Chapter 6: Experimental Results

A. Dynamic Magnetic Phenomena

6.1 Spin-wave eigenmodes of permalloy squares with closure domain structure

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Substantial efforts have been put recently into the identification of excitation spectra of small ferromagnetic elements [1–8]. 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 gyromagnetic regime. In the last 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 [1–5]. Significantly less is known about 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 [6–8] and seem to be well understood. Another, more complex magnetic structure with reduced symmetry is a square in the flux closure Landau state with four-fold symmetry in the magnetization distribution. Regarding the dynamic mode spectrum in this structure, no reliable theoretical prediction and only few experimental findings [8] have been reported up to now.

Here we report on the discovery and the properties of the eigenmodes of micrometer sized Permalloy squares with the Landau domain structure. Up to five eigenmodes are identified and their mode profiles are determined with a spatial resolution better than 300 nm.

Single Permalloy squares of 16 nm thickness with a lateral width $L$ between 0.75 and 4 µm 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 50Ω 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. Before each measurement the samples were demagnetized.

Fig. 1: Schematic layout of a sample: a magnetic permalloy square with a closure domain four-fold 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 BLS.

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Fig. 2: Spectra of thermal spin waves for the squares with a lateral width $L$ of 0.75 µm (a), 1 µm (b), 2 µm (c), and 4 µm (d). The arrows follow to the shift of the peaks with increasing size of the square. Dashed lines in the part (d) indicate the frequencies corresponding to the distributions of the dynamic magnetization presented in Fig. 3.

using a gradually decreasing AC magnetic field applied perpendicularly to the plane of the samples. The presence of a four-fold closure domain structure was checked for each sample by means of magnetic force microscopy.

First, spectra of thermally excited quantized spin waves were studied using a micro-focus Brillouin light scattering setup described elsewhere [9]. 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 wavevectors up to $2 \times 10^5$ cm$^{-1}$. The results of these measurements are presented in Fig. 2. During 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 hours. The lower frequency limit (2 GHz) was determined by the influence of the elastically scattered light, non-filtered by the Brillouin spectrometer due to its finite finesse.

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 a behavior 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.

In order to classify the detected eigenmodes, space resolved measurements were performed allowing for an imaging of 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, the 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 samples by means of transmission of 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 four-fold symmetry of the system being investigated, only half of the square was scanned as shown in Fig. 1. The measured distributions of dynamic magnetization are presented in Fig. 3. The frequencies corresponding to the distributions shown are indicated in the figure near each of the images. Note 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 presented values of the frequencies indicate the center of the frequency interval only, at which a given spatial mode distribution has been observed. These values are indicated in Fig. 2d 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.

As seen from Fig. 3, all the eigenmodes can unambiguously be labeled by the number $n$ of antinodes 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. 3c has one antinode along this direction, 3d - two antinodes, and 3e - 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 [1] the frequencies of the modes increase with increasing quantization number. In addition to the modes with $n = 1, 2, 3$, two modes with practically uniform profile along the direction perpendicular to the static magnetization can be seen in Figs. 3a and b. 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. 3a has an antinode at the center of the domain, whereas the mode in Fig. 3b shows there a node. Thus, they demonstrate a second quantization along the direction of the static magnetization in the domain, which will be 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 quan-
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tization 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 the main ones. This fact might be considered as a hint to the longitudinal quantization for higher-order transversal modes.

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 [10]. In fact, the frequency of a spin wave with the wavevector oriented perpendicularly to the static magnetization strongly increases with increasing wavevector. Consequently, a standing spin wave with larger number of antinodes (larger effective wavevector) 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 wavevector results in rather weak changes in the spin-wave frequency. This might be a 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 four-fold closure domain structure. It is shown that the spectrum comprises modes 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 increasing number of antinodes. The frequency splitting due to the longitudinal quantization is much smaller. As a result, it is only pronounced in the squares with submicrometer lateral dimensions.

This work was supported in part by the priority programme SPP1133 “Ultrafast magnetization phenomena” of the Deutsche Forschungsgemeinschaft, by the European Community under contract IST-2001-37334 “Low Power Magnetic Random Access Memory with Optimised Writing Time” (NEXT), and by the European Communities Human Potential programme under contract number HRPN-CT-2002-00318 ULTRASWITCH. V.E.D. acknowledges the support from the Alexander von Humboldt Foundation.

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