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Reconfigurable magnonic crystal consisting of periodically distributed domain walls in a nanostrip

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ABSTRACT

We study spin wave propagation in a new type of magnonic crystal consisting of a series of periodically distributed magnetic domain walls in a nanostrip by micromagnetic simulation. Spin wave bands and bandgaps are observed in frequency spectra and dispersion curves. Some bandgaps are caused by the Bragg reflection of the spin wave modes at the Brillouin zone boundaries, while others originate from the coupling between different incident and reflected spin wave modes. The control of the spin wave band structure by changing the magnetocrystalline anisotropy or applying an external magnetic field is studied. Increasing the magnetocrystalline anisotropy leads to an increase of the bandgaps. The external field applied perpendicular to the nanostrip gives rise to a doubling of the domain-wall magnonic crystal period. As a result, more bandgaps appear on the frequency spectra of propagating spin waves. The results presented here may find their use in the design of reconfigurable magnonic devices.

1. Introduction

Magnonic crystals (MCs) are artificial magnetic material structures with periodic variation of magnetic or geometric parameters. Similar to photonic crystals or phononic crystals, spectrum of spin waves propagating in such structures consists of a series of allowed frequency bands and forbidden bands (or bandgaps in which the propagation of SW is forbidden) [1–3]. In recent years, MCs have attracted considerable and growing interest because of its potential applications for signal processing and information transfer devices [4–9]. Different types of MCs have been designed and fabricated. Most of them are composed of arrays of magnetic strips [10–13], magnetic nano-dots [14–16] or anti-dots [17–20], and modulated waveguides [21–25]. The spin wave band structure in such structures can be manipulated by using material parameters or geometry of the structures. A drawback of the material- or geometry-modulated MCs consists in that, once they are fabricated, their modulated parameters are usually fixed. Therefore, the spin-wave band structure is less facilely tuned. In addition, preparations of these periodic nanostructures normally involve complex fabrication procedures.

Recently, a new type of magnonic crystals based on periodic distribution of magnetization was reported, and the majority of work is focused on the configuration that the magnetic periodic unit cell consists of two nanostrips with parallel magnetization (FMO) or antiparallel magnetization (AFO) [26–29]. The band structure of these MCs can be reprogrammed by changing the magnetic state of the two nanostrips. In this paper, we present a domain-wall MC composed of a series of periodically distributed magnetic domain walls in a single nanostrip. Micromagnetic simulations are employed to study the transmission characteristics of spin waves in such a structure. Simulated results show that the control of the spin-wave band structure by using the magnetocrystalline anisotropy and external magnetic field is feasible.

2. Simulation details

The magnonic crystal waveguide studied here is a Permalloy nanostrip with 1500 nm length in the x direction, 50 nm width in the y direction, and 5 nm thickness in the z direction as shown in Fig. 1. The material parameters corresponding to Permalloy are used for micromagnetic simulations: saturation magnetization $M_s = 8.6 \times 10^5$ A/m, exchange stiffness $A = 1.3 \times 10^{-11}$ J/m, anisotropy constant $K = 0$, and the Gilbert damping constant $\alpha = 0.01$. Simulations are performed with the micromagnetic code OOMMF [30], which is employed to solve the Landau–Lifshitz–Gilbert equation. The simulation cell size is set to be $2 \times 2 \times 5$ nm^3. The temperature is assumed to be zero. A series of prototype Neel domain walls are first placed in the nanostrip equidistantly and then relaxed to stable state. The distance between two nearest

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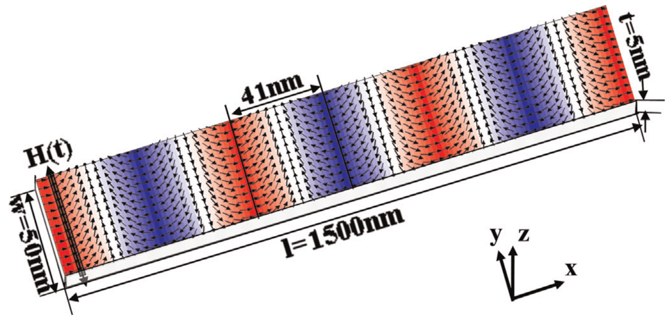

Fig. 1. Illustration of the domain-wall magnonic crystal with the geometry and dimensions. The domain walls are equidistantly distributed in the nanostrip. The magnetization direction is represented by arrows. The gray area with $H(t)$ represents the region where spin waves are excited. The Cartesian coordinate system is shown on the lower right.

Neel domain walls is about 41 nm. In order to simulate the spin-wave propagation in the nanostrip, a sin c-function field $H_0 \sin(2\pi f_H t)/(2\pi f_H t)\ \hat{y}$ along the y axis with $f_H = 50$ GHz and $H_0 = 100$ mT is applied locally in an area ($2 \times 50 \times 5$ nm^3) to excite spin waves. The temporal evolution of the z-component of magnetization in each cell is recorded every 1 ps. The local spin-wave density is calculated for each cell using a standard fast Fourier transform method. The frequency resolution resulting from the FFT transform is 50 MHz. And the spin wave spectra with frequency range from 0 to 50 GHz can be obtained. The dispersion curves of spin waves are gained by FFTs of the temporal z-component oscillations along the x axis. The cut-off value and resolution of the wave vector are 3.14×10^9 rad/m and 4.36×10^6 rad/m, respectively.

3. Results and discussion

Fig. 2 presents the frequency spectra of the spin waves propagating in the domain wall MC along the x axis at $y = 25$ nm. For comparison, the spin-wave propagation in a uniformly magnetized nanostrip with the same geometric dimensions is also shown. It can be seen from Fig. 2(a) that, for the uniformly magnetized nanostrip, there is a cutoff frequency below which the spin-wave propagation is forbidden. This cutoff frequency corresponds to the ferromagnetic resonance with zero wavenumber and is mainly determined by the shape anisotropy of the nanostrip. When a series of domain walls are periodically distributed in the nanostrip, the spin waves display quite different propagating characteristics (Fig. 2(b)). The allowed and forbidden spin-wave bands are clearly shown in the frequency spectra. In addition, the cutoff frequency existing in the domain wall MC is very small. The lowest resonance frequency is only 250 MHz. This is understandable considering that effective shape anisotropy is greatly reduced in domain wall MC comparing with the uniform nanostrip. Along the propagation distance, a clear period oscillation of the spin-wave intensity is visible, which is originated from the multiple reflections of the spin wave between two domain walls. The detail of the spin-wave band structure can be more clearly revealed by integrating the spin-wave intensity over a period of MC as shown in Fig. 2(c). Five forbidden bands are observed at 9.8, 11.65, 18.65, 20.96 and 26.05 GHz (defined as the central frequency of the bandgaps), with band widths of 1.0, 1.75, 2.35, 1.6 and 0.5 GHz, respectively.

The simulated dispersion curves of the spin-wave modes in the uniform nanostrip and domain wall magnonic-crystal are plotted in Fig. 3(a) and (b), respectively. Since the spin-wave intensity varies along the nanostrip width and different spin-wave modes have different width distribution, here, the dispersion curves are averaged over the width. In homogenous magnetized nanostrip, there are two continuous parabolic dispersion curves, which correspond to the lowest fundamental and third width spin wave modes ($m = 1$, 3) [31]. However, in domain-wall magnonic crystal, the dispersion curves display evident band features, as shown in Fig. 3(b). From low to high frequency, the first and fifth bandgaps appear exactly at the Brillouin zone (BZ) boundaries (positions indicated by the black dotted lines), i.e. $k_x = n\pi/a$, $n = 1$, 2. a is the MC period and equal to 41 nm. They are caused by the Bragg reflection of the lowest spin wave mode in a periodic potential system. Generally, we label the bandgaps as $G_{mm',n}$, where m and m' represent the incident and reflected spin wave modes, respectively. n denotes the index of the BZ boundaries or the index of bandgaps. Therefore, the first and fifth bandgaps correspond to $G_{11,1}$ and $G_{11,2}$. But the other three bandgaps do not occur at the BZ boundary. This kind of bandgaps was observed earlier in a periodically width-modulated nanostrip [21,22]. It was assumed that they originate from the coupling between two different propagating spin-wave modes. From Fig. 3(b), it can be seen that, in addition to the fundamental and third width spin wave modes, the second width spin wave mode with $m = 2$ is also excited in DW MC, and the second bandgap comes from the coupling between the fundamental mode and the second width mode and can be labeled as G_{12}. The third and fourth bandgaps correspond to the coupling between the fundamental mode and the third width mode (labeled as G_{13}) and the coupling between the second and the third width modes (labeled as G_{23}), respectively. It needs to point out that except for the aforementioned five bandgaps, there are other bandgaps originating from the coupling between high-order spin wave modes, such as bandgaps $G_{22,1}$ and $G_{33,1}$, which are visible in the dispersion curves, but cannot be distinguished on the frequency spectra of the propagating spin waves. As the strength of the excited high-order spin wave modes is much weaker than the strength of the fundamental spin wave mode, only the bandgaps concerning the fundamental mode are evidently exhibited.

The position and width of the bandgaps are mainly determined by the MC period and the spin-wave dispersion relation. The dispersion relation is correlative with the magnetization configuration. By changing the magnetic anisotropy and, hence, the domain-wall structure, one can manipulate the spin-wave band structure. Although magnetocrystalline anisotropy K is a material parameter, it can be tuned experimentally by strain [32,33] or electrical field which has been reported recently for various ferromagnet/ferroelectric heterostructures [34,35]. Fig. 4 shows the spin-wave propagation characteristics and the corresponding dispersion curves in domain wall MCs with different magnetocrystalline anisotropy constant K. The spin-wave intensity over a period of MC for different magnetocrystalline anisotropy is also presented in Fig. 2(c). Comparing to that of $K = 0$, one can see that, with the increase of K, the bandgap positions are almost not changed, but the bandgap widths gradually increase with K. When K is equal to 0.5×10^5 J/m^3, the first and second bandgaps merge together, and the same occurs to the third and fourth bandgaps. It is not difficult to understand the results. The frequency position of the bandgaps is mainly determined by the period. The gap width is determined by the periodic field. A rapid spatial variation of periodic potential usually gives rise to a large bandgap width. With the increase of K, although the width of domain wall is changed, the period of magnonic crystal remains the same value, so the positions of bandgaps do not vary. On the other hand, the increase of the magnetocrystalline anisotropy tightens the domain wall and, consequently, enhances the intensity of the periodic field, which makes the bandgaps wider.

An advantage of the magnetization configuration-modulated MCs, like the domain wall MC, consists in that the spin-wave band structure can be easily tuned by manipulating the magnetization