Spin waves band structure in planar Magnonic Crystals

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Abstract

The application of Brillouin light scattering to study the spin waves band structure of planar one- and two-dimensional magnonic metamaterials, consisting of arrays of interacting ferromagnetic elements is reviewed. The dispersion curves of collective spin modes are characterized by periodical oscillations determined by the width of the artificial Brillouin zone. Remarkably, both the frequency position and width of the magnonic band depend on the geometrical parameters of the elements and on the magnetic ground state. In the case of two-dimensional array of saturated dots, because of the uniaxial symmetry introduced by the application of an external magnetic field, the dynamical coupling and the frequency dispersion of collective modes depend on the relative orientation between the spin wave in-plane vector and the direction of the applied magnetic field.

1. Introduction

Magnonic Crystals (MCs) represent a new class of metamaterials with periodically modulated magnetic properties where spin waves are used to carry and manipulate information, similarly to light in photonic crystals. [1] Since the wavelengths of these excitations are shorter than those of light in the gigahertz range, MCs offer better prospects for miniaturization at these frequencies, with the advantage that frequency position and width of the band gap are tuneable by the applied magnetic field. This suggests an unprecedented opportunity to design and exploit a new generation of spin logic devices, filters and waveguides operating in the GHz frequency range. However, tailoring and knowledge of the magnonic band structure of a specific MC is preliminary to any desired application. A MC can be formed starting from uncoupled resonators and making them coupled by some interaction, such as dipolar or exchange magnetic coupling. Alternatively, one can artificially process a continuous medium, to make a periodical profile of magnetic properties such as the saturation magnetization and the exchange constant. In the former case, collective spin modes are formed because the magnetic coupling removes the degeneracy of the discrete frequencies of resonances inside each element. In the latter case, one starts from the continuous frequency dispersion of spin waves and forbidden bands appear as the result of Bragg interference effects. Examples of one-dimensional (1D) discrete MCs are arrays of closely spaced parallel magnetic stripes or arrays of stripes of different magnetic materials in direct physical contact with each other. Similar to the 1D case, two-dimensional (2D) MCs can also be fabricated in the form of ordered arrays of closely packed magnetic dots (coupled by dipolar interaction).

2. Sample preparation and characterization

We exploit Brillouin Light Scattering (BLS) technique to investigate the band structure of collective spin excitations in two different prototypes of planar 1D and 2D MCs.[2] These are constituted by an array of $Ni_{80}Fe_{20}$ parallel stripes of different width (330 nm and 900 nm) [3] and by a square matrix of $Ni_{80}Fe_{20}$ square dots with 450 nm lateral size, respectively.[4] Scanning electron micrographs (SEM) of the investigated arrays are presented in Fig.1. In both cases the inter-element separation is 70 nm and stripes thickness is 40 nm while dots are 30 nm thick. For stripes array the BLS scattering experiment were performed in the Magnetostatic surface wave (MSSW) geometry (wavevector *k* perpendicular to the applied field) while for the dots both the parallel (MSSW) and perpendicular orientation (MSBVW) of *k* with respect to H were explored. For the stripes the spin wave dispersion was meas-

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ured both in the saturated “ferromagnetic” state, where the magnetizations of wide and narrow stripes are parallel, and the “anti-ferromagnetic” state, characterized by an anti-parallel alignment of the static magnetization in adjacent stripes. This anti-ferromagnetic ground state was obtained by applying a appropriate magnetic field sequence along the stripes length and its presence is due to the different coercive fields of the stripes having different widths.[3] In the case of squared dots a magnetic field of 1.5 kOe ensures the static magnetization to be uniformly aligned to the magnetic field, with exception of the small regions close to the dots edges.[4]

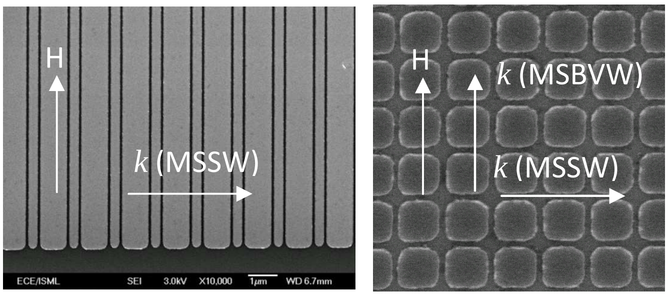

Fig. 1 SEM images of the stripes and dots arrays. In both case the magnetization inside each element is almost uniform.

3. Results and Discussion

In Fig. 2 (a) BLS measurements as a function of the transferred in-plane wave vector, are reported for the array of stripes both in the ferromagnetic and anti-ferromagnetic ground state. All the observed modes exhibit an oscillating dispersive character with the appearance of Brillouin zones (BZs) at k=$n\pi/a$, determined by the artificial periodicity of the stripes array. Each mode exists in its frequency range (Magnonic band) separated from the neighbouring one by a prohibited zone (Magnonic band gap). This is different from the case of the non-interacting stripes where dispersionless quantized spin waves have been observed.

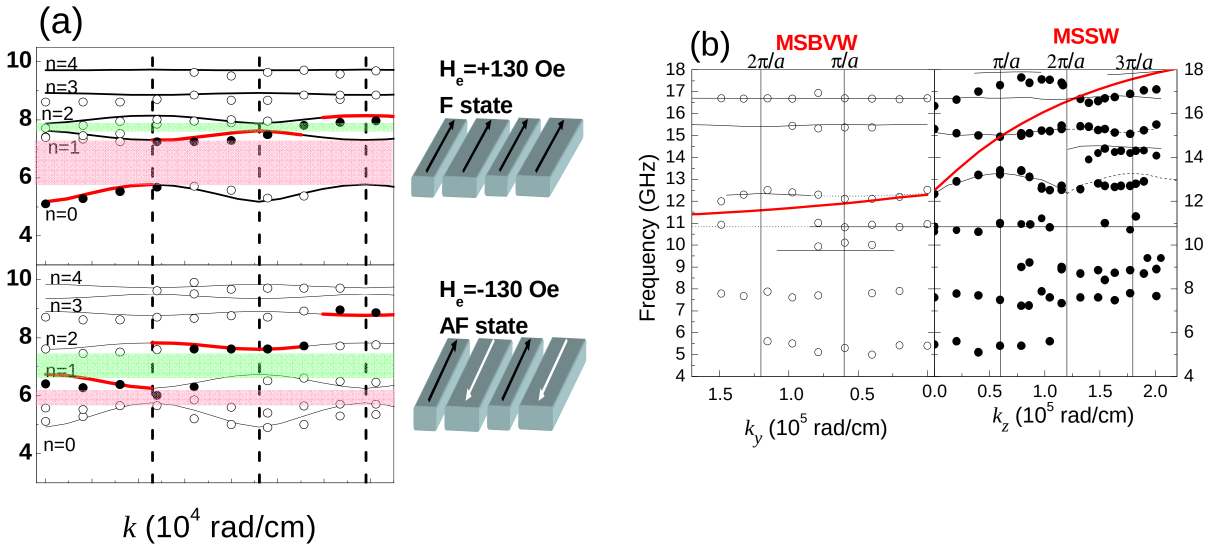

Fig. 3. (a) Sequence of measured (points) and calculated (lines) dispersion curves in the stripes array at two different applied fields. (Upper panel): H= +130 Oe and (Lower panel) H= -130 Oe. Insets show the corresponding ground state of the array at the two different field values. The shadowed areas correspond to the first two forbidden band-gaps. (b) Collective mode dispersion in the square dots array at an applied field H_e= 1.5 kOe measured in the MSSW (full circles) and MSBVW (open circles) configuration. The red curves are the dispersion of the DE mode and BA mode of the continuous film measured in the same experimental conditions. Continuous and dotted curves are the spin-wave dispersions calculated by the numerical simulations described in Ref. [3] and Ref. [4].

The frequency oscillation amplitude is more pronounced for the fundamental collective mode (the lowest frequency mode resonating along the stripes width) and decreases for the highest modes. This is in agreement with our prediction above, which was based on the modes' dipole (stray) fields outside the stripes. The lowest frequency mode has a frequency minimum at the centre of the first Brillouin zone (k=0), where magnetization precession in all stripes is in-phase, while the maximum is reached at its edge (k=$k_{BZ}=\pi/a$) which corresponds to an anti-phase precession of nearest neighbours stripes in the direction of k. An opposite behaviour has been observed for first higher order mode (n=1), which exhibits the maximum and the minimum of the spin-wave frequency at the centre and at the edge of the first Brillouin zone, respectively. It is interesting to note that, the lowest frequency band gap largely reduces passing from 1.5 GHz for the ferromagnetic stripes alignment (H= +130 Oe) to 0.5 GHz in the anti-ferromagnetic one (H= -130 Oe). This suggests the idea that such an array of stripes, with complex unit cell, can be considered as a prototype of a one-dimensional magnonic metamaterial, where the ground state and the consequent dynamic response are field controlled.

Spin wave dispersion measured in the array of squared dots for two different orientation of k-vector with respect to the applied magnetic field reveals a considerable anisotropy of dynamical coupling for propagating collective modes (Fig. 2 (b)). In such a case, the quasi-uniform precession mode (fundamental mode) is not the mode at lowest frequency mode in the spectrum, because of the presence of edge modes, associated to non uniform magnetization of the dots. The fundamental mode propagating perpendicular to the applied magnetic field (MSSW geometry) may acquire considerable group velocities $v_g = d(2\pi\nu)/dk = 1.97\,\mu m/ns$, whereas the mode with Bloch wave vectors along the field are characterized (MSBVW geometry) by negligible velocities $v_g = -0.41\,\mu m/ns$. This can ascribed to the fact that the frequency dispersion of the continuous (unpatterned) film represents the upper and lower limit for the dispersion of collective modes on the periodically-patterned samples. In addition, the static demagnetizing field associated to the lateral confinement, increases the distance between central portion of the dots where the fundamental mode is localized. This makes dynamical dipolar coupling between spin modes of individual elements much more pronounced in the direction perpendicular to the applied field than in the parallel direction.

4. Conclusion

We reviewed the main experimental results obtained by Brillouin light scattering technique for the collective spin-wave excitations in 1D and 2D planar Magnonic Crystal. In the case of stripes array, band-gap tunability has been demonstrated as a function of the applied magnetic field, while for 2D array of dots a considerable anisotropy in the dispersion relation has been observed. We believe these findings will be important for both fundamental and applicative reasons, paving the way to innovative collective responses and novel functionalities of magnonic metamaterials at elevated frequencies.

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