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MAGNETISM

Localized Spin-Wave Resonance Modes of Ferromagnetic Microstrips in the Field of a Magnetic Probe

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Abstract—Some results of the micromagnetic modeling of forced magnetization oscillations in planar microstrips of NiFe with easy plane anisotropy and Co/Pt with perpendicular easy axis anisotropy in the field of a magnetic spherical probe are considered. It has been shown that the probe field provokes the appearance of a hedgehog–antivortex coupling state in the NiFe strips, due to its lateral components and a skyrmion magnetization state in the Co/Pt layer. These effects destroy spatial magnetization oscillations in the microstrips and lead to the appearance of additional resonances in the spectrum of oscillations corresponding to the modes localized in the probe field.

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1. INTRODUCTION

In recent years, a great deal of attention has been paid to the study of local ferromagnetic resonance (FMR) modes produced by the effect of the nonuniform field of a magnetic-resonance force microscope (MRFM) probe on thin-film ferromagnetic specimens [1–3]. On the one hand, such a probe effect leads to undesirable distortions in the character of magnetization oscillations in studied objects; however, on the other hand, the conditions of strong interaction between a probe and a specimen enable the implementation of new methods of studying the local super-high-frequency (SHF) properties of ferromagnetic structures [4–6]. In this work, the specific features of the effect of a magnetic spherical probe on the magnetization oscillations in test specimens shaped as thin-film ferromagnetic microstrips with easy plane and perpendicular easy axis anisotropies were studied by micromagnetic modeling methods.

2. METHOD OF CALCULATIONS

Micromagnetic modeling was based on the numerical solution of the Landau–Lifshitz–Gilbert equation for the specimen magnetization with the Object Oriented MicroMagnetic Framework (OOMMF) software suite [7]. The used test objects were rectangular microstrips of 2000 × 1000 × 10 nm in size. Calculations were performed for two different systems. The first system represented a permalloy ($Ni_{80}Fe_{20}$) microstrip with the following parameters: saturation magnetization $M_{\mathrm{NiFe}} = 8 \times 10^5$ A/m, exchange constant $A_{\mathrm{NiFe}} = 1.3 \times 10^{-11}$ J/m. The second system was a multilayered Co/Pt structure with perpendicular anisotropy and the following parameters: saturation magnetization $M_{\mathrm{CoPt}} = 8 \times 10^5$ A/m, exchange constant $A_{\mathrm{CoPt}} = 10^{-11}$ J/m, and anisotropy parameters $K = 6 \times 10^5$ J/m^3 [8, 9]. In calculations, the dissipation parameter was 0.01. The field of a Co ball with uniform magnetization along axis z (Fig. 1) was selected as a model MRFM probe field. The probe diameter of 200 nm corresponded to the typical dimensions of MRFM probes [10, 11]. Specimen magnetization oscillations were studied in an alternating magnetic field h of 0.1 mT oriented along axis y in the plane of a specimen. The time dependences of steady-state oscillations in all the magnetization components were determined in the process of calculations [12]. The exciting SHF field frequency ν was changed with a step of 0.1 GHz. To analyze the spectra of oscillations, the frequency dependences of the system-average amplitude of alternating magnetization component oscillations

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

were plotted.

To analyze the mode composition of resonances, the time implementations of the spatial amplitude distributions of alternating magnetization component oscillations under pumping at resonance frequencies were calculated [13, 14].

3. RESULTS AND DISCUSSION

First, we studied ferromagnetic resonance in a NiFe microstrip in the absence of a probe. A uniform

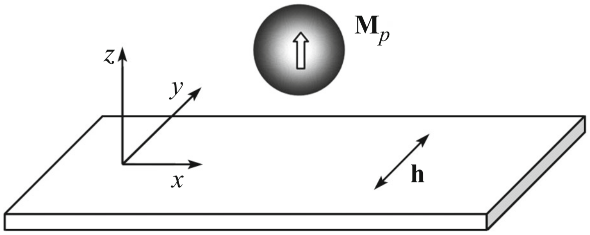

Fig. 1. Schematic view of a magnetic probe over a ferromagnetic strip.

state was created in this strip by applying a constant magnetic field of 30 mT along its long side (axis x). The spectrum of magnetization oscillations is shown in Fig. 2a. This spectrum has three characteristic resonance peaks. The first peak corresponds to the magnetization oscillation mode localized near the microstrip edge (Fig. 2b). The second resonance at a frequency of 5.5 GHz represents a superposition of standing magnetostatic and exchange spin waves with different wave vectors k_x (Fig. 2c) [14]. The third resonance is a superposition of standing spin waves with different wave vectors k_x and k_y (Fig. 2d).

When the probe is moved more closely to a specimen, its field first indicates small microstrip magnetization disturbances, leading to reversal magnetization effects at rather short probe–specimen distances (<40 nm) [15]. As a result, the effect of the lateral probe field components leads to the formation of a nonuniform hedgehog–antivortex state in a microstrip (the magnetization distribution over the microstrip area in the vicinity of the probe is shown in Fig. 3a). The effect of the probe shifts the major resonance towards the low-frequency spectrum region (Fig. 3b). In this case, the resonance of edge modes is complemented with the low-frequency resonance of an antivortex state (Fig. 3c), and the major oscillation and spin-wave resonance modes are deformed (Figs. 3d and 3f, respectively). Moreover, additional resonance peak *3* corresponding to the oscillation mode shown in Fig. 3e appears in the FMR spectrum.

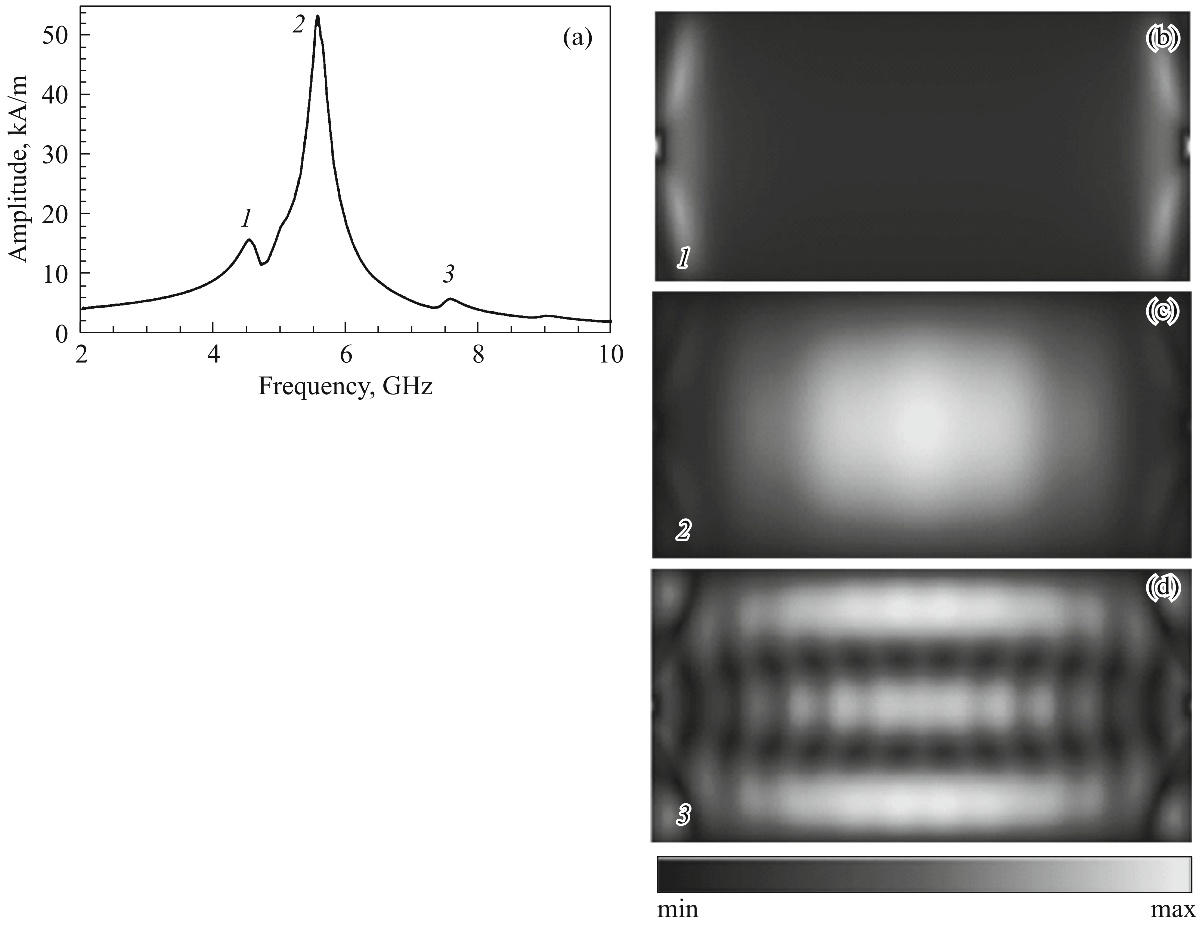

Fig. 2. (a) Spectrum of magnetization oscillations in a uniformly magnetized NiFe strip and (b–d) normalized spatial distributions of the magnetization oscillation amplitude for resonance peaks *1*–*3* in the spectrum shown in Fig. 2a.

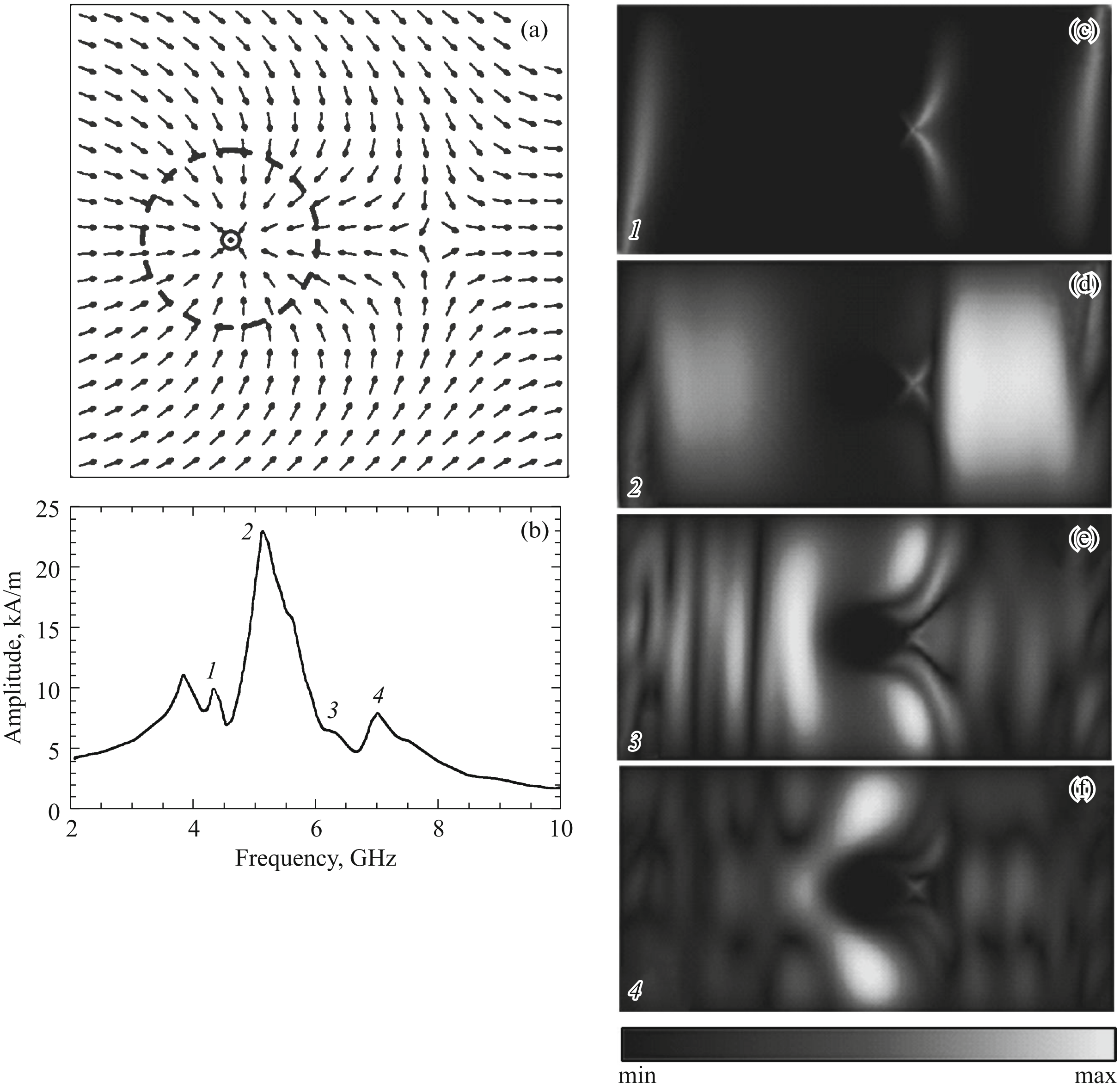

Fig. 3. (a) Magnetization distribution over a 450 × 450-nm NiFe microstrip area located immediately under the MRFM probe (its position over a specimen is shown as a dashed outline), (b) spectrum of magnetization oscillations in a NiFe strip in the probe field, and (c–f) normalized spatial distributions of the magnetization oscillation amplitude for resonance peaks *1*–*4* of the spectrum shown in (b).

Similar effects are observed in the Co/Pt microstrip with perpendicular magnetization. In the absence of a probe, the oscillation spectrum of the strip in a uniformly magnetized state contains a number of resonances of different order (Fig. 4a). The major resonance (peak *1*) corresponds to quasi-uniform magnetization precession (Fig. 4b). The two others are spin-wave resonances of higher order (Figs. 4c and 4d). The probe field first provokes small microstrip magnetization disturbances and leads to reversal magnetization effects at a short probe–specimen distance [16]. For the considered parameters of the system, the critical distance was 40 nm. In this case, probe magnetic field symmetry promotes the formation of a skyrmion state in a Co/Pt strip (Fig. 5a). Such an effect of the probe leads to a shift of the major resonance to the high-frequency spectrum region (Fig. 5b) and distorts the spatial distribution of oscillation in the major mode (Fig. 5c). Moreover, the reversal magnetization effect leads to the appearance of an additional resonance peak corresponding to the magnetization oscillation mode shown in Fig. 5d in the FMR spectrum (Fig. 5b, peak *2*).

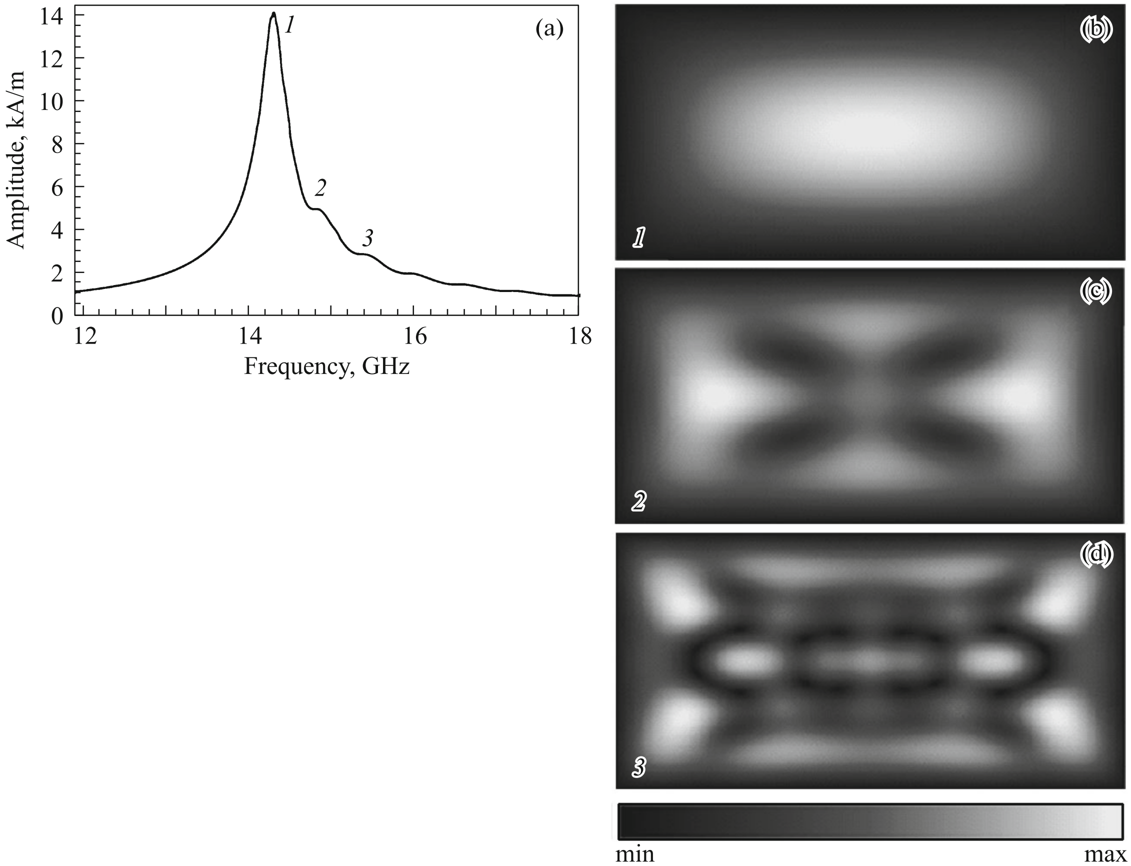

Fig. 4. (a) Spectrum of magnetization oscillations in a uniformly magnetized Co/Pt microstrip and (b–d) normalized spatial distributions of the magnetization oscillation amplitude for resonance peaks *1*–*3* of the spectrum shown in (a).

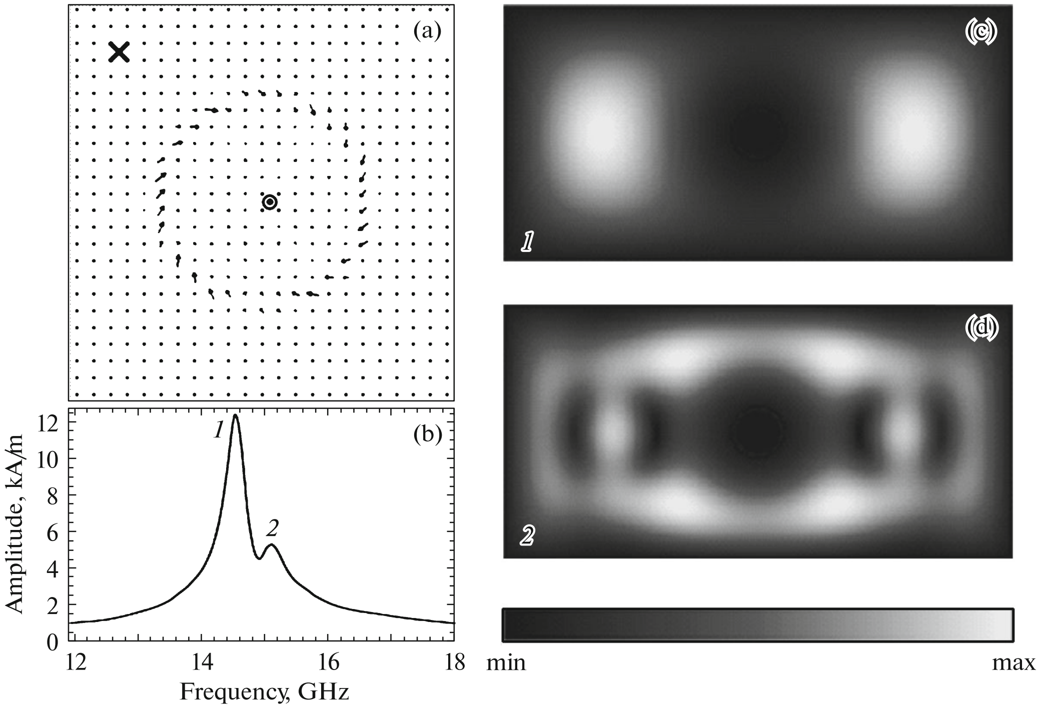

Fig. 5. (a) Magnetization distribution over a 700 × 700-nm Co/Pt microstrip area located immediately under the MRFM probe. Magnetization is oriented upwards (along axis z) in the central area and in the opposite direction in the periphery. (b) Spectrum of magnetization oscillations in a Co/Pt strip in the probe field and (c–d) normalized distributions of the magnetization oscillation amplitude for resonance peaks *1* and *2* of the spectrum shown in Fig. 5b.

4. CONCLUSIONS

Hence, we have performed the micromagnetic modeling of the effects of a MRFM probe nonuniform field on the spectra and spatial structure of magnetization oscillation modes for NiFe microstrips with easy plane anisotropy and microstrips of multilayered Co/Pt structures with perpendicular easy axis anisotropy. It has been shown that there occurs local reversal magnetization in specimens at short probe–specimen distances. This leads to the appearance of a hedgehog–antivortex coupling state in permalloy strips due to the lateral probe field components and an additional resonance corresponding to the localized magnetization oscillation mode in the FMR spectrum. A skyrmion magnetization state is implemented in the Co/Pt strip, and this is accompanied by the appearance of an additional resonance produced by magnetization oscillations in the probe field. These effects must be taken into account in the MRFM studies of ferromagnetic films with different types of anisotropy.

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