Modification of the thermal spin-wave spectrum in a Ni$_{81}$Fe$_{19}$ stripe by a domain wall

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Abstract
The thermal spin-wave distribution in a Ni$_{81}$Fe$_{19}$ stripe with an asymmetric transverse domain wall has been investigated using Brillouin light scattering microscopy. Clear evidence has been found that the existence of the domain wall influences the spin-wave distribution of the thermal modes. The thermal spin-wave modes are quantized due to confinement in the radial direction. They vanish near the domain wall and a new mode evolves inside this complex domain wall structure. This effect is attributed to the change in the effective internal field in the domain wall region. The experimental results agree well with static and dynamic micromagnetic simulations.

1. Introduction
The research field of spin waves in confined magnetic structures with a controlled inhomogeneous internal field is of fundamental interest for understanding magnetization dynamics (see, e.g. [1–3]). Such an inhomogeneous internal field can be caused by the finite size of the magnetic object due to stray field effects at the boundaries [1,4–6] and/or by a magnetic domain structure [3, 7–9]. Several investigations of spin-wave spectra in finite elements without and with a domain structure have been reported (see, e.g. [9–31]). Here we report on the modification of the thermal spin-wave distribution by a domain wall. As one main result we report the finding of a spin-wave mode localized to the domain wall region caused by the spin-wave potential well generated by the domain wall. To approach the problem, two main obstacles have to be overcome: firstly and most importantly, a non-destructive measurement technique capable of resolving the dynamic properties with high spatial resolution for resolving the domain pattern is needed. Secondly, domain walls must be created in a reliable and reproducible way.

Brillouin light scattering spectroscopy using a scanning microfocus sample stage, hereafter referred to as BLS microscopy, is by now a well-established technique which meets the experimental requirements regarding imaging of dynamic magnetic properties [9–12]. A spatial resolution of 250 nm has been achieved with sensitivity down to thermal spin-wave excitations. This microscopy technique opens the door for investigating spin waves in a narrow Ni$_{81}$Fe$_{19}$ stripe with a well-defined domain wall.

2. Sample design and experimental setup
The structure design of curved wires follows an idea presented by Saitoh [32] and has also been discussed in [33] as the so-called domain wall pendulum. A semi-circular Ni$_{81}$Fe$_{19}$ structure contains a circular anti-notch located at the pole of the semi-circle acting as a pinning site for the domain wall (see figure 1). In particular, the chosen semi-circular sample design allows for a defined nucleation and annihilation of a single domain wall in the vicinity of the anti-notch by applying a magnetic field in the transversal or parallel direction, respectively, and subsequent relaxation of the magnetization to remanence.

The samples have been produced using a combination of molecular beam epitaxy and electron beam lithography employing a standard lift-off process. The Ni$_{81}$Fe$_{19}$ films have a thickness of 10 nm. The Ni$_{81}$Fe$_{19}$ structures have been prepared using a 120 nm thick PMMA resist layer (polymethylmethacrylate, molecular weight 950 K, solid
fraction of 4%) spun onto a thermally oxidized silicon substrate (500 µm silicon covered with 100 nm silicon oxide). The radii of the structures vary between 5 and 50 µm in steps of 5 µm. The wire width is 500 nm and the radius of the anti-notch is 250 nm revealing a total width of 750 nm at the anti-notch position. The patterned structures show an induced transverse anisotropy. A schematic view of one of the semi-circles is shown in figure 1(a). Here the Ni$_{81}$Fe$_{19}$ structure is displayed in dark colour. The bright spots indicate the data acquisition positions used. The magnetic field directions used to nucleate a domain wall or to saturate the sample are also defined in figure 1(a). Figure 1(b) shows a corresponding scanning electron micrograph of the sample design.

For analysing the spin-wave modes BLS microscopy was employed. As described above, this method is a powerful non-destructive tool to obtain space-resolved information in the GHz frequency regime with a high lateral resolution. The BLS investigations were carried out exemplarily for the semi-circles with a radius of 5 µm. For magnetostatic domain analysis and dynamic spin-wave distribution analysis OOMMF [35] simulations are presented to support the interpretation of the experimental results.

3. Experimental results

An essential prerequisite for the investigation of the modifications of spin waves in the Ni$_{81}$Fe$_{19}$ structures due to the presence of a domain wall is a well-characterized domain wall, which is reproducibly induced and located near the anti-notch. Since BLS microscopy does not allow for direct in situ domain imaging, the domain analysis experiments have been made in collaboration with the group of Professor John Chapman, Glasgow University, using Lorentz microscopy. The results are reported in [34]. In summary, employing standard electron transparent Si$_3$N$_4$/Si substrates the domain structure of the Ni$_{81}$Fe$_{19}$ wires was investigated. It was found that the domain wall induced in the semi-circular structures by applying a defined field sequence exhibits the character of an asymmetric transverse domain wall and can reproducibly be located close to the position of the anti-notch.

To analyse the spin-wave modes present in the Ni$_{81}$Fe$_{19}$ curved nanowires the spectra of thermally activated spin waves have been investigated. The measured BLS spectra are summarized in a colour coded intensity map, where dark blue represents the lowest spin-wave intensity and red the highest intensity. Each vertical line in the colour map represents a BLS spectrum taken at the position indicated at the x-axis. The spectra have been taken with a step size of 0.1 µm equidistantly along the central perimeter of 6.1 µm length in the vicinity of the anti-notch (see figure 1(a)). First, the sample was initialized in the parallel direction by saturating the sample in a field $H_{\text{parallel}}$ = 880 Oe, thus ensuring that no residual domain walls were present. Subsequently the sample was relaxed to remanence. Figure 2(a) shows the resulting BLS colour map and the corresponding magnetization distribution obtained by OOMMF simulations [35]. For the numerical simulations, the semi-ring with the corresponding radius (inner radius 5 µm, outer radius 5.5 µm) has been simulated. To optimize computation time, only a section of 5.8 µm × 1.4 µm of a thickness of 10 nm was taken into account. The mesh size was 7.5 nm × 7.5 nm × 10 nm and the standard values for Ni$_{81}$Fe$_{19}$ (exchange stiffness constant $A = 1.6 \times 10^{-6}$ erg cm$^{-1}$, gyromagnetic ratio $\gamma = 1.76 \times 10^{-2}$ GHz Oe$^{-1}$, and a damping constant $\alpha = 0.01$) have been used. A saturation magnetization of only 650 G instead of 860 G has been chosen to take account of the heating effect of the sample by the laser spot [9].

In this remanence case without a domain wall two modes of standing spin waves with frequencies of about 2.4 and 3.4 GHz can be clearly identified. These modes exhibit mainly the characteristics of magnetostatic surface waves, the so-called Damon–Eschbach modes, whose direction of propagation is in-plane perpendicular to the magnetization of the structure. They are quantized in the transversal direction due to the lateral confinement of the structure and travel forth and back between the stripe boundaries. In this regard no influence of the changing boundary conditions due to the anti-notch is evident in the BLS spectra.

Next, the change in the thermal spin-wave spectrum due to the presence of the asymmetric transverse domain wall has been analysed. To do so, the sample has been initialized by applying an external magnetic field in the transversal direction (see figure 1(a)). After removal of the field an asymmetric transverse domain wall is nucleated in the structure and pinned in the vicinity of the anti-notch [34]. The corresponding BLS intensity map and the corresponding magnetization distributions obtained by OOMMF simulations [35] are shown in figure 2(b)).

By comparing the intensity maps obtained with and without a domain wall, obvious differences in the spectra can be determined: instead of the original modes observed outside the domain wall with frequencies of 2.4 and 3.4 GHz a new mode with a frequency of about 4.8 GHz arises at the position of the anti-notch whereas the other modes vanish in this area (see figure 2(b)).

This behaviour can be understood in terms of a change in the magnitude and direction of the effective local internal magnetic field $\vec{H}_{\text{eff}}$ [5]. Such a local change in the magnetic field caused by the asymmetric transverse domain wall can act as a spin-wave potential well supporting a localized mode [9]. Due to the two-dimensional character of this problem an analytical approach to calculate the mode frequency is impractical—instead dynamical micromagnetic simulations have been carried out for a direct comparison.

The dynamic simulations have been performed by applying a weak out-of-plane Gaussian-shaped magnetic field pulse (amplitude 1 Oe, pulse width 20 ps) to the semi-circle at remanence and, thus, excite the eigenmode spectrum of the magnetic element. These data have been Fourier-transformed point by point afterwards to the frequency domain to obtain the spin-wave mode distribution. In comparison with the experiment the simulations reveal a frequency shift of about 1 GHz, which can be understood by a difference between the sample properties and the parameters of the simulation, e.g. possible variations of the effective stripe width of the sample caused by fabrication defects which are not taken into account in the simulation.
Figure 1. (a) Schematic view of the sample design and data acquisition procedure. Measurements have been carried out along the positions marked by bright spots. The externally applied magnetic fields are shown as $H_{\text{transversal}}$ and $H_{\text{parallel}}$. (b) Scanning electron micrograph of the Ni$_{81}$Fe$_{19}$ semi-circles each comprising an anti-notch as domain wall pinning site.

In general, the experiment and the simulation show very good qualitative agreement. Figure 3 shows the first modes in the structure without an applied external magnetic field. In figure 3(a) the first mode without a node can be observed along the whole semi-circle perimeter, suppressed only in the area of the domain wall. The second mode shown in figure 3(b) shows the typical node in the middle of the stripe due to quantization of the spin waves in the radial direction. For both modes a clear disturbance is observed in the region of the domain wall. Figure 3(c) shows a weakly excited mode at higher frequencies, which is mainly localized in the area of the anti-notch, where the domain wall is pinned. This mode corresponds to the experimentally observed mode localized in the domain wall (see figure 2(b)). For comparison, the simulations have been carried out for the same structure and at remanence but without a domain wall, i.e. in an uniformly magnetized semi-circle (see figure 2(a)). The results are shown in figures 3(d) and (e) for the corresponding frequencies. In this configuration no major change in the mode structure in the vicinity of the anti-notch can be observed. This result proves that the pinned domain wall is the reason for the changes in the mode structure.

To further analyse this new mode localized in the vicinity of the domain wall the behaviour of the spin-wave modes under the influence of an increasing transversal as well as an increasing parallel magnetic field was investigated. First, the domain wall growth and annihilation expected for an increasing transversal magnetic field is discussed. During this procedure the area of the domain wall width is increasing. For a better comparison between the intensity maps at different fields, only the BLS frequencies between 2 and 6 GHz are shown in figure 4. Additionally, the results of the corresponding micromagnetic simulations are added for selected fields. As seen from the BLS intensity maps and comparison with the micromagnetic simulations, the new mode inside the domain wall is pronounced as long as the asymmetric transverse domain wall exists. The mode starts to vanish when the domain wall width is increasing due to the externally applied transversal field. The asymmetric transverse domain wall loses its character at 109 Oe. For a further increase in the transversal field the magnetization follows the external field even in the area of the anti-notch.

Second, the spin-wave distribution with increasing parallel magnetic field was investigated. In this measurement geometry the asymmetric transverse domain wall is expected to extend and depin from the pinning site, as demonstrated in [34]. This time the domain wall was initialized as before but the sample was rotated afterwards by 90° and a parallel, slightly increasing field was applied. The results as well as corresponding micromagnetic simulations are presented in figure 5.
Figure 3. Spatially resolved Fourier-transformed spin-wave mode distributions obtained by micromagnetic simulations for a frequency of (a) 3.3 GHz, (b) 4.7 GHz and (c) 5.7 GHz at remanence. Panel (a) shows the first mode along the semi-circle perimeter in the presence of a domain wall. In (b) the node due to the quantization in the radial direction can be clearly seen. Both mode profiles are strongly disturbed in the region of the anti-notch, where the domain wall is localized. Panel (c) shows the weakly excited mode in the area of the anti-notch for high frequencies. Panels (d) and (e) show the results of the simulation in the absence of a domain wall but at the same frequencies as before. It can be seen that the mode structure does not change significantly in the vicinity of the anti-notch.

Figure 4. Experimental intensity map summarizing the spectra of thermally activated spin waves in the semi-circular Ni$_{81}$Fe$_{19}$ structure of radius 5 $\mu$m while applying a transversal field ranging from 0 to 430 Oe. The BLS intensity is shown colour coded ranging from dark blue (low intensity) to red (high intensity). Each vertical line in the two-dimensional map represents a BLS spectrum taken at the position as indicated on the $x$-axis. The white dashed lines show the position of the anti-notch. Right side: corresponding magnetization distributions obtained by OOMMF simulations. The intensity maps show the disappearance of the original modes at the position of the anti-notch and the appearing new mode in this area. With increasing fields, the modes shift to higher frequencies and the domain wall broadens. In the last maps which correspond to high field values, the domain wall vanished and only the effect of the increased stripe width at the position of the anti-notch on the mode frequency can be observed.

As seen from the simulations, the domain wall is depinned already at a field of 10 Oe and driven to the left by the external field. This change in the magnetization distribution can also be observed in the BLS intensity maps. As long as the domain wall is pinned in the vicinity of the anti-notch the eigenmode spectrum with the first mode at 2.5 GHz on the left-hand side does not show a significant change. As soon as the domain wall is depinned and starts to move in this direction, the modes existing only outside the domain wall vanish at the position of the wall which can clearly be seen starting from 12 Oe. Consequently, the domain wall displacement also causes a change in the spin-wave mode profile in the area of the anti-notch, as the domain wall is no longer localized at this position. The mode localized in the domain wall disappears at
Figure 5. BLS intensity maps summarizing the spectra of thermally activated spin waves in the semi-circular Ni$_{81}$Fe$_{19}$ structure of radius 5 $\mu$m for different applied parallel fields. For this measurement the domain wall has been nucleated by applying a transversal field and relaxation to remanence, afterwards the sample has been rotated by 90$^\circ$ and a parallel field has been applied. The BLS intensity is shown colour coded ranging from dark blue (low intensity) to red (high intensity). Each vertical line in the two-dimensional map represents a BLS spectrum taken at the position as indicated on the x-axis. The white dashed lines show the position of the anti-notch. Right side: corresponding magnetization distributions obtained by OOMMF simulations. The field driven displacement of the domain wall can be seen from the intensity maps as a change in the mode spectrum. As long as the domain wall is pinned in the vicinity of the anti-notch the characteristics of the mode spectrum on the left-hand side of the wall do not change while the field changes. As soon as the wall is depinned due to the increased external field, the mode spectrum also on the left-hand side changes accordingly.

4. Conclusion

This paper reports on the analysis of the thermal spin-wave mode distribution in Ni$_{81}$Fe$_{19}$ semi-circles with defined asymmetric transverse domain walls employing Brillouin light scattering microscopy. The spectra of thermally excited spin waves reveal a clear influence of the presence of the domain wall, which is nucleated and pinned in the vicinity of the anti-notch of the structure. Comparing the spin-wave spectra in the absence and presence of the domain wall it can be observed that the original spin-wave modes quantized in the radial direction vanish in the vicinity of the domain wall and new modes are formed located only inside this complex domain wall structure. The experimental results are confirmed by static and dynamic OOMMF simulations. By investigating the field dependence of these new modes it could be proven that the domain wall growth and destruction in a transversal applied field as well as the depinning behaviour in a parallel applied field can be monitored by BLS microscopy employing the spatially resolved detection of the mode localized in the domain wall structure.

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