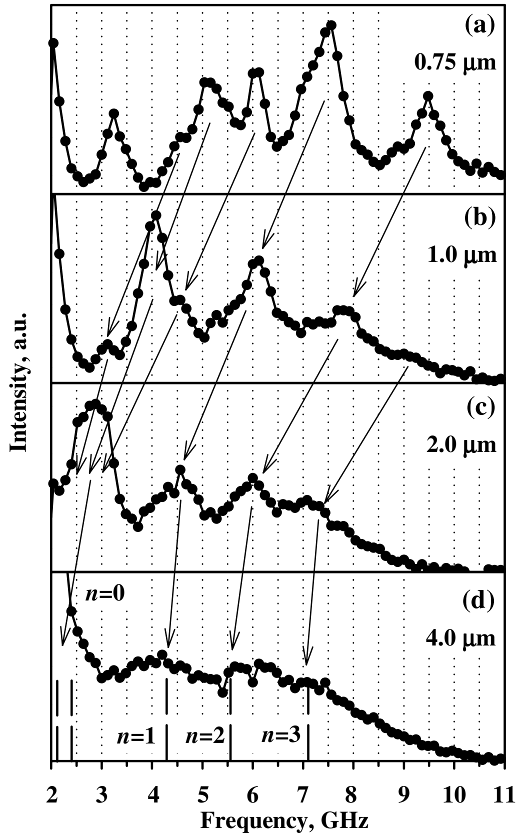

FIG. 2. Spectra of thermal spin waves for the squares with a lateral width L of (a) 0.75 μm, (b) 1 μm, (c) 2 μm, and (d) 4 μm. The arrows follow to the shift of the peaks with the increasing size of the square. Dashed lines in part (d) indicate the frequencies corresponding to the distributions of the dynamic magnetization presented in Fig. 4.

step. Using spatial averaging and Fourier transformation, the frequency spectrum was obtained, as shown in Fig. 3. In contrast to the BLS spectrum shown in Fig. 2(d), the peaks in this spectrum are better resolved. The reason for this is likely that the tipping field used in the TRSKEM method excites primarily those spin-wave modes that have a long wavelength, i.e., a small wave vector. In contrast, the BLS technique is sensitive to modes with a higher wave vector as well, resulting in a broader peak due to inclusion of the higher wave vector modes.

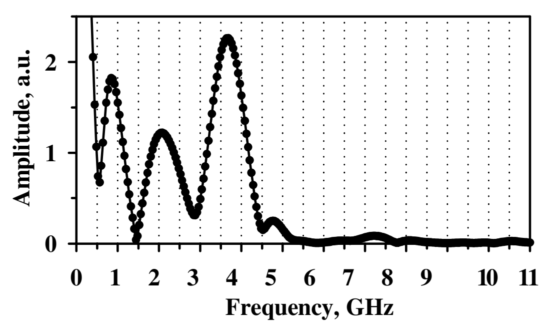

FIG. 3. Fourier spectrum of the oscillation of the averaged magnetization for the $L = 4$ μm square measured by TRSKEM.

In order to classify the detected eigenmodes, space resolved measurements were performed, allowing for an imaging of the lateral distributions of the dynamic magnetization. For this purpose the largest ($L = 4$ μm) square was chosen for the reason of maximum spatial resolution. Since the frequencies of the eigenmodes of such a square were not clearly resolved, microfocus BLS imaging was performed for frequencies in the range from 2 to 8 GHz with a frequency step size of 100 MHz. In order to improve the sensitivity and to filter modes with fast spatial variations, an external excitation field at a fixed frequency was applied to the sample by applying a monochromatic microwave current through the excitation loop. The probing laser spot was scanned in two dimensions with a step size of 200 nm. Since BLS imaging with high spatial resolution is very time consuming, and taking into account the fourfold symmetry of the system being investigated, only half of the square was scanned as shown in Fig. 1. Several different mode profiles were observed at different frequencies of the external field. It was found that transitions between profiles of adjacent modes demonstrating qualitatively different distributions of the dynamic magnetization are smooth and take place in a certain frequency interval. Therefore the frequencies of the eigenmodes were assigned to the center of the frequency interval, at which a given spatial mode distribution has been observed. These values are indicated in Fig. 2(d) by dashed lines. They are in agreement with the overall dependence of the frequencies of the eigenmodes on the size of the square obtained for smaller squares.

Similar two-dimensional distributions were obtained by TRSKEM measurements. For this purpose the measured local temporal dependences of the amplitude of the dynamic magnetization were Fourier transformed in every point of the square, and the spatial distributions of the amplitude were reconstructed.

The measured distributions of the dynamic magnetization are presented in Fig. 4. Figures 4(b)–4(d) measured at 2.1, 2.3, and 4 GHz, respectively, show composite images where the upper parts represent the TRSKEM data, whereas the lower parts show the distributions obtained by microfocus BLS. For the high-frequency modes presented in Figs. 4(e) and 4(f) (measured at 5.5 and 7.1 GHz) only BLS data are available, whereas the low-frequency eigenmode at 0.8 GHz [Fig. 4(a)] can be measured using TRSKEM only. As seen from Fig. 4, profiles obtained by means of the two different measurement techniques agree very well with each other. For two composite images [Figs. 4(c) and 4(d)] the mean values of the mode frequencies obtained by TRSKEM and BLS are slightly different, the difference being less than 10%. The exact reason for this difference is not clear until now. However, one can argue that the strong external excitation used in the TRSKEM measurements might cause changes in the frequencies of the eigenmodes due to nonlinear effects appearing at large precession angles.

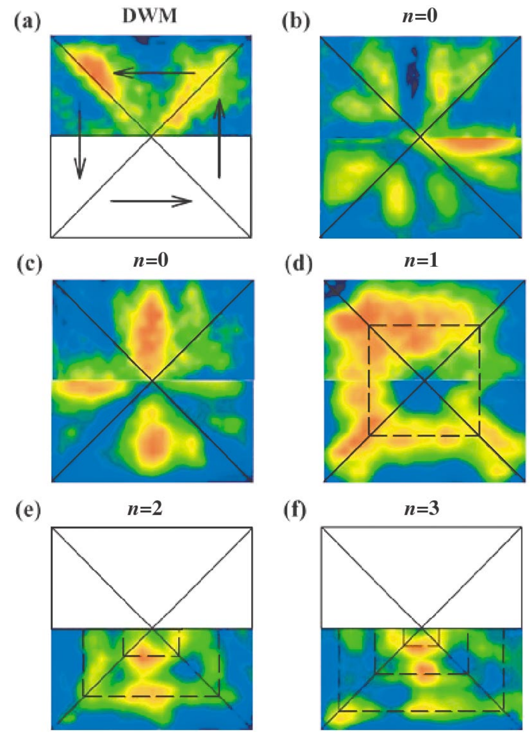

FIG. 4 (color). Distributions of the amplitude of dynamic magnetization corresponding to the eigenmodes. Upper and lower parts of the images are measured using TRSKEM and microfocus BLS, respectively. Diagonal solid lines indicate the domain walls. Arrows in (a) indicate directions of the static magnetization. DWM stands for the domain-wall mode. The corresponding transversal quantization numbers n are indicated near the distribution.

Let us first address the mode with the lowest frequency of 0.8 GHz [Fig. 4(a)], which has already been observed in Refs. [10,15]. This mode is located in and/or near the domain walls and is strongly localized. Similar to the domain-wall (DW) mode [11,15] or the spin-wave well (SWW) modes [6], this mode has an exchange character. However, it has a low frequency due to the small value of the internal field in the DW or SWW regions [6].

In contrast, all modes observed at higher frequencies are spread over the entire domain and clearly show a quantization behavior. They can unambiguously be labeled by the number n of antinodes of the amplitude of the dynamic magnetization along the direction from the center of the square to its edges, i.e., along the direction perpendicular to the static magnetization in the domain (below we address this quantization as ‘‘transversal quantization’’). The mode shown in Fig. 4(d) has one antinode along this direction, 4(e) has two antinodes, and 4(f) has three antinodes. Consequently, we label these modes with the transversal quantization number n equal to 1, 2, and 3, respectively. Similar to the spin-wave modes observed in magnetically saturated stripes [2] the frequencies of the modes increase with increasing quantization number. This fact is discussed below.

In addition to the modes with $n = 1, 2, 3$, two modes with a practically uniform profile along the direction perpendicular to the static magnetization can be seen in Figs. 4(b) and 4(c). In agreement with the above notation we label them with $n = 0$. However, these two modes clearly differ from each other as the distribution of the dynamic magnetization along the direction parallel to the static magnetization is concerned: the mode in Fig. 4(b) has an antinode at the center of the domain, whereas the mode in Fig. 4(c) shows there a node. Thus, they demonstrate a second quantization along the direction of the static magnetization in the domain, which is referred to as "longitudinal quantization."

As seen from Fig. 2, with decreasing size L of the squares, the wide low-frequency peak corresponding to closely lying modes with $n = 0$ and different longitudinal profiles splits into several individual peaks, which can be clearly distinguished for the smallest square. Since the frequency splitting caused by the longitudinal quantization is very small, the presence of the longitudinal quantization is unambiguously confirmed experimentally for the modes with the transverse quantization number $n = 0$ only. However, one should expect a similar longitudinal quantization for the modes with $n > 0$. Most probably, the frequency splitting due to the longitudinal quantization is smaller for the higher-order transversal modes, which does not allow for the observation of individual peaks. However, as seen from Fig. 2, the peaks corresponding to the eigenmodes with $n > 0$ are clearly asymmetrical. They demonstrate shoulders at their low-frequency slopes, which can result from small-amplitude peaks located very close to the main ones. This fact might be considered as a hint to the longitudinal quantization for higher-order transversal modes.

To our knowledge, a rigorous theory of quantized spin waves in the Landau domain structure is not existing yet. However, the observed quantized modes can be qualitatively understood based on the dispersion law for plane spin waves of a continuous film, magnetically saturated in its plane [21]. In fact, the frequency of a spin wave with the wave vector oriented perpendicular to the static magnetization strongly increases with an increasing wave vector. Consequently, a standing spin wave with a larger number of antinodes (larger effective wave vector) along the direction perpendicular to the static magnetization should have a higher frequency. This is in agreement with our experimental findings. As far as longitudinal quantization is concerned, the estimations show that for the used thickness of the samples and the value of the saturation magnetization of $Ni_{80}Fe_{20}$ the same increment in the longitudinal component of the wave vector results in rather weak changes in the spin-wave frequency. This might be the reason why the observed longitudinal quantization is less pronounced than the transversal one.

In conclusion, we have determined the spin-wave eigenmode spectrum of $Ni_{80}Fe_{20}$ squares with a fourfold closure domain structure. It is shown that the spectrum comprises a mode localized inside the domain walls and a series of modes spread over the entire domain. The latter modes are quantized in both in-plane directions. The quantization along the direction perpendicular to the static magnetization is characterized by a significant frequency separation between the modes and can be clearly observed in micrometer-sized squares. The frequencies of eigenmodes quantized in this direction increase with an increasing number of antinodes. The frequency splitting due to the longitudinal quantization is much smaller. As a result, it is pronounced only in the squares with submicrometer lateral dimensions.

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