Angle-dependent spin waves in antidot bilayers*

Hu Chun-Lian(胡春莲)[a)†], Liao Leng(廖 棱)[a)], and Stamps R[b)]

[a)] *Chongqing Jiaotong University, Chongqing* 400074, *China*

[b)] *SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, G*12 8*QQ, UK*

(Received 20 March 2014; revised manuscript received 13 June 2014; published online 10 October 2014)

Ferromagnetic resonance is introduced to examine the microwave frequency response of NiFe/IrMn bilayers, patterned as antidot arrays. In the experiment, field direction dependence on mode is obtained by rotating the applied magnetic field. We find that at a given resonance frequency, the dependence of the resonance field on the angle has a tendency of sinusoid/cosine variation in the experiment. From micromagnetic simulation it can be seen that spin waves are localized between dots from a given mode profile. This is caused by a demagnetization distribution with a larger value in the center of the two nearest dots than that of the next-nearest dots.

Keywords: spin waves, antidot, magnetic property

PACS: 75.30.Ds, 75.70.Cn, 75.90.+w **DOI:** 10.1088/1674-1056/23/12/127501

1. Introduction

With the increase in information needed, patterning has received more and more attention in designing and fabricating magnetic storage devices.[1–7] Patterning in a film is an easy and effective way of fabricating these devices, which many researches have focused on, with a patterned shape of triangle, dot, square, and so on.[8–10] It is interesting to reveal the intrinsic properties of spin waves in patterned structures, owing to the localization of spin waves. This will be very helpful for more applications in magnetic storages with different patterned shapes.[11–13] Most notably, patterning on magnetic materials with suitable length scales offers exciting possibilities for controlling spin wave dynamics. In the present work, periodic antidot arrays in a film are fabricated and measured by ferromagnetic resonance (FMR) equipment. In the measurement, a rotating field is used to obtain its FMR frequency dependence. We find that at a given FMR frequency, the magnetic field has a sinusoid/cosine variation tendency with a rotating field angle from our measurement. Then, a simulation method is employed to reveal the intrinsic spin wave property for different angles at a given FMR frequency. Here, the software package NMAG is used. It is found that the spin wave has a tendency to localization between dots. The detailed descriptions for the experiments and simulation are discussed in the following section.

2. Experimental and simulation method

In the experiments, bilayers of Cu(5 nm)/NiFe(30 nm)/IrMn(15 nm)/Cu(5 nm) constitute the structure of antidot arrays. The dot diameter is 220 nm and the distance between two dots (antidot pitch) is 415 nm. In our measurement, what is rotated is the sample direction rather than the magnetic field direction, because the sample size is small and easy to rotate. On the contrary, the equipment of the magnetic field is very large and cannot be rotated. In the experiments, FMR frequency is set at 12 GHz. The corresponding ferromagnetic field is measured with a rotating sample, which has the same effect as a rotating field. The detailed descriptions for the construction and measurement of the antidot arrays can be found in Refs. [14] and [15].

With regards to the simulation, the software package NMAG is employed here. In NMG, the finite element method is used, and the maximum mesh triangle size is 12 nm. In the simulation, a fixed step numerical integration is used in time steps of 1×10^{-12} s, i.e. 1 ps. In order to precisely describe the intrinsic property of the permalloy antidot structure, parameters in our simulation are exactly the same as those in the experiments, including antidot diameter, and dot period. However, the simulation size of the permalloy antidot arrays cannot be set to the same as those in the experiments due to the large size of the sample. By simulation, we find that a 3×3 size is enough for describing spin wave properties in periodic antidot arrays. Comparison between larger systems and different maximum mesh sizes shows that the edge effect is negligible for the center cell in the 3×3 period arrays. Thus, 9 unit cells are used for 3 layers of cells, each with a thickness of 10 nm in our simulation. The ferromagnetic frequency is obtained by first relaxing the periodic structure to a static ground state configuration by using a large damping coefficient in a given field, and then reducing the damping coefficient to a very small value. The simulation is run until the average precessional amplitude falls below 10^{-3}. Then, data in nanoseconds are collected. A fast Fourier transform method is employed in order to extract

*Project supported by the National Natural Science Foundation of China (Grant No. 11304407) and the Scientific Research Foundation for Returned Scholars, Ministry of Education of China (Grant No. 47).

†Corresponding author. E-mail: clhu@cqjtu.edu.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd

ferromagnetic frequencies. Then, by using the obtained FMR frequencies, spin wave configurations in permalloy antidot arrays can be calculated.

The detailed results for the experimental and simulated results are discussed in the following section.

3. Results and discussion

The experimental and simulated results for FMR frequencies are given in Fig. 1. In the experiments, angular measurements are carried out by rotating the sample on the waveguide with respect to antidot lattice direction. The experimental results are shown in Fig. 1(a). It can be seen that there are three modes observed in the experiments, as denoted by a black solid square, red solid circle, and blue solid down triangle. Moreover, magnetic field dependence on the applied field direction at a given resonance frequency of 12 GHz has a sinusoid/cosine variation tendency for each of all the three observed modes in a field angle range from 0° to 360°. Basically there are three modes which are degenerate for certain symmetry directions. This has been observed recently by Neusser, *et al.*[12] However, in calculation, it is hard to obtain the dependence of the resonance field on field direction at a given frequency due to the different methods used in experiment and calculation. The easier way in our calculation is to set a given field and obtain the corresponding resonance frequency. The calculated results of resonance frequency dependence on the applied magnetic field are given in Figs. 1(b) and 1(c) with field directions at 22.5° and 45°, respectively. Here, 22.5° and 45° are defined as the angles of field directions with respect to the antidot lattice direction respectively. Moreover, the corresponding experimental results are plotted. With the increase of the magnetic field, resonance frequency increases both in 22.5° and 45° of the field direction. The simulated results using the Kittel formula for a continuous film are given by a dotted line.[14]

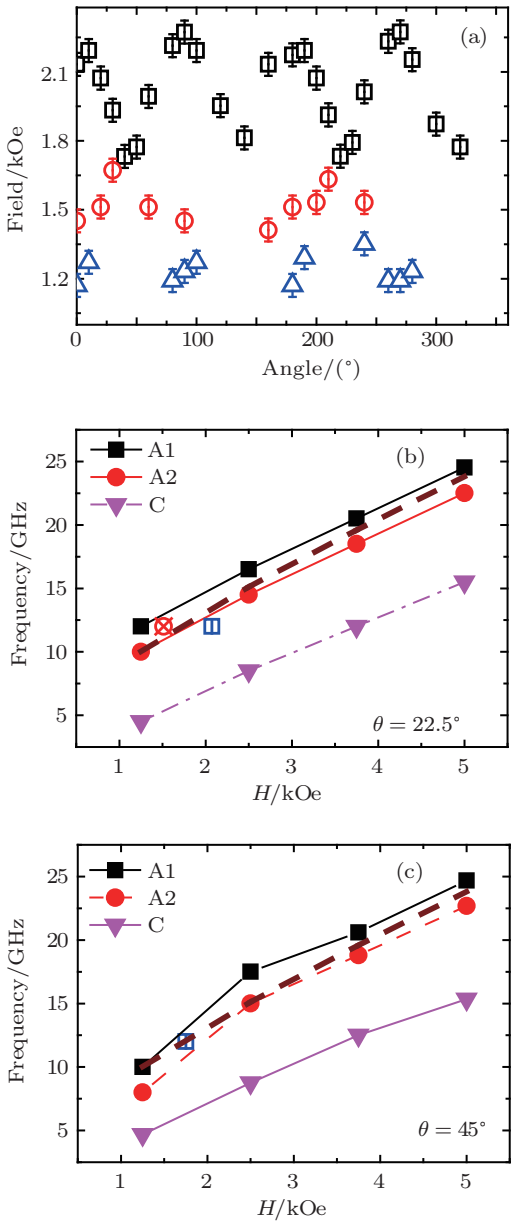


Fig. 1. (color online) (a) At a given frequency of 12 GHz, the experimental resonance magnetic field dependence on the direction of the magnetic field for the antidot arrays; (b) At 22.5°, the simulated and experimental data of the spin-wave modes in antidot arrays; (c) at 45°, the spin-wave modes for the simulation and experiment in antidot arrays. The unit 1 Oe = 79.5775 A·m^{-1}.

In order to see the intrinsic spin wave properties for these modes, the mode profile is employed in our calculation. Here, the mode profile is defined as the absolute value for the difference between the magnetization at the peak of the precession and the magnetization of the ground state. Mode profiles for mode C, A1, and A2 at angles 22.5° and 45° are plotted in Fig. 2. Field directions for 22.5° and 45° are also shown in the figure. In Fig. 2 it can be seen that in the left columns mode profiles are for field direction 22.5° and in the right columns these are for field direction 45°. From top to bottom they are type C, type A1, and type A2 modes. Dark (light) shading (red on line) denotes large (small) spin precession amplitude. From the mode profiles shown on the top of Fig. 2 it can be seen that for type C mode, spin waves precess at the edge of the periodic dots. Thus, type C mode is also called edge mode. For type A1 and type A2 modes, spin waves precess between the nearest and next nearest dot. For 22.5°, spin waves both in type A1 and type A2 modes precess between two nearest dots but in different directions. In type A1 mode, it precesses in the direction perpendicular to the antidot lattice direction. But in type A2 mode, it precesses in the direction parallel to the lattice direction. For field direction 45°, both type A1 and type A2 modes, the spin wave precesses between the two next-nearest antidot lattices. Moreover, it can be seen that spin waves are

trapped between two next-nearest dot regions. The reason for this is the dipole field distribution. The dipole field is much stronger in the nearest dots than in the next-nearest dots. This leads to the localization of spin waves in the next-nearest dot region.

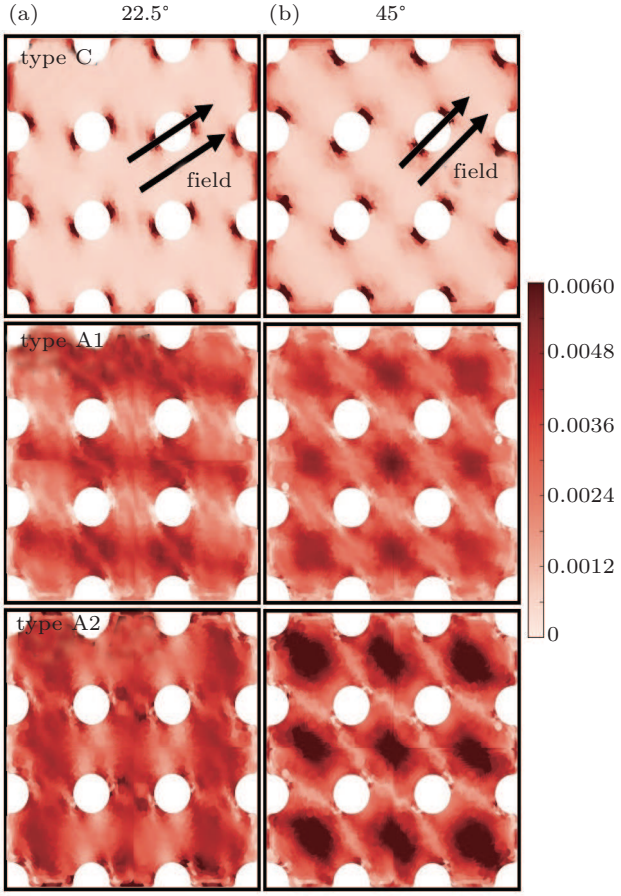


Fig. 2. (color online) Spin-wave mode profiles with different directions for antidot arrays under a magnetic field of 5×10^3 Oe (1 Oe = 79.5775 A·m^{-1}).

The distribution of the dipole field dependence on the magnetic field is plotted in Fig. 3. The top one illustrates the central region for the nearest dots (1 and 2) and next-nearest dots (3). Moreover, the lattice direction is plotted as x direction and the applied field direction is shown in Fig. 3(a). Demagnetization field dependence on the applied magnetic field is plotted in Fig. 3(b). It can be seen that the evolutions of 1 and 2 regions have exactly the same tendency, both slightly decrease with the increase of the magnetic field. For region 3 (center of next-nearest dots), it can be seen that it has the smallest absolute demagnetization field. Moreover, it increases with the increase of the applied field. The localization of spin waves can be explained by the distribution of the dipole field. For the nearest center of dots both parallel and perpendicular to the lattice direction, the dipole field has the same value, which is much larger than that in the center of the next-nearest dots. Thus, the spin wave has a tendency to be localized in the next-nearest dots region.

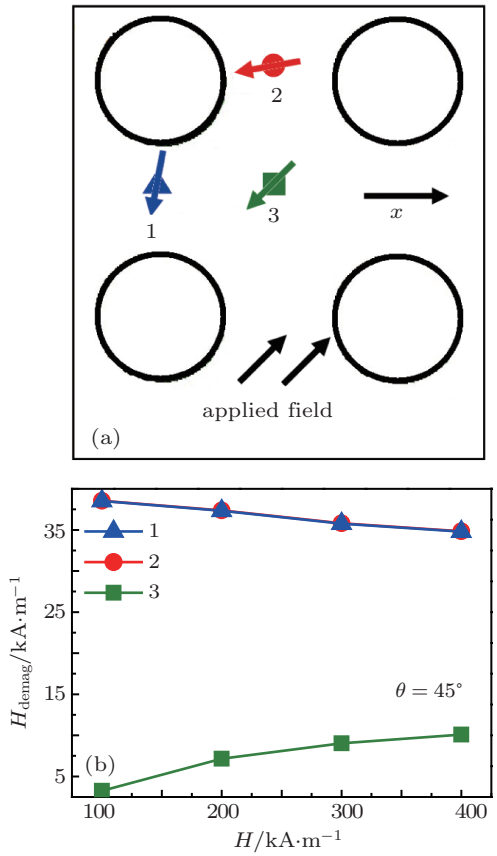


Fig. 3. (color online) Distributions of dipole field dependence on magnetic field. (a) Center region for the nearest dots (1 and 2) and next-nearest dots (3). Lattice direction is plotted as x direction and applied field direction is shown, and (b) demagnetization field dependences on applied magnetic field.

4. Conclusions

In this paper, spin wave modes are observed for antidot arrays at different angles of an applied field. In a given resonance frequency, the resonance field has a tendency of sinusoid/cosine variation with the applied field direction for these observed modes. Moreover, the NMAG software package is used here to simulate resonance frequency. The simulated results are in agreement with experimental ones. In order to see the spin wave intrinsic property for these modes, mode profiles are shown at given field directions. A new dot-localized mode is predicted, which is analogous to the edge mode of a stripe. Spin wave localizations in these modes are shown to be caused by the distribution of the demagnetization field.

References

[1] Yu Chengtao, Pechan Michael J and Mankey Gary J 2003 *Appl. Phys. Lett.* **83** 3948

[2] Garcia-Sanchez F, Paz E, Pigazo F, Chubykalo-Fesenko O, Palomares F J, Gonzalez J M, Cebollada F, Bartolome J and Garcia L M 2008 *Europhys. Lett.* **84** 67002

[3] Pechan Michael J, Yu Chengtao, Compton R L, Park J P and Crowell P A 2005 *J. Appl. Phys.* **97** 10J903

[4] Schneider T, Serga A A, Leven B, Hillebrands B, Stamps R L and Kostylev M P 2008 *Appl. Phys. Lett.* **92** 022505

[5] Allwood D A, Xiong G, Faulkner C C, Atkinson D, Petit D and Cowburn R P 2005 *Science* **309** 1688.

[6] Wang F and Xu X H 2014 *Chin. Phys. B* **23** 036802

[7] Zhou W P, Yun G H and Liang X X 2009 *Chin. Phys. B* **18** 5496

[8] Madami Marco, Montoncello Federico, Capuzzo Giulia, Giovannini Loris, Nizzoli Fabrizio, Gubbiotti Gianluca, Tacchi Silvia, Carlotti Giovanni, Tanigawa Hirobonu and Ono Teruo 2010 *IEEE Trans. Magn.* **46** 1531

[9] Madami M, Carlotti G, Gubbiotti G, Scarponi F, Tacchi S and Ono T 2011 *J. Appl. Phys.* **109** 07B901

[10] Zhang W J, He S K, Li B H, Cheng F, Xu B, Wen Z C, Cao W H, Xiao H, Han X F, Zhao S P and Qiu X G 2012 *Chin. Phys. B* **21** 077401

[11] Cowburn R P, Adeyeye A O and Bland J A C 1997 *Appl. Phys. Lett.* **70** 2309

[12] Neusser S, Duerr G, Bauer H G, Tacchi S, Madami M, Woltersdorf G, Gubbiotti G, Back C H and Grundler D 2010 *Phys. Rev. Lett.* **105** 067208

[13] Martyanov O N, Yudanov V F, Lee R N, Nepijko S A, Elmers H J, Hertel R, Schneider C M and Schonhense G 2007 *Phys. Rev. B* **75** 174429

[14] Hu C L, Magaraggia R, Yuan H Y, Chang C S, Kostylev M, Tripathy D, Adeyeye A O and Stamps R L 2011 *Appl. Phys. Lett.* **98** 262508

[15] Tripathy D and Adeyeye A O 2009 *J. Appl. Phys.* **105** 07D703