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Dynamic excitation of 2π vortex in a hard/soft bilayer nanodot

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Abstract. The dynamic behaviors of 2π vortex in nanodot driven by microwave magnetic fields is investigated by micromagnetic simulations. The spin dynamics are analyzed by extracting the magnetic excitation spectrum from Fourier transform. Four resonance peaks are observed. Domain-wall resonance mode has been identified at the domain wall in the lowest frequency of the spectrum and a set of high-frequency spin wave excitations above 4.83 GHz. The resonant mechanism and associated underlying physics are completely different from those of vortex core with rotational mode. These results distinguish a 2π vortex from other spin-texture objects in dynamics and will be instrumental to the excitation of vortex for applications.

Introduction

A better understanding of magnetization dynamics in nano-scale magnets is essential for both their fundamental and technological investigations, which have been a hot subject of research in the fields of nanomagnetism and spintronics [1-3]. The excitation modes in the gigahertz regime of spatially non-uniform ground states in magnetic elements are also relevant for the high-density memories and logic devices [4]. An interesting example is the magnetic vortex state, where the magnetization is pointing out of the film plane, surrounded by in-plane magnetization [5]. When excited by a magnetic field, vortex exhibit a rich variety of fundamental dynamic [6]. Generally, the magnetization distribution of a vortex features gyrotropic precessional modes associated with the translational motion [7, 8]. Here, we present a numerical study of the microwave-frequendcy dynamics in a hard/soft bilayer nanodot with 2π-vortex texture, where the inner domain is upward magnetized, whereas the outer domain is downward magnetized. In addition, the magnetization rotates in the plane perpendicular to the radial direction. We show that multiple resonant dynamics can occur in such bilayer nanodot due to the spin texture. The low-frequency peak are characterized by domain-wall mode. We verify numerically that the existence of these high-frequency excitations is identified as spin-wave modes.

Model and methods

It is known that the spin structures in a micromagnetic system are governed by the competition of exchange energy, dipole-dipole energy and magnetocrystalline anisotropy energy. To achieve 2π-vortex elements, it is important to be able to control the geometries and magnetic parameters. We adopt an exchange-coupled hard/soft multilayer nanodot as shown in Fig. 1(a), so that the magnetization is constrained with the interface and the local dipolar interaction. The micromagnetic simulations were performed by using the OOMMF code [9]. We have set the dimensions of these cells to 4 nm × 4 nm × 1 nm, which is lower than the value of the exchange length. The material parameters of hard layer chosen include saturation magnetization $M_s = 6.9 \times 10^5$ A/m, exchange stiffness $A_{ex} = 1 \times 10^{-11}$ J/m, and uniaxial anisotropy constant $K_u = 4 \times 10^5$ J/m^3 with the direction perpendicular to the nanodot plane. For soft layer the saturation magnetization was $M_s = 8.6 \times 10^5$ A/m, the exchange stiffness was $A_{ex} = 1.3 \times 10^{-11}$ J/m, and the anisotropy was negligible. An

interlayer exchange constant between hard and soft layer of 1.1×10^{-11} J/m was also used. We assume a damping constant of 0.5 to reach convergence quickly in static magnetization configurations. To study the dynamics, an external microwave magnetic field was applied along perpendicular direction of the nanodot. We recorded the magnetization dynamics over 40 ns, with data taken every 10 ps, using a smaller value of the damping constant $\alpha = 0.01$, which allowed for better frequency resolution of the excited modes.

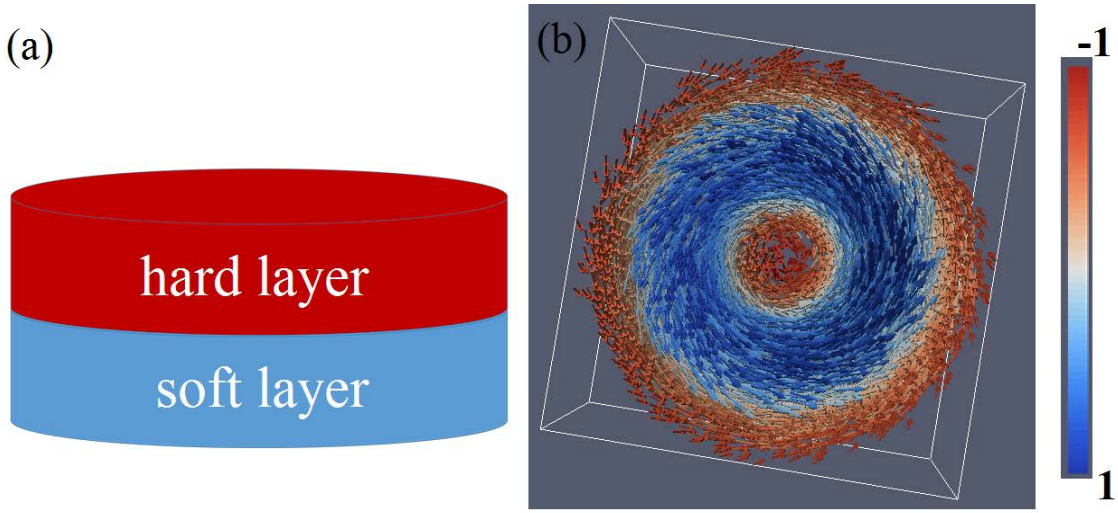

Fig. 1 (a) Calculation model for the hard/soft bilayer nanodot. (b) Magnetization distribution of the bilayer nanodot. The colors represent the magnitude of the out-of-plane magnetization component and the arrows indicate the direction of the magnetization component at every point.

Results and discussion

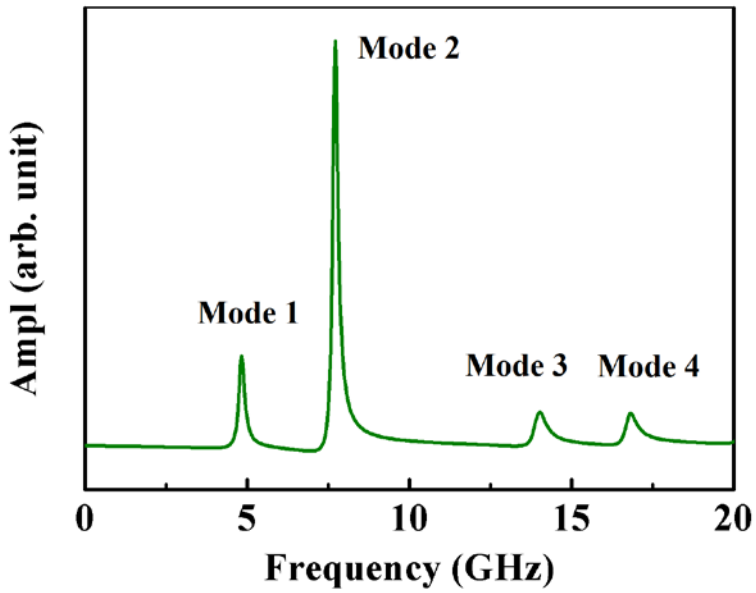

Fig. 2 The fast Fourier transform spectrum for the hard/soft bilayer nanodot. The mode numbers are shown in the simulated spectrum.

Coupled bilayer nanodot with 2π-vortex spin texture has been obtained without taking into account the Dzyaloshinsky-Moriya interaction, as shown in Fig. 1(b). After a perturbation applied on the static magnetization, the time evolution of the magnetization of each cell is calculated. The discrete-time Fourier transform (DTFT) is then performed on the time evolution of the out-of-plane component of magnetization in each cell. Figure 2 show the calculated spectra for the 2π-vortex state in the hard/soft bilayer nanodot excited by out-of-plane microwave field. From the simulated data a clear multi-resonance mode is observed. Four resonance peaks can be seen, located at 4.83 GHz, 7.71

GHz, 14.01 GHz and 16.82 GHz, respectively, as a consequence of the highly nonuniform oscillations. The second peak has the highest intensity, while the peak at the lower frequency is also significantly intense as compared to the main peak. Mode 3 and 4 are of very low intense, which appear at much higher frequencies.

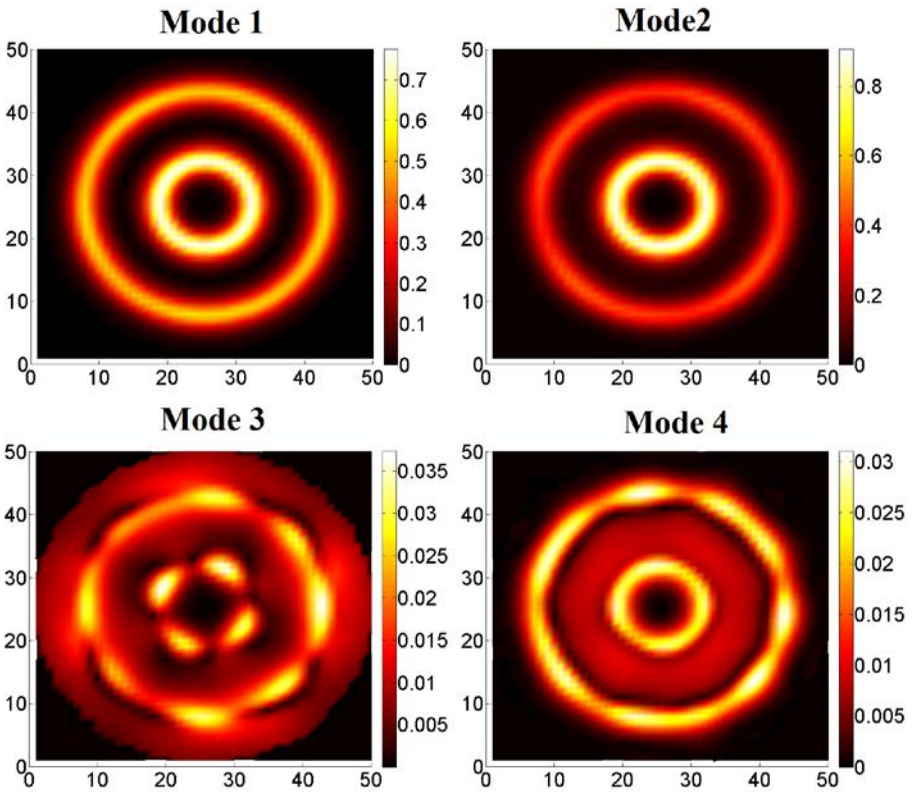

Fig. 3 The amplitude of the dynamic magnetization vector components in Mode 1, 2, 3 and 4, respectively.

The spatial distribution of the amplitude of the dynamic magnetization vector according to the resonant modes in fig. 2 are shown in fig. 3. The DTFT values was plotted at the frequencies of interest versus x and y. For the lowest-frequency peak (Mode 1), the mode is strongly localized at two circular rings and is equivalent to the domain-wall mode in 2π vortex. We found that this behavior is consistent with the ones observed for the Bloch-type excitation in thin films with perpendicular anisotropy [10]. The domain wall mode has lower frequencies than the modes with amplitude over the whole nanodot. For higher frequency, the amplitude of 7.71 GHz mode is distributed at the center and around an inner circle, corresponding to the eigenfrequency of the radial mode. In contrast, instead of being continuous along the azimuthal direction as in a circular vortex, the Mode 3 is discretized in a pattern consistent with the symmetry of the nanodot. It is obviously observed that the azimuthal modes change phase around the center of the vortex, which is parallel to the static magnetization. As the frequency increases, Mode 4 is the combination of radial and azimuthal modes, where the phase changes not only radially, but also around the center.

Summary

In summary, the magnetic dynamic properties of 2π vortex have been investigated by numerical simulations for a broad range of microwave frequencies. The precessional modes of magnetization are analyzed by the time-dependent simulation method, Fourier transform spectrum and the phase profiles of the resonant modes. In the magnetic excitation spectrum, we observe four resonance modes, evidencing that the uniform magnetic structure is the intrinsic origin of microwave dynamics. We further study the sπn dynamics by the phase profile calculated from Fourier transformation. Mode 1 corresponds to a strongly nonuniform mode concentrated at the domain wall. However, spin-wave

modes are observed in Mode 2, 3 and 4. Our results can be very useful for the identification of the non-uniform ground state and to understand the fundamental physics of the dynamical properties of 2π-vortex.

Acknowledgements

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