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Ferromagnetic Resonance in Square Lattices of Planar Magnetic Cross-Shaped Elements

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Abstract—Ferromagnetic resonance (FMR) in planar thin film structures comprised of magnetic cross-shaped elements arranged into square lattices has been studied by micromagnetic simulation. FMR spectra and spatial distributions of amplitudes of resonant oscillations were determined for vortex and antivortex states of magnetization in lattice crosses. Resonant modes have the shape of rotating magnetization distributions. Herewith, modes with the same configuration of magnetization but rotating in reverse directions are frequency split. The observed nonreciprocity of propagation of resonant spin oscillations is determined by the sign of magnetization distribution vorticity.

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INTRODUCTION

Artificial patterning of ferromagnetic thin film items by e-beam lithography provides considerable capabilities for the creation of nanostructures with heterogeneous distribution of magnetization [1–4]. Such structures attracts great attention both for investigation into features of spin dependent electron transport and propagation of spin waves, and for their application aimed at development of data storage systems, magnetic logic elements, and planar SHF nanoelectronics [5–7]. Magnetization distributions in the form of magnetic vortices and antivortices are especially interesting due to their unusual topological properties [1–3, 8]. Such distributions are characterized by vorticity n and spirality γ [8]. Vorticity is determined by rotation direction of magnetization vector upon bypassing core about closed circuit and equals to $+1$ for vortex and -1 for antivortex. Spirality is relate with the angle between radius vector originated in the core and magnetization direction [8]. Vortex and antivortex magnetization distribution are experimentally implemented in ferromagnetic cross-shaped structures [1–3].

This work investigates into FMR spectra and mode composition of spin wave resonance in square lattices comprised of cross-shaped elements with vortex and antivortex states of magnetization.

EXPERIMENTAL

Micromagnetic simulation was based on the numeric solution of the he Landau–Lifshitz–Gilbert equation of magnetization using Object Oriented MicroMagnetic Framework (OOMMF) [9]. The sizes of one cross-shaped lattice element were 500 × 500 × 30 nm. The cross bar width was 100 nm. The calculations were based on material parameters corresponding to permalloy ($Ni_{80}Fe_{20}$): saturation magnetization 8×10^5 A/m, exchange constant 8.4×10^{-12} J/m. This selection is stipulated by the fact that permalloy is one of the main materials for metallic UHF devices because it has sufficiently low decay coefficient of magnetization oscillations ($\alpha = 0.01$ [10]).

Minimum simulated region had the sizes of 1 × 1 μm, it combined four cross-shaped elements (Fig. 1). Lattice elements were simulated on the basis of periodic boundary conditions for minimum region. Such selection of the region makes it possible to simulate magnetization distribution with the period exceeding geometrical lattice constant of vortices and antivortices with alternating spirality. Cell size of numeric lattice was 5 × 5 × 30 nm. This cell size was selected because in this work we do not consider waves propagating along the element width.

The numeric experiment was carried out as follows. Initially the system was equalized, then it was affected by alternating magnetic field h with the amplitude of 0.1 mT at the angle of 45° to the axis of cross bars, and average amplitude of the established magnetization amplitude was recorded. The frequency of exciting UHF field varied in the range from 0 to 15 GHz in increments of 0.1 GHz (in the region of resonant peaks—in increments of 0.01 GHz). No external constant magnetic field was applied. Mode resonant composition was analyzed by spatial distributions of oscil-

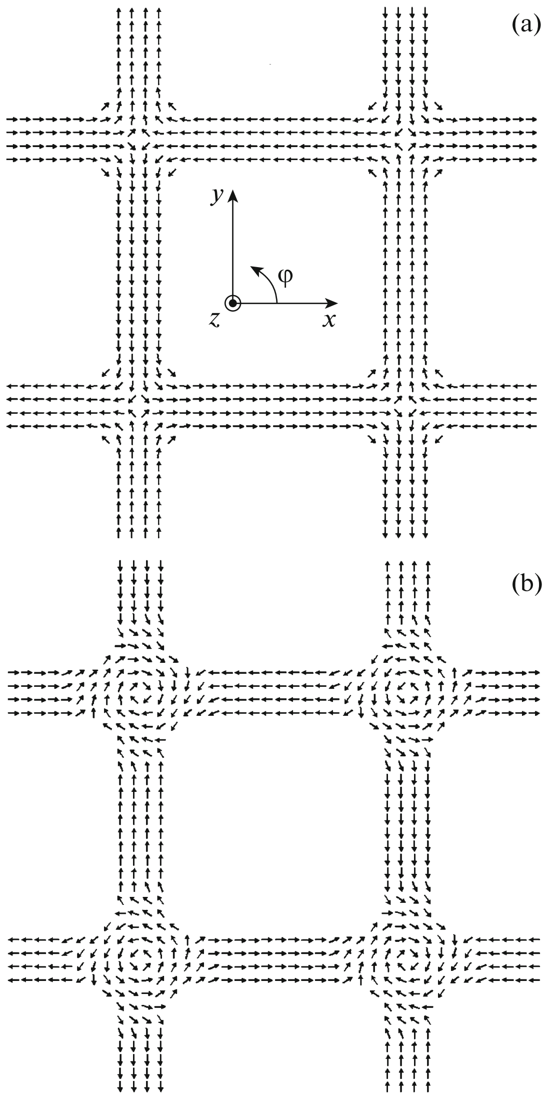

Fig. 1. Magnetization distribution in minimum cell of square lattice for antivortex (a) and vortex (b) states.

lations of z component of magnetization: $m_z(x, y)$ and oscillation amplitude $m(x, y)$ calculated as follows:

$$m = \sqrt{m_x^2 + m_y^2 + m_z^2},$$

where m_x, m_y, and m_z are the amplitudes of projections of magnetization [11].

RESULTS AND DISCUSSION

Calculations were carried out for two different magnetization states in cross-shaped elements: antivortex (Fig. 1a) and vortex (Fig. 1b). In the latter case vortices are intentionally swirled in different directions in order to illustrate that FMR spectrum does not depend on vorticity. For both cases the cores are directed against z axis (from us).

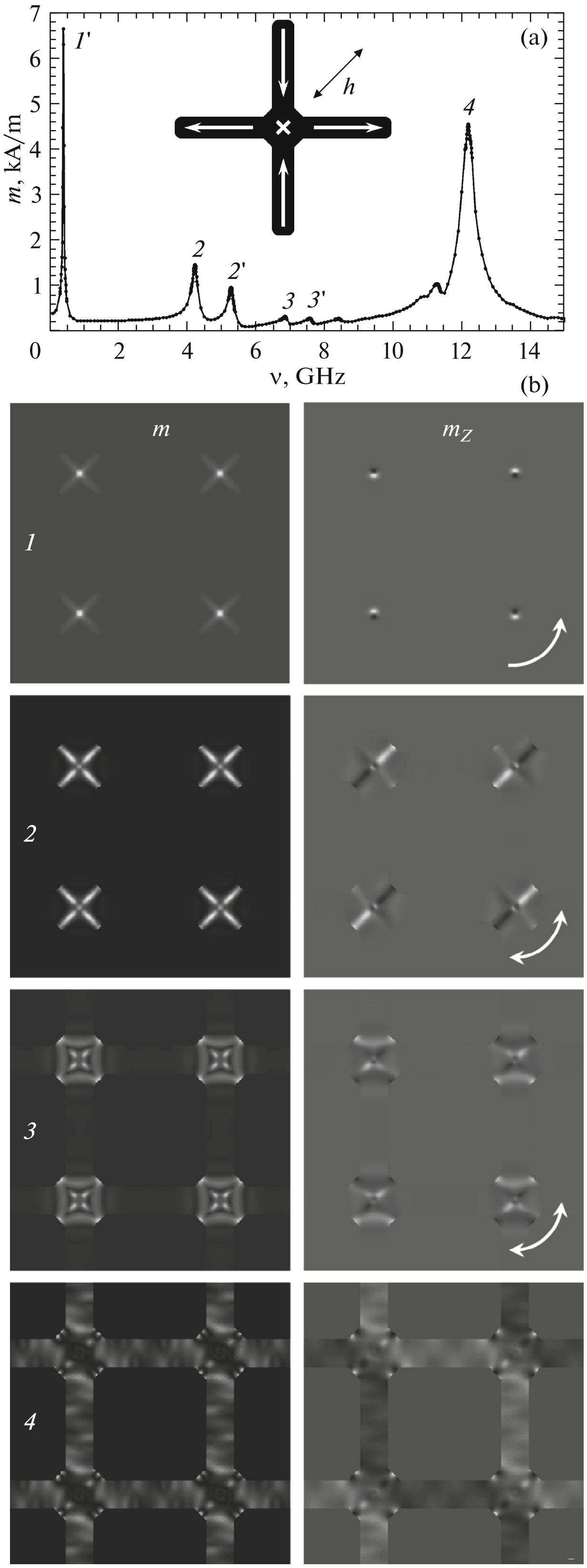

Fig. 2. (a) FMR spectrum of square lattice with antivortex distribution of magnetization, (b) distribution of amplitudes m and m_z of magnetization variable constituent corresponding to the numbered resonant peaks of FMR spectra.

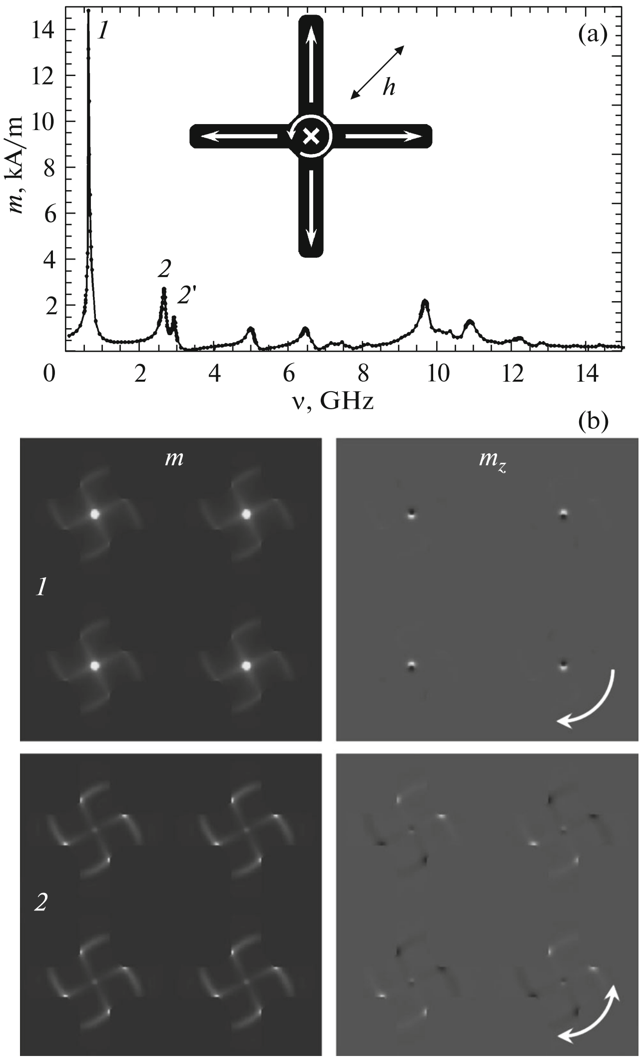

Fig. 3. (a) FMR spectrum of square lattice with vortex distribution of magnetization, (b) distribution of amplitudes m and m_z of magnetization variable constituent corresponding to the numbered resonant peaks of FMR spectra.

FMR lattice spectrum with antivortex states and spatial distributions of oscillation amplitude corresponding to resonant modes are illustrated in Fig. 2. Major portion of resonances in this system could be appropriately classified along the rotation direction of magnetization distribution about the center of symmetry (the core center): +φ (oscillating magnetization distribution rotates counterclockwise towards the core) and –φ (oscillation mode rotates clockwise towards the core). Peak 1' corresponds to the core precession of antivortex and its surrounding. This precession takes place along the direction +φ. Subsequent resonances are split. Modes 2 and 2' are characterized by similar spatial structure but different rotation direction, the mode corresponding to peak 2 rotates towards –φ, and that corresponding to peak 2' towards +φ. The situation is similar for peaks 3 and 3'. Peak 4 corresponds to quasi-homogeneous resonance [12, 13] of cross bar magnetization.

FMR spectrum and resonance modes for lattice of cross-shaped elements in vortex state are illustrated in Fig. 3. Peak 1 (Fig. 3a) is similar to peak 1' (Fig. 2a), but in this case the core precession takes place towards –φ. Peaks 2 and 2' correspond to the resonances where magnetization changes from the vortex distribution in cross center to homogeneous distribution in cross bar. Mode 2 rotates towards –φ and mode 2' towards +φ. It should be mentioned that in the case of antivortex magnetization distribution the modes rotating towards –φ are below in terms of frequency than those rotating towards –φ. Precession of core and its surrounding is directed towards +φ. The reverse situation is observed for vortex distribution: the minimum frequency is characteristic for modes rotating towards +φ and precession of core and its surrounding is directed towards –φ. Directions of mode rotation do not depend on the sign of spirality for the vortex state. Since the rotation directions of vortex and antivortex cores in calculations coincided, such difference in resonant frequencies is probably related to the different vorticity of vortex and antivortex distributions of magnetization.

CONCLUSIONS

Therefore, micromagnetic simulation of FMR was carried out in lattices of magnetic cross-shaped elements with vortex and antivortex states of magnetization. For both magnetic states it is possible to observe excitation of modes rotating about the core center. These modes are split in frequencies and differ in rotation direction (+φ and –φ). Direction of core resonant precession as well as the ratio of resonant frequencies of rotating modes and direction of their rotation are determined by the sign of vorticity and do not depend on the sign of spirality of vortex and antivortex distributions of magnetization.

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