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Collective spin excitation in finite size array of patterned magnonic crystals

H.-G. Piao [a], J.-H. Shim [b], L. Pan [a], S.-C. Yu [b], D.-H. Kim [b,*]

[a] College of Science, China Three Gorges University, Yichang 443002, China
[b] Department of Physics, Chungbuk National University, Cheongju 361-763, South Korea

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ABSTRACT

We explore further details of the collectively excited spin wave mode in finite arrays of elliptically shaped ferromagnetic nanoelements as two-dimensional magnonic crystals by means of micromagnetic simulations. Under a pulsed magnetic driving field, collective spin wave modes were intensively investigated with variation of nanoelement dimensions and interelement separation as structural parameters of the magnonic crystal as well as changing the applied bias magnetic field. Via observing and analyzing the dynamic behavior of collective spin wave modes, we have found that the dynamic behavior strongly depends on the bias magnetic field with a quasi-linear dependency. The quasi-linear dependency of spin wave frequency transition can be achieved to a high sensitivity of the pT/Hz level. By modulating the magnonic crystal lattice structures and the bias magnetic field, the spin wave dynamic behavior is tunable which might be a promising property for a future magnonic crystal application and multi-functional sensors.

1. Introduction

Spin wave excitation has been attracting much attention due to its possible applications such as spintronic devices and microwave communications [1–5]. In particular, collective spin-wave excitation as a magnetostatic surface wave mode is considered to be one of the promising candidates for future application in artificial magnonic crystals, thanks to the tunability of the properties by changing the structural parameters of the magnonic crystal. Due to the formation of collective spin-wave excitations coming from the mutual coupling of each ferromagnetic element in a magnonic crystal, design and modulation of the magnonic crystal structure are important technologies to excite the collective spin wave mode. Therefore, understanding and control of the spin wave dynamics in nanostructured ferromagnetic materials become the hot topic of spintronic researches based on the spin-wave excitation.

Recently, numerous studies have been focused on study of the collective spin wave mode in various periodically structured ferromagnetic materials. In various arrays of ferromagnetic nanoelements, numerous experimental and micromagnetic studies have been reported on the collective spin wave excitation [6–20], even experimentally observed the collective spin wave mode by a pump-probe time-resolved scanning Kerr microscopy [21]. By the tunable characteristic of spin wave dispersion relations (magnonic bands), a scheme of very sensitive magnetic field sensor is proposed in one-dimensional (1D) magnonic crystals created by metallic gratings on the ferromagnetic film were proposed [22–24]. The magnetic field sensor achieved a highly sensitivity of 9336%/Oe utilizing the propagation effect of magnetostatic surface wave modes in the magnonic material. In the magnonic crystal structure, rejection bands of magnetostatic surface waves were also found in experiment [25], which can be modulated by geometry and dimension of the metallic array. Moreover, the magnonic crystal structure can be used also in sensing applications based on spin wave resonances [23]. However, little have been known about the response effect of magnetostatic surface wave modes on the bias magnetic field in two-dimensional (2D) magnonic crystals.

In this work, the collective spin wave excitation are explored in further detail for finite 3×3 arrays of ferromagnetic nanoelements as 2D magnetic crystals by means of micromagnetic simulations. Under the pulsed magnetic driving field, the dynamic behavior of collective spin wave modes are investigated with variation of the nanoelement geometry and the interelement separation as well as changing the external bias magnetic field. Furthermore, the magnetic field response effect of collective spin wave modes is examined in 2D magnetic crystal structures.

* Corresponding author. Address: Chungdae-ro 1, Seowon-Gu, Cheongju, Chungbuk 28644, South Korea.
E-mail address: donghyun@chungbuk.ac.kr (D.-H. Kim).

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2. Micromagnetic simulation

We have carried out micromagnetic simulations using OOMMF based on Landau–Lifshitz–Gilbert equation [26]. The unit cell dimension is set to be $1 \times 1 \times 5$ nm^3 and the Gilbert damping constant $\alpha = 0.01$. Material parameters of Permalloy are used with the exchange stiffness coefficient of 13×10^{-12} J/m and a saturation magnetization M_s of 8.6×10^5 A/m. Permalloy is considered to have zero magnetocrystalling anisotropy so that the Permalloy nanoelement array system becomes an ideal playground in examining the spin wave properties and subsequent collective spin wave mode dynamics.

The nanoelement in the present study has been defined to have an elongated circular shape with various dimensions. Geometry and dimension of the 3×3 nanoelement array are shown in Fig. 1. The thickness of the nanoelement is kept constant to be 5 nm. The long axis is fixed to be 80 nm while the short axis '*s*' is changed from 30 to 80 nm. The interelement separation '*d*' of ferromagnetic arrays is varied from 10 to 40 nm. With variation of interelement separation '*d*' and the shorter diameter '*s*' as the magnonic crystal lattice parameters, the collective spin wave modes are intensively investigated under the external magnetic driving field. The array of patterned nanoelements is initially saturated to a certain direction on the plane by the external static magnetic bias field (H_b) along the $+x$ direction, while the magnetic field pulse of 100 ps width and 10 mT strength has been applied to the $+y$ direction perpendicular to the bias field. The rising and falling time of the pulse field was all set to be 50 ps.

3. Results and discussions

In Fig. 2, the magnetization profile after the pulse applied is plotted for various *s* from 30 to 80 nm with a constant *d* (10 nm) under the 50 mT bias field. The *y*- (the pulse field direction) and *z*-component (out-of-the-plane direction) of magnetization is normalized by the saturation magnetization in graphs. The pulse field profile is denoted by the dotted line at each figure. The *y*-component of the magnetization exhibits a larger oscillation compared to the *z*-component of the magnetization, since the magnetization along the thickness direction (*z*-axis) is suppressed by the demagnetizing field of the flat nanoelement along the out-of-the-plane direction. The M_y/M_s oscillation is delayed by a phase of $\pi/2$ relative to M_z/M_s (see the inset of Fig. 2(b)), which implies that the magnetization of each nanoelement behaves as a whole and thus, can be roughly approximated to be a single "macro-spin" acting. In the case of $s=30$ nm, the time-dependent magnetization profile evolves with a precessional motion damping out after a few nanoseconds. With increase of the short axis *s* of each nanoelement, the time-dependent magnetization profile exhibits a quite different property, which becomes clear to be a beating behavior, as clearly shown in Fig. 2(c) and (d). The beating behavior becomes more clear with larger magnetization amplitude as well as with a higher beating frequency with the increase of the short axis *s*. The existence of the beating behavior indicates that there exists a dynamic dipolar field interaction between adjacent elements, since there should be just a monotonic damping out behavior for non-interacting isolated nanoelements (see Fig. 3(e)). Increases of the magnetization profile amplitude and the beating frequency means that the interelement interaction force becomes stronger with the *s* increasing from 30 to 80 nm, which is understandable based on the fact that the *s* increase leads to the increase of free poles generated on the edge of each nanoelement as well as the decrease of the shape anisotropy energy in each ferromagnetic nanoelement. The increase of free poles on the edge of each element would allow a stronger interelement interaction, the surface charges (poles) actually is the source of the magnetostatic field.

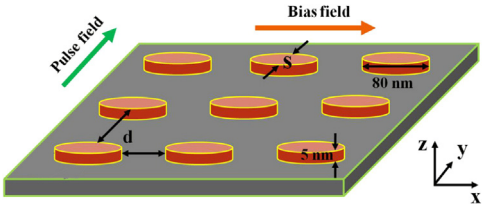

Fig. 1. Geometry and dimension of 3×3 ferromagnetic nanoelements array shown with the rectangular coordinate system. A bias field and a pulse field direction is perpendicular to each other on the plane as denoted by arrows, together with the interelement separation '*d*' and the short axis '*s*' of the elongated circular nanomagnet.

The interacting spin wave mode as a collective spin wave mode in various array configurations are demonstrated in Fig. 3(a) and (b), where the time-dependent M_y/M_s profiles are plotted with variations of *s* and *d*. For instance, in the case of $s=30$ nm (see Fig. 3(a)), we have fount that there was no significant difference in magnetization precession behaviors with damping for a few nanoseconds. Although the interelement separation *d* is changed from 10 to 40 nm, the magnetization profiles are almost the same to each other. The magnetization profile is expected with a negligible beating behavior, since there is only a negligible interaction among the nanoelements. In the case of $s=40$ nm (see Fig. 3(b)), the beating behavior of the time-dependent M_y/M_s is no longer clearly observed if the interelement separation *d* increases but the case of $d=10$ nm. With increase of the interelement separation *d*, the beating behavior is diminished even seems to disappear for the case of $d=40$ nm. It is concluded that the dynamic dipolar field interaction between adjacent elements was more significantly suppressed with the increase of interelement separation *d*, which is represented by the beating behavior.

The excited collective spin wave mode is analyzed by the fast Fourier transform (FFT) with the 10^{-11} s sampling interval time for various configurations of *d* and *s*. In the case of $d=10$ nm (see Fig. 3(c)), the FFT magnitude with respect to the frequency shows the quite contrasting behavior with variation of the short axis *s*. With the increase of the *s* and thus, with the increase of the dynamic dipolar field interaction, a double-peak structure of the FFT spectrum becomes more clear. The double-peak structure has been experimentally observed for the small separation by Gubbiotti et al. [9]. As the fact that the middle row nanoelements of the array experience a different effective magnetic field excitation with the outer rows, the presence of the double-peak structure is due to the existence of dynamic dipolar field interaction between adjacent nanoelements. To confirm the fact, excited spin wave modes between the isolated element of $80 \times 80 \times 5$ nm^3 and the 3×3 array of $80 \times 80 \times 5$ nm^3 elements with $d=10$ nm were compared by the M_y/M_s averaged over the entire matrix under the bias magnetic field of $H_b=20$ mT, as shown in Fig. 3(d). We have checked the validity of the macro-spin assumption by examining the spin wave modes of central and edge region on the center element. From the figure, we have found that only a spin wave mode of 1.5 GHz was excited in case of the isolated element with one-peak structure of the FFT spectrum, which significantly differ from the double-peak structure in case of 3×3 elements array. The difference of the isolated element and the array comes from the dynamic dipolar field interaction between adjacent nonoelements, which differs from results of Demidov and Nembach works [27,28]. Since excited collective spin wave modes of the isolated element as a 2D nanostructure differ from the microstructure of Ref. [27] and the thicker nanostructure of Ref. [28], as shown in Fig. 3(e). On the double-peak behavior in case of 3×3 elements array, we have confirmed with the FFT analysis of local magnetization that, the lower energy peak (open inverse triangle) at the