Journal of Magnetism and Magnetic Materials 414 (2016) 49–54

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Spin-wave propagation spectrum in magnetization-modulated cylindrical nanowires

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ARTICLE INFO

Article history:
Received 11 December 2015
Received in revised form
8 April 2016
Accepted 17 April 2016
Available online 20 April 2016

Keywords:
Magnonic crystal
Spin wave
Magnetic cylindrical nanowire
Micromagnetic simulation

ABSTRACT

Spin-wave propagation in periodic magnetization-modulated cylindrical nanowires is studied by micromagnetic simulation. Spin wave scattering at the interface of two magnetization segments causes a spin-wave band structure, which can be effectively tuned by changing either the magnetization modulation level or the period of the cylindrical nanowire magnonic crystal. The bandgap width is oscillating with either the period or magnetization modulation due to the oscillating variation of the spin wave transmission coefficient through the interface of the two magnetization segments. Analytical calculation based on band theory is used to account for the micromagnetic simulation results.

1. Introduction

Magnonic crystals (MCs) are magnetic materials with periodic variation of magnetic [1–3], geometric [4–6], or other external parameters [7,8] modifying the propagation of spin waves (SWs). Depending on the dimensionality of the system, MCs can be one-dimensional (1D) structures [9–11] (such as periodic multilayers and nanostrip waveguides), 2D [12–14] (such as 2D arrays of magnetic nanoelements) and 3D [15–17]. Similar to photonic or phononic crystals, a band structure with a series of allowed and forbidden SW bands [18,19] will form for SWs propagating in MCs. The SW band structure can be manipulated through changing the periodic parameters, applying external field or spin-polarized electrical current [20,21]. By exploiting the SW propagation in MCs for carrying and processing information, one can design high-quality magnetic devices with low energy consumption and high operation rates compared with traditional electronic devices [22,23].

The MC waveguide with spatial periodical variation of saturation magnetization has been studied both theoretically and experimentally [1–3,24,25]. Most of those works focused on nanostrips or multilayers, and the results showed that the width and position of forbidden bands depend strongly on the level of the magnetization variation and the size of the area with the modified magnetization. Cylindrical nanowires and arrays are magnetic nanostructures which have many applications in data storage or microwave absorption [26–28]. Compared to nanostrips and multilayers which usually involve complex fabrication procedures, cylindrical nanowires and arrays can be easily fabricated by template-assisted electrodeposition [29,30]. However, to the best of our knowledge, no MCs based on cylindrical nanowires have been reported heretofore. In this paper, we theoretically study the SW propagation in cylindrical nanowire MCs with periodic variation of saturation magnetizations using micromagnetic simulations. The SW band structures are found be easily controlled by either tuning the level of the magnetization variation or the MC period.

2. Model and simulation technique

The cylindrical nanowire MCs studied in this work consist of two alternating ferromagnetic materials with saturation magnetization M_1 and M_2, as shown in Fig. 1. The nanowire with diameter 30 nm is 5000 nm long in the x direction. The MC period is $P = P_1 + P_2$, where P_1 and P_2 are the lengths of M_1 and M_2 segments, respectively. The magnetic parameters corresponding to $Fe_{1-x}Ni_x$ alloys are used. The magnetization of $Fe_{1-x}Ni_x$ alloy can be easily tuned by changing the relative composition of Fe and Ni component. In micromagnetic simulations, the magnetization M_1 is fixed to be 8×10^5 A/m, and M_2 is changed from 5×10^5 A/m to 7×10^5 A/m so that the influence of magnetization modulation on the spin-wave propagating spectrum can be investigated. For

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http://dx.doi.org/10.1016/j.jmmm.2016.04.057

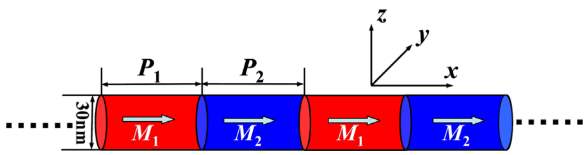

Fig. 1. Illustration of the cylindrical nanowire magnonic crystal consisting of alternating magnetization segments. The white arrows indicate the direction of magnetization.

simplicity, the same exchange stiffness $A=1.3\times10^{-11}$ J/m is assumed for both magnetization segments and the magnetocrystalline anisotropy is neglected. The Gilbert damping constant α is taken to be 0.01. Cylindrical nanowire MCs with different period P (P=70–115 nm) are simulated.

Simulations are performed with the micromagnetic code OOMMF [31], which is employed to solve the Landau–Lifshitz–Gilbert equation. The simulation cell size is set to be $5\times2\times2$ nm^3. To excite SWs, a sinc-function field $H_0\sin(2\pi f_H t)/(2\pi f_H t)\,\hat{y}$ along the y axis with f_H=60 GHz and H_0=100 mT is applied locally to an area of $5\times30\times30$ nm^3 at the left end of the nanowire. The temporal evolution of the z-component of magnetization in each cell is recorded every 5 ps. The SWs propagating along the waveguide with frequencies ranging from 0 to 60 GHz are thus excited and their spectra can be calculated through a standard fast Fourier transform method (FFT) [32,33]. The frequency resolution resulting from the FFT transform is about 50 MHz. The SW dispersion curves are obtained by performing discrete Fourier transform of the magnetization z-component oscillations along the x axis. In order to avoid the excitation of the SW edge modes, the magnetizations at the two ends of the nanowire are pinned.

3. Results and discussion

Fig. 2(a) and (b) shows the frequency spectra of SWs propagating in a homogenous nanowire and in the nanowire MC with $M_1=8\times10^5$ A/m, $M_2=5\times10^5$ A/m and P=100 nm ($P_1=P_2$=50 nm) along the nanowire central axis, respectively. The SWs with frequencies larger than a cutoff frequency 12 GHz can propagate through the homogenous nanowire (Fig. 2(a)), while the propagation is forbidden for SWs with frequencies lower than 12 GHz. This cutoff frequency corresponds to the minimum of the spectrum of the backward volume magnetostatic spin waves (seen in Fig. 3(a)). For the magnetization-modulated MC, as seen from Fig. 2(b), the SWs display quite different propagating characteristics. Allowed and forbidden SW bands form above the cutoff frequency. Five bandgaps are clearly shown in the frequency spectra, which are located at 12, 15.95, 22.07, 30.45 and 40.52 GHz (defined as the central frequency of the bandgaps). The corresponding bandgap widths are about 1, 1.8, 2.85, 1.6 and 4.65 GHz, respectively. Furthermore, a clear periodic oscillation of the SW intensity along the propagation direction is visible, which comes from the SW multiple reflections at the boundaries of two magnetization segments.

The SW band structure is also revealed by the SW dispersion curves. For the homogenous nanowire, there is one continuous parabolic dispersion curve as shown in Fig. 3(a), which corresponds to the lowest fundamental SW mode (m=1) [34]. As the nanowire studied here is very thin (only 30 nm in diameter), high-order propagation SW modes are not excited. It is worth noting that the SW intensity is close to zero for small wave vectors. This is because that the SWs propagating along the long axis in the uniformly magnetized nanowire have the characteristics of backward volume magnetostatic SWs, and exhibit a negative group velocity [35,36] in the dipole-dominated range. For the nanowire MC, the dispersion curves exhibit clear band features as shown in Fig. 3(b). From low to high frequency, five bandgaps appear exactly at the Brillouin zone (BZ) boundaries (positions indicated by blue dotted lines), i.e. $k_x=n\pi/P$, n=2, 3, 4, 5 and 6. They come from the Bragg reflection of the SWs at the BZ boundaries. For simplicity, we label the bandgaps as G_n, n is the index of the BZ boundaries. The five SW bandgaps in Fig. 3(b) correspond to G_2, G_3, G_4, G_5 and G_6, respectively. The first bandgap G_1 is not detected as it is located in the dipole-dominated SW range. Moreover, the width of bandgap G_7 is almost equal to zero, which is due to the almost zero reflection of SWs at the 7th BZ boundary. A more detailed discussion about the relationship between the bandgap width and the SW transmission will be given later.

In the following, we will discuss the evolution of the SW band structure with the degree of the magnetization modulation and the MC period. Generally, the band structure is mainly determined by the periodic potential. The periodic potential in the nanowire MC originates from the demagnetization field generated by the magnetic charges appearing at the interface of two segments with

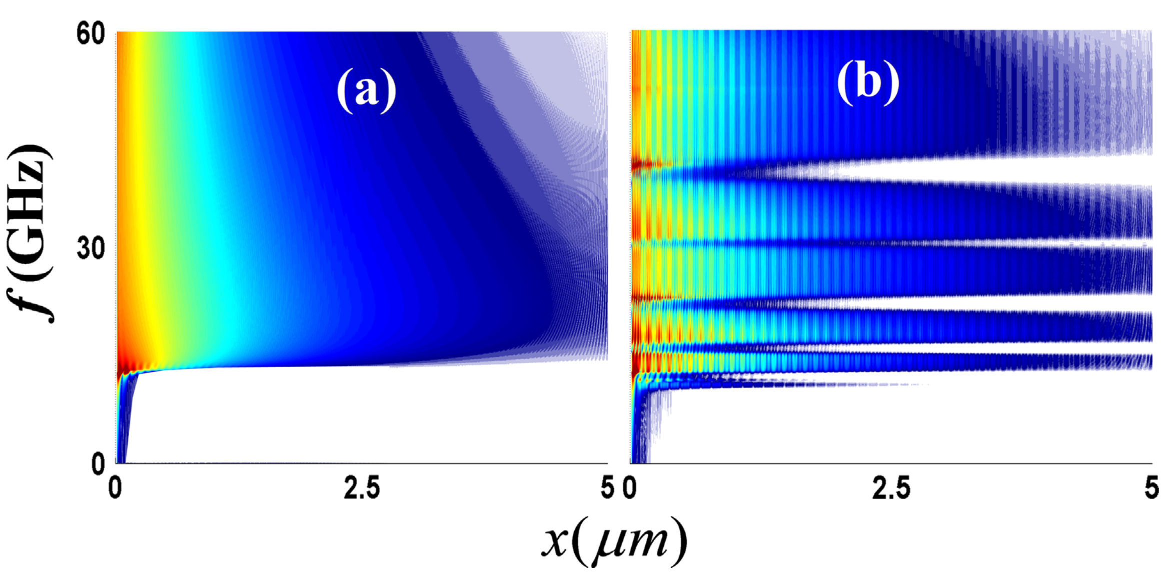

Fig. 2. Frequency spectra of the spin waves propagating in the homogeneous nanowire with $M_s=8\times10^5$ A/m (a) and in the nanowire MC with $M_1=8\times10^5$ A/m, $M_2=5\times10^5$ A/m, P=100 nm and $P_1=P_2$ (b) as a function of the propagation distance at central axis (y=15 nm).