Excitation of spin waves edge modes in chains of ferromagnetic pillars

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Abstract. We report on studies of spin waves properties in finite waveguides, formed by discrete arrays of ferromagnetic pillars. Dispersion characteristics of spin waves in such structures can be altered by changing the magnetization configurations of chain of pillars, thus creating the conditions for the bulk and edge modes to exist. Using theoretical and numerical methods we study the frequencies and spatial distributions of different spin waves modes formed by the presence of the boundaries and shape anisotropies of the waveguide.

1. Introduction

The studies of magnetization dynamics in magnetic and ferromagnetic systems [1,2] are still relevant due to the perspective for using spin waves and spin currents for the data processing [3,4] and data storage [5]. For this purpose, a variety of magnetic nanostructures were developed and studied [6,7,8]. The properties of spin waves in such structures can be shaped by the geometry of such structures. In the spatially confined geometries such as thin films, wires and dots the shape effects and the interactions with external forces leads to the existence of new topological states of the spin waves. Devices designed on such principles use the properties of spin waves associated with the topology of magnetic structures, for example, the creation of dedicated directions for the propagation of spin waves and the exchange of energy between the spin waves in individual elements of the devices. Artificial structuring of magnetic films and material parameters of magnetic films allows one to create structures with configurable allowed or forbidden directions of propagation, or, by changing the boundary conditions, allows one to control the dispersion properties of propagating nanoscale spin waves [9]. The magnetic configuration can be further controlled by the application of the external bias (magnetic field, temperature gradient, electric field or strain in magnetic systems) [10]. The interaction between discrete ferromagnetic nanopillars and nanowires were studied in the number of recent papers [11,12]. The theoretical formalism was developed to describe the properties of spin waves propagating in the infinite periodical and semi-infinite clusters of pillars [13,14]. However, the topological effects of confined structures on spin wave properties are an area of interest for future research. In this work, we present the theoretical and numerical studies of spin wave properties in finite chain of ferromagnetic pillars, where the influence of edge effects and shape anisotropies on dispersion characteristics is taken into account.
2. Theoretical model and numerical calculations

The properties of finite-size magnetic structures [15,16] in spintronics and magnonics, such as waveguides and resonators, differ from infinite and semi-infinite structures, which are often encountered in the construction of theoretical models. We present a theoretical study of a finite waveguide for spin waves, formed by a discrete linear chain of ferromagnetic pillars [17]. For such structures, bulk and edge modes of spin waves modes exist due to the presence of a boundary in structures with finite spatial dimensions or in the presence of shape anisotropies in the discrete elements of structure.

In this way, resonant properties of such spin waves in the chain of ferromagnetic pillars in an external magnetic field are considered with the presence of the dipole-dipole interaction between them. A theoretical study of the properties of spin waves in such structures by solving the Landau-Lifshits-Gilbert’s (LLG) equations in macrospin approximation is presented. Such an approach makes it possible to distinguish the edge modes of spin waves, whose frequencies depend on the magnetization configuration at the chain boundaries and defects. In addition to the resonance frequency of the bulk spin wave mode, the edge mode is localized near the edge of the chain with distinct frequency. Pillars with different magnetization can act as a defect in the chain of identical pillars, and the defect mode with its own frequency will be localized near it.

To take into account full spectrum of the interactions between pillars we numerically solve the system of LLG equations. The time evolution of the magnetization is obtained from the micromagnetic numerical calculations using the MuMax software. We chose to use permalloy (Py) as a ferromagnetic material (Py) for pillars (Fig.1). The equilibrium magnetization for cylindrical pillars with height \( h=100 \) nm and radius \( R=25 \) nm is non-uniformly distributed inside each pillar due to shape effects.

The effective magnetic field distribution is depicted in the Fig. 2 for 3 pillars in the middle of the chain and the area of free space near them. The static dipole-dipole interaction between pillars leads to the different effective magnetic field distribution inside pillars in the middle and at the edge of the chain. This distribution along the axis of the symmetry for each pillar is shown in the Fig. 3, where we can see that \( x- \) and \( z- \)component of the effective magnetic field \( B_{\text{eff}} \) can be separated into 3 regions: top part \( (h<z<2h/3) \), middle part \( (2h/3<z<h/3) \), and bottom part \( (h/3<z<0) \). The shape anisotropy effects from edges of the pillar are localized in the top and bottom regions.

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**Figure 1.** The chain of ferromagnetic pillars with numbers \( i=1,...,7 \) and constant and time dependent components of external magnetic field.

**Figure 2.** The distribution of the effective magnetic field in the top \( (x,y) \)-plane (a) and central \( (x,z) \)-plane (b). The arrows shows only direction of the field. Colors denotes the direction of the field. White and black colors are for +z and -z directions, other colors are for directions in \( (x,y) \)-plane.
Figure 3. The distribution of the effective magnetic field inside the pillars with numbers $i=1,2,3,4$ along z-axis with the external magnetic field $B^\text{ext}_z=0.3 \, T$.

From the magnetostatic approach the eigenfrequency of spin waves $f$ can be formulated by analytical formula:

$$f = \gamma ((H_{\text{ext}} + (N_x - N_z)M_{\text{sat}}) (H_{\text{ext}} + (N_y - N_z)M_{\text{sat}}))^{1/2}$$

Where $N=(H_x, N_y, N_z)$ is the demagnetization tensor for region. Each region can be approximated by its own demagnetizing tensor. Further we can average the magnetization for each pillar with index $i$ over each region and perform the Fourier transformation for the time evolution $m_i(t)$ in order to analyze frequency characteristics of the eigenmodes.

In our model we use the periodic external magnetic fields and an external force of the spin wave excitation. The short pulse of this field is circularly polarized in $(x,y)$-plane and has carrying frequency $f=14 \, \text{GHz}$. In Fig. 4 the time and frequency dependencies ($m_i(t)$ and $m_i(f)$) are calculated for single isolated cylindrical pillar. From the frequency spectrum we established that there are two resonance frequencies corresponding to different regions of the pillar. These frequencies are $f_{\text{edge}}=5 \, \text{GHz}$ and $f_{\text{bulk}}=10 \, \text{GHz}$, and their amplitudes localized near the edges of the pillar and in the middle of the pillar correspondingly.

Figure 4. Time evolution of the magnetization $m_i(t)$ and frequency spectrum $m_i(f)$ for single isolated pillar averaged over middle, top and bottom regions.

3. Excitation of the spin waves in the chain of pillars

If the external magnetic field is applied to one pillar with index $i=1$ at the edge of the chain, then the excitation is transferred to neighboring pillars by the dipole-dipole interaction (Fig. 5).
Figure 5. The frequency dependency of the amplitudes $m_i^x$ for the pillars with numbers $i$, averaged over top (left picture) and middle (right picture) regions of the pillar.

In Fig. 5, 3 main resonance frequencies correspond to the frequency of the excitations $f^{ext}$ of the external magnetic field and two modes of the spin waves. These modes are the bulk mode with frequency $f^{bulk}=9$ GHz and edge mode $f^{edge}=4$ GHz. Due to the coupling in the chain of pillars the resonance frequencies has lesser resonance values than single isolated pillar. The additional demagnetization at the edge of the chain leads to the frequency shift of the magnetic oscillation for the pillars $i=1,2$.

4. Summary

In conclusion, we present the results of theoretical investigations of frequency characteristics of spin waves in finite chains of ferromagnetic pillars. We considered the excitation of spin wave modes with the pulse of external magnetic field. For cylindrical pillars with finite height it was shown that the demagnetization and shape effects leads to the appearance of two resonance frequencies. The dipole-dipole interaction in the finite chain of such pillars causes the negative frequency shift. The additional resonance frequencies for the edge modes of the spin waves exists for the boundary elements due to the demagnetization at the edges of the chain.

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