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Influence of shape effects on the spectrum of spin waves in finite array of ferromagnetic pillars

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The aim of this paper is to investigate the frequency characteristics of spin waves [1, 2] in the array of ferromagnetic pillars. We estimate the influence of shape effects on frequency characteristics of single ferromagnetic nanopillar. The magnetization oscillations affected by the external magnetic field are obtained from the solution of Landau–Lifshitz–Gilbert (LLG) equations, that are solved numerically using the MuMax3 micromagnetic simulation program [3]. This magnetization distribution in time and space domains provides us with the information about the eigenfrequencies characteristic in different parts of the pillars, since their magnetization, internal demagnetizing and effective magnetic fields are non-uniformly allocated in the volume of the pillar. The calculations are performed for the permalloy ferromagnetic nanopillars [4], with following geometric parameters of pillars: the radius $R = 25\,\text{nm}$ and the height $h = 4R$. The external magnetic field $\mu_0 H^{\text{ext}} = 0.1\,\text{T}$ is applied along the z-axis (Fig. 1a, b). The excitation is introduced in the form of magnetic field short pulse with circular polarization in (x, y)-plane $\mathbf{h}^{\text{ext}}(t) = (\cos(2\pi f_{\text{ext}} t), \sin(2\pi f_{\text{ext}} t), 0) \times \times h^{\text{ext}}/\sqrt{2\pi}\,\text{Exp}[-(t-t_0)^2/(2\sigma^2)]$, with the pulse width $\sigma = 0.1\,\text{ns}$.

Due to the shape effects, there are two resonance frequencies f_1 and f_2 of magnetization oscillations for a single isolated pillar. These eigenmodes of magnetic oscillations are separated into "bulk" and "edge" modes [5], and localized in the middle and near surfaces of the pillar, correspondingly.

The frequency characteristics of spin waves are investigated in finite linear chains of total $N = 7$ ferromagnetic pillars with dipole-dipole interaction between them. In this case the additional inhomogeneity in effective magnetic fields and magnetization inside pillars is present at the edges of the chain. The Fourier transformation of the value $m_x(t)$ averaged over different regions of the pillar in the chain of $N = 7$ pillars (Fig. 1c, d). The magnetization oscillation amplitude $m_x(f)$ dependence on frequency shows 3 main resonance frequencies: f_{ext} – the frequency of the external magnetic field $\mathbf{h}^{\text{ext}}(t)$, f_1 and f_2 – two resonance frequencies of oscillations in ferromagnetic pillar. The frequency $f_{\text{ext}} = 14\,\text{GHz}$ is chosen to be outside of resonance eigenfrequencies f_1 and f_2.

If the chain of magnetic pillars is finite [6–9], then the edge spin wave modes exist with resonance frequency that is greater than the resonance frequency of the spin wave mode on the frequency f_1. This relation is valid for frequencies f_1 and f_e (Fig. 1c, d). The effect is similar to one described in theoretical study [10], which was formulated for macrospin approximation of the pillars and was not taking into account shape effects inside pillars. Additionally, the excitation of spin waves by the means of spin-polarized current pulse is possible, if the polarization vector is oriented in the (x, y)-plane. Without the harmonic components in the external magnetic field, only one resonance frequency f_1 is present for the spin waves.

For cylindrical pillars with finite heights it was shown that the demagnetization and shape effects lead to the appearance of two resonance frequencies for eigenmodes of magnetization oscillations. For the spin waves in such chains additional resonance frequency exists for the edge mode of the spin wave, that is localized at the edge of the chain.

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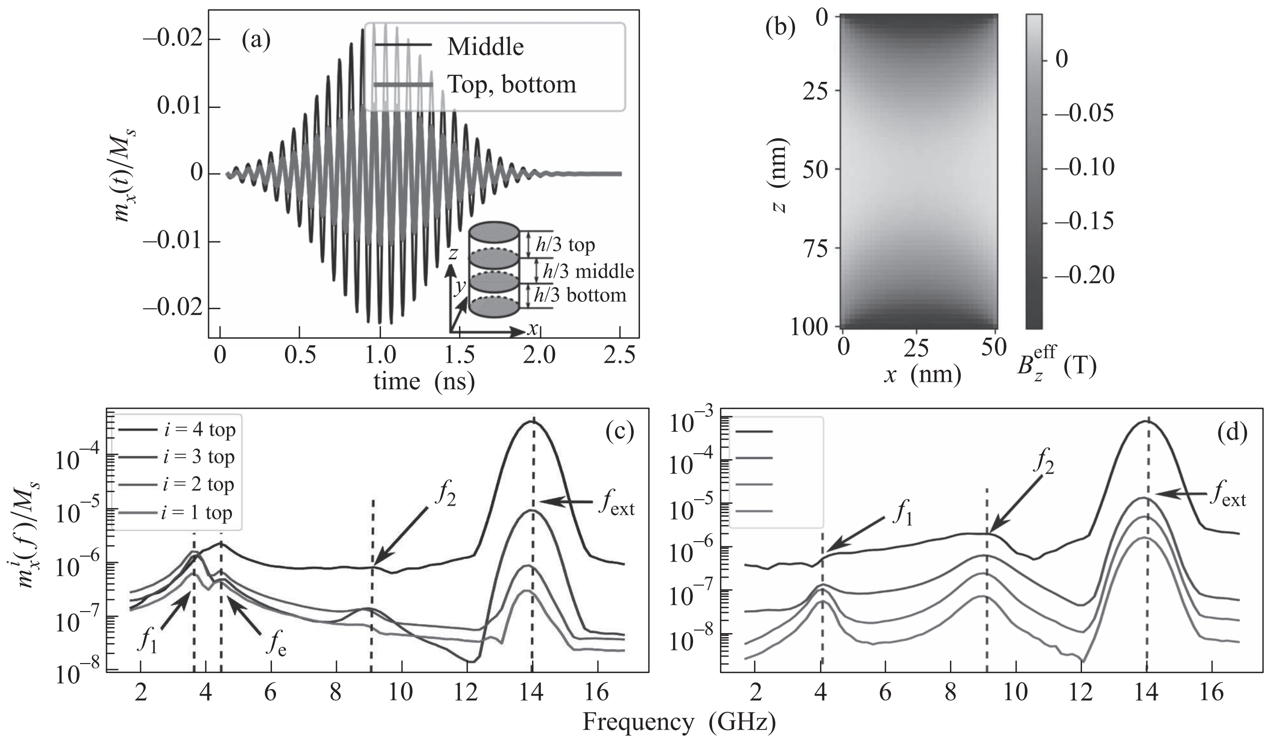

Fig. 1. (Color online) (a) – The amplitude of magnetization oscillation $m_x(t)/M_s$ averaged over the different regions of the pillars. (b) – The distribution of the effective magnetic field B_z^{eff} inside the pillar. Magnetization amplitudes $m_x^i(f)/M_s$ distribution in the frequency range f for the linear chain of $N = 7$ pillars with numbers $i = 1, ..., 4$, where magnetization is averaged over the top (c) and middle (d) regions of each pillar

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