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Research articles

Spin-wave resonances of ferromagnetic films with spatially modulated anisotropy

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ABSTRACT

We study the dynamical properties of a magnetic film with spatially modulated perpendicular anisotropy by numerical simulations. Both topologically charged states (magnetic skyrmions) and uncharged uniform and nonuniform states are considered. The dependences of the ferromagnetic resonance (FMR) spectra on the geometry and material parameters of the system are analyzed. It is found that the spectra contain resonances of the localized and delocalized modes of the magnetization oscillations. In the case of nonuniform states the localized modes have the form of rotating magnetization distributions. The direction of the rotation depends on the local density of the toroidal moment of the state. The magnetic states with different FMR spectra can be easily switched by a temporary applying of a uniform external magnetic field that can be used in the tunable microwave devices.

1. Introduction

Soliton-like magnetization distributions carrying topological charge in magnetic materials are well known since the late 1970s [1,2]. The new rise of the interest to this topic is caused by experimental observation of the topological solitons in the chiral magnets [3–5]. In the case if the direction of magnetic moment of the soliton varies continuously and wraps around a unit sphere the soliton has the topology of a 2D skyrmion. The topological nature of such states affects dynamics of conduction electrons causing unusual spin-electronic properties of skyrmions, such as topological Hall effect [6–9], current-driven motion in ultra-low currents [10,11] and also intrinsic magnetoelectric coupling [12]. Due to these unique characteristics the skyrmions have huge potential to be exploited for spin-based high-dense information storage and processing integrated in the same device [13]. Recently the dynamical properties of the magnetic skyrmions in the alternating electromagnetic fields were also studied because of their potential application in microwave devices. The most attention in this way is paid to the skyrmions naturally stabilized by the Dzyaloshinskii-Moriya interaction (DMI) in the non-centrosymmetric magnetic materials [14–18]. On the other side the skyrmion states can be stabilized even without DMI by the proper spatial nanostructuring of the magnetic films with perpendicular anisotropy. It can be realized by periodical modulation of the magnetic film thickness [19] or its material parameters, for example value of anisotropy [20,21]. Evidently the radio frequency (RF) resonance properties of this system should be different in comparison with DMI-stabilized skyrmion lattices. Besides, nanostructuring opens additional opportunities to artificially tune the RF properties of this system. Our investigation is also inspired by recent development of the novel possibilities for the local measurements of the nonuniform FMR modes in magnetic nanostructures by magnetic resonance force microscopy [22–24].

Here we study the RF dynamical properties of the artificial skyrmion lattices stabilized in the film with spatially modulated perpendicular anisotropy by means of micromagnetic simulations. The aim of our work is to answer two questions. (1) How could the RF properties of this system be tuned by changing geometry and material parameters of the structure? (2) Is there an easy way to control the RF spectra of the system by changing its magnetic configuration? The answers will help to understand the ways of utilization of the artificial skyrmion lattices in the microwave devices.

2. Micromagnetic simulation

The micromagnetic modeling is performed using Object Oriented MicroMagnetic Framework (OOMMF) software [25] based on a numerical solution of the system of Landau-Lifshitz-Gilbert (LLG) equations for the magnetization:

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$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma[\mathbf{M} \times \mathbf{H}_{eff}] + \frac{\alpha}{M_s}\left[\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}\right], \quad (1)$$

where **M** is the magnetization, γ is the gyromagnetic ratio, α is the dimensionless damping parameter, and M_s is the magnetization at saturation. The effective field

$$\mathbf{H}_{eff} = -\frac{\partial E}{\partial \mathbf{M}}, \quad (2)$$

is a variation derivative of the energy. According to the Eq. (1) in the limit of small dumping the value of the effective field determines the frequency of the ferromagnetic resonance as

$$\omega = \gamma H_{eff}. \quad (3)$$

Usually the total energy E of the magnetic system is defined as

$$E = E_h + E_{ex} + E_{dem} + E_a. \quad (4)$$

Here E_h is the energy of the interaction between the magnetization and an external magnetic field, E_{ex} is the energy of the exchange interaction, E_{dem} is the demagnetization energy of the system and E_a is the energy of the magnetic anisotropy. Expressions for these terms have a conventional form [26,27]. In the simulations the geometric configuration and the material parameters of the system are chosen correspondingly to the recent experiments [21] where the dense artificial skyrmion lattice is observed. The considered system is the magnetic film with perpendicular anisotropy which value is locally decreased in some areas. The areas with the decreased anisotropy are the circular spots arranged in the rectangular lattice (Fig. 1). In the simulations we use an elementary cell of such lattice infinitely extended in the plane using 2D periodic boundary conditions. The circular area with the changed anisotropy is located in the elementary cell center and has the diameter twice less than the cell size. The film thickness is 7.5 nm, the elementary cell size is 100 or 200 nm, so the area with the reduced anisotropy has the diameter 50 or 100 nm respectively. The material parameters for simulation correspond to Co/Pt multilayers [21], the magnetization in saturation M_s = 200 G, the initial uniaxial anisotropy of the film $K_0 = 3.65 \times 10^5$ erg/cm^3, and the exchange coefficient $A = 2.5 \times 10^{-8}$ erg/cm. The chosen value of the anisotropy coefficient corresponds to the easy-axis direction of the magnetization in the film. The simulation grid size of $2.5 \times 2.5 \times 7.5$ nm^3 is less than the exchange length.

Whereas the anisotropy of the film should be perpendicular to realize skyrmion lattice, the anisotropy in the spot can vary in wide ranges. If it is still perpendicular the skyrmion takes the form of the small magnetic bubble domain (denoted as MB in Fig. 1b). We simulate this situation for two values of K_1 equal to 2.8×10^5 erg/cm^3 and 2.4×10^5 erg/cm^3. This allows us to study the influence of the anisotropy value on the FMR spectra of the system.

For the smaller K_1 when the effective anisotropy (together with demagnetizing) becomes of the easy plain type, the topologically charged skyrmionic state can be realized as a vortex inside the central spot surrounded by perpendicularly magnetized film. If the vortex core is directed oppositely to the film magnetization (denoted as OV in Fig. 1b) it carries the topological charge equal to + 1. Vice versa the topological charge of the system is equal to zero if the vortex core is codirectional to the film magnetization (denoted as CV in Fig. 1b). So this codirectional vortex is not a skyrmion [20].

These states of the system are simulated with $K_1 = 10^5$ erg/cm^3. The magnetization is supposed to be uniform in the perpendicular direction. All simulated magnetic states are represented in Fig. 1. For the reference we name examined states as "uniform" (UN), "magnetic bubble" (MB), "opposite magnetic vortex" (OV), and "co-directional vortex" (CV). There are the schematic pictures of the magnetization configuration as well as the distribution of the

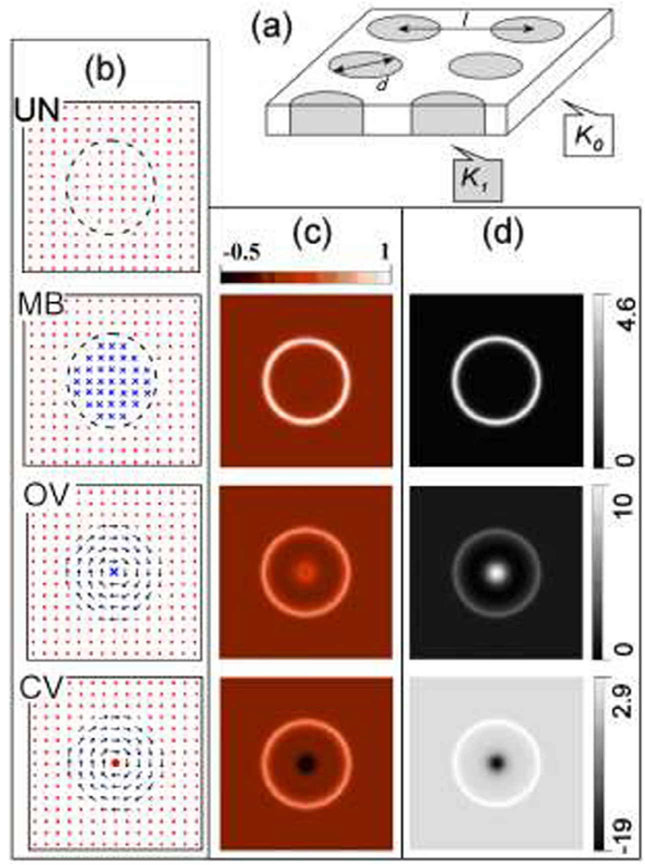

Fig. 1. (a) The geometry of the simulated system. The spots with the reduced anisotropy (diameter d) form a rectangular lattice (period l). (b) Four possible magnetization configurations of the system. UN is uniform state, MB is magnetic bubble, OV is opposite vortex (magnetization of the core is opposite to the film magnetization), CV is co-directional vortex (magnetization of the core is codirectional to the film magnetization). Points (red) and crosses (blue) denote the magnetic moments directed perpendicular to the film plain in the opposite directions (up and down respectively). Dashed circle is the boundary of the central area. (c) The distributions of the toroidal moment density .in the MB, OV and CV states respectively. (d) Distributions of the topological charge density (in 10^{-4}) of the same states. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

topological charge density in the corresponding state. The topological charge density is defined as [7]

$$\phi(x,y) = \frac{1}{4\pi}\mathbf{n}\frac{\partial \mathbf{n}}{\partial x} \times \frac{\partial \mathbf{n}}{\partial y}, \quad (5)$$

where $\mathbf{n} = \mathbf{M}(\mathrm{r})/|\mathbf{M}(\mathrm{r})|$ is the unit vector of local orientation of the magnetization. Evidently in the case of the uniform state $\phi \equiv 0$. The topological charge defined as the integral of the topological charge density ϕ (x,y) over the system surface is equal to 1 for MB and OV, so they are skyrmions [20]. In these two states the magnetization is continuously changed from up direction in the center to down at the periphery in all radial directions away from the center. It wraps a sphere pointing in all directions as it is usual for the 2D magnetic skyrmion. In the case of the MB the skyrmion charge density is concentrated near the 180° Bloch domain wall, while in the case of the OV the topological charge is the sum of vortex core topological charge (1/2) and the charge of 90° domain wall between the vortex and the periphery (also 1/2). In the CV the topological charge of vortex core (1/2) is totally compensated by the topological charge of wall between the vortex and the periphery (−1/2). So CV is topologically uncharged state. It can be continuously deformed to the uniform state where $\phi \equiv 0$ in every point.