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Study of the spin excitations in antidot lattices with line defects

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ABSTRACT

The propagation of spin waves in antidot lattices with line defects has been studied by both microfocused Brillouin light scattering and micromagnetic simulations. The samples under investigation are NiFe square antidot lattices with circular holes of 250 nm of diameter, periodicity of 700 nm and thickness of 60 nm. Line defects have been introduced in the antidot lattices by removing one row (column) of holes every three rows (columns). Microfocused BLS has been used in order to map out the intensity profile of the main eigenmodes which are excited by a microwave current injected into a coplanar waveguide deposited on top of the sample surface. The comparison between micromagnetic simulations and μ-BLS measurements shows a good agreement not only for the measured frequency but also for the spatial profiles of the modes with the highest intensity in BLS spectra. These eigenmodes extend along the channels between dots rows and their frequency is different in presence of row- or column-defects because of the modification of the internal field felt by the precessing spins.

1. Introduction

In the recent past, considerable work has been done for studying the magnetic properties of antidot lattices (ADLs), i.e. periodic arrays of nanometric holes drilled into a planar ferromagnetic films. The holes can be considered as a regular mesh of defects which, depending on their symmetry (square, rhombic and honeycomb) as well as their size, shape and periodicity can modify the magnetization configuration of the system, magnetization reversal, coercivity as well as magnetic anisotropy and magnetoresistive properties [1–3]. The dynamic response of magnetic ADLs, considered as magnonic crystals where the modulation of the magnetic properties gives rise to forbidden and allowed band gaps, has been also investigated [4,5].

To enhance the parameters available for engineering the magnetic properties, researchers have started to investigate ADLs with alternated diameters [6] and single and bi-component [7,8], ADLs made of two different magnetic materials. Recently, the role of tailored imperfections in ADLs has been experimentally addressed. Hu and co-workers [2] have studied the influence of individual lattice defects consisting of a missing antidot on the spin configurations in rectangular permalloy antidot lattices while Gieniusz et al. [9] have measured the diffraction effect of surface magnetostatic spin waves from a single antidot. The role of line defects has been investigated only very recently by Lenk et al. [10] on in-plane magnetized ADLs and by Schwarze et al. [11] on perpendicularly-to-plane magnetized ADLs.

In this work, we have used microfocused Brillouin light scattering (μ-BLS) [12] and micromagnetic simulations to address the spin excitations of ADLs with periodic line defects, i.e. missing rows or columns of holes. A regular ADL (without line defects) has been also studied and used as reference sample.

2. Experimental and micromagnetic simulations

The samples under study were fabricated using multi-level lithography process including electron-beam (e-beam) lithography, Ar^+ ion-milling and e-beam evaporation. Two square arrays of NiFe ADLs with line defects were fabricated removing either a row or a column every three rows (or columns) of 250 nm diameter holes from the original device layout. The resulting samples are named missing-row and missing-column samples in the following. A reference ADL with square array of holes, without defects, was also fabricated and used as reference. The thickness of the NiFe in all samples is 60 nm, while the lattice period in the reference ALD is 700 nm. Finally, a 2-μm wide Cr (10 nm)/Au (200 nm) microstrip antenna was patterned on top of the ADL using e-beam lithography for rf excitation of spin waves. Scanning electron microscopy (SEM) images of the resultant ADLs with specific defect locations are shown in Fig. 1 (left panels).

In the μ-BLS experiment a beam of monochromatic light (532 nm of wavelength) was focused on the sample surface by using a 100× dark field objective which enables to reduce the

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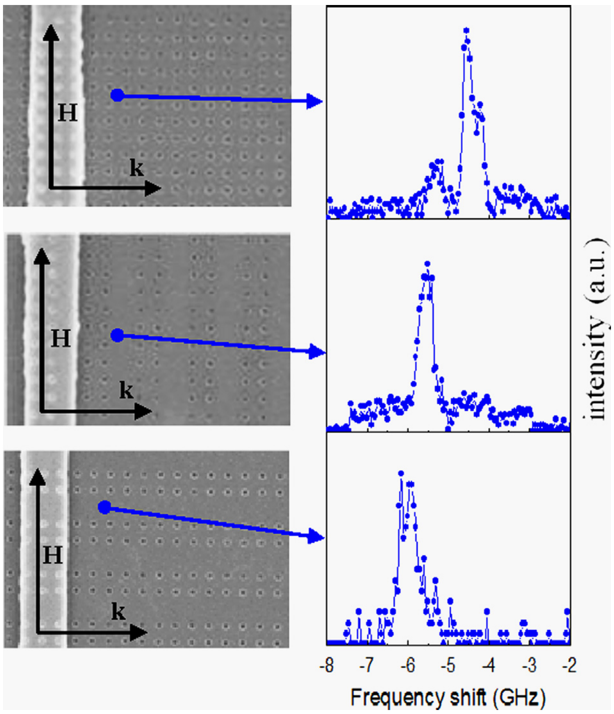

Fig. 1. (Left panels) SEM images of reference ADL (top), of the missing-column (center) and missing-row (bottom) samples. The vertical gray region is the microstripe antenna and the black arrows indicate the direction of the applied magnetic field ($H=500$ Oe) and of the spin-wave wavevector (k) respectively. (Right panels) μ-BLS spectra for the three samples.

laser spot diameter down to about 250 nm allowing for two-dimensional mapping of spin waves [11]. The spin waves are excited by an rf current injected into the microstrip antenna by a microwave generator. The range of wave vectors for the spin waves excited by the microwave field is [0–1.5 × 10^4 cm^{-1}] with the upper bound (π/w) imposed by the width of the antenna w. All μ-BLS measurements have been performed applying a magnetic field of 500 Oe parallel to the microstrip antenna.

Micromagnetic simulations of the modes frequency and spatial profiles are performed with the open source OOMMF code developed by NIST [13]. Two dimensional periodic boundary conditions (2D-PBC) are applied to take into account the periodicity of the studied ADLs. Since the three ADLs have different periodicities we use unit cells of different dimensions namely: a 700 × 700 nm^2 unit cell for the reference antidote lattice, a 2100 × 700 nm^2 unit cell for the lattice with vertical line defects and a 700 × 2100 nm^2 unit cell for the system with horizontal line defects. The unit cells are then discretized into a two-dimensional grid of 10 × 10 nm^2 cell size. The height of the cells, instead, is equal to the thickness of the magnetic layer (i.e. 60 nm). This choice is necessary to reduce the simulation time; nonetheless we checked that a reduction of the cell thickness introduces negligible variations on the eigenmodes frequencies and spatial profiles. The magnetic parameters used for NiFe in the simulations are: $A=13\times10^{-12}$ J/m for the exchange stiffness constant, $M_S=860\times10^3$ A/m for the saturation magnetization and no magnetocrystalline anisotropy. In order to calculate the resonance frequencies of the system we first calculate the static spin configuration for a fixed value of the external applied field of $H=500$ Oe. Then, retaining this value of the in-plane dc uniform field which is constant in time, we excite the system with a uniform out-of-plane Gaussian field pulse with a full width at half maximum of 1 ps and an amplitude of 1.0 Oe [14]. After the field pulse the system is left free to evolve following the Landau–Lifshitz–Gilbert equation of motion with a damping factor set to a realistic value of $\alpha=0.01$ and an effective gyromagnetic ratio of $\gamma=2.31\times10^5$ m/A s. The time evolution of the magnetization of each micromagnetic cell is tracked over the next 10 ns with a time step (Δt) of 10 ps. Then a Fourier analysis of the magnetization ringdown in each micromagnetic cell enables us to calculate the local power spectra of the magnetization components [15]. After that the average power spectrum is calculated summing the local power spectra. Several peaks are present in this average power spectrum corresponding to the different eigenfrequencies of the system. A surface plot of the imaginary part of the Fourier coefficients for each eigenfrequency provides the spatial profile of the corresponding eigenmode.

3. Results and discussion

The first step in our work was to detect the spectrum of spin waves excited during a frequency scan by sweeping the microwave generator frequency in the range between 2 and 8 GHz with

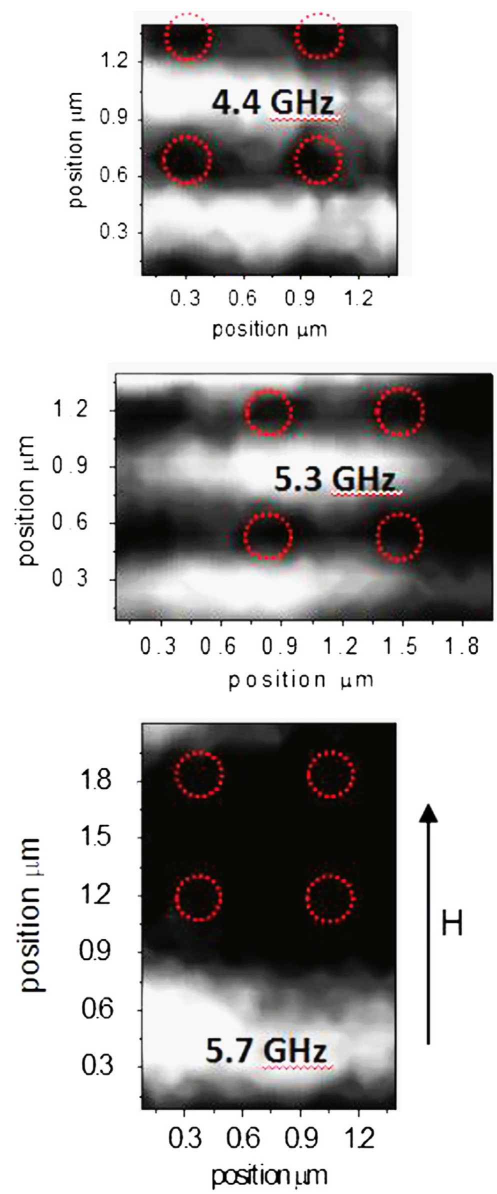

Fig. 2. Measured spin wave intensity profiles of selected spin wave modes for the ADLs with lines defect and the reference ADL. An external magnetic field $H=500$ Oe is applied along the vertical direction, parallel to the microstripe antenna which is located on the left of the images at a distance of about 1 μm.