Physica B 405 (2010) 1325–1328

Contents lists available at ScienceDirect

Physica B

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

Dynamic micromagnetic simulation of permalloy antidot array film

C.P. Mu, W.W. Wang, B. Zhang, Q.F. Liu, J.B. Wang *

Institute of Applied Magnetics, Key Laboratory for Magnetism and Magnetic Materials of MOE, Lanzhou University, Lanzhou 730000, PR China

A R T I C L E I N F O

Article history:
Received 28 July 2009
Received in revised form
27 November 2009
Accepted 27 November 2009

Keywords:
Micromagnetic simulation
Antidot array film
Periodic boundary condition
Permalloy
Dynamic susceptibility

A B S T R A C T

Dynamic magnetic susceptibilities of permalloy antidot array film were studied using three-dimensional (3D) object oriented micromagnetic framework (OOMMF) code with two dimensional periodic boundary condition (2DPBC) extension. Two major resonance peaks associated with different regions were found in the investigated systems. Both resonance frequencies decrease with increasing inter-hole distance. The frequency corresponding to lower resonance peak increases with increasing film thickness for $t < 20$ nm, and then the resonance frequency varies weakly with the thickness. High frequency resonance peak increases with decreasing inner radius, and disappears when the inner radius is below 10 nm. Low resonance frequency varies from 1.72 to 6.4 GHz when inner radius changes from 5 to 40 nm.

1. Introduction

Magnetic nano-scale materials have attracted much attention in recent years, not only due to its importance in fundamental investigation, but also its potential technological applications. Fundamental magnetic properties of single nanoelement have been investigated for a long time, such as nanodot [1], nanopillar [2], nanostripe [3–5], nanowire [6], nanoring [7,8]. Many patterned magnetic nano-structures, such as array of nanospheres [9,10], nanowires [11,12] and nanotubes [13] have also been investigated in analytical, numerical and experimental studies. Magnetic nanoelement arrays have received a great deal of attention because of their potential applications in high density magnetic recording media [14,15], sensors [16,17], microwave devices [18] and nanoelectromechanical systems [19]. Among those structures, antidot arrays show novel magnetic configurations by introducing periodic holes into continuous magnetic film. Static magnetic properties, such as domain structure [14,20], magnetization reversal process [21–23], magnetoresistance effect [24] and equilibrium magnetic configurations [25] have been investigated mostly. However, high frequency properties of arrays of nano-structure are still lacking, which may restrict practical applications in high density magnetic recording. For example, the storage areal density of antidot array come to the order of 750 Gb/in^2 [26]. The reading and writing speeds in magnetic recording media had been up to the order of 0.5 Gb/s [27], which are ultimately limited by the dynamic magnetic properties [23], and the study of dynamic magnetic properties of antidot array is exceeding important for future applications [23]. Ferromagnetic resonance has also been used to investigate dynamic properties of antidot arrays by experiment and simulation [23,28,29]. The behavior of isolated single antidot cannot adequately reflect the behavior of the antidot array. It is difficult to simulation a large antidot array film in micromagnetic, due to the limit of computational lower. So periodic boundary condition was introduced. We used the same method with Lebecki [30] to calculate the demagnetization interaction of a system with 2DPBC [31]. And we have implemented our algorithm [31] in the OOMMF. In this paper, we investigate the dynamic susceptibility spectra of permalloy antidot array film and isolated single antidot by using 3D OOMMF [32] with 2DPBC extension.

2. Micromagnetic theory

2.1. Method

All micromagnetic simulations are performed using 3D OOMMF code with 2DPBC extension. The simulation has been performed by solving the Landau–Lifshitz–Gilbert (LLG) ordinary differential equation [32],

$$\partial \boldsymbol{M}(\boldsymbol{r},t)/\partial t = -|\gamma|\boldsymbol{M}(\boldsymbol{r},t)\times \boldsymbol{H}_{eff}(\boldsymbol{r},t)+\alpha/M_s[\boldsymbol{M}(\boldsymbol{r},t)\times \partial \boldsymbol{M}(\boldsymbol{r},t)/\partial t],$$

$$\boldsymbol{H}_{eff}(\boldsymbol{r},t) = -(1/\mu_0)[\partial E/\partial \boldsymbol{M}(\boldsymbol{r},t)]$$

where $\boldsymbol{M}(\boldsymbol{r},\ t)$ is the magnetization distribution of the mesh, $\boldsymbol{H}_{\rm eff}(\boldsymbol{r},\ t)$ is the effective field of the mesh, M_s is the saturation magnetization, γ is the Gilbert gyromagnetic ratio (2.211×10^5 mA^{-1}s^{-1}), and α is the Gilbert damping constant. The average

---

* Corresponding author. Tel.: +86 9318914171; fax: +86 9318914160.
E-mail address: wangjb@lzu.edu.cn (J.B. Wang).

0921-4526/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.physb.2009.11.079

energy density $\boldsymbol{E}$ includes exchange, self-magnetostatic (demagnetization), anisotropy and Zeeman energy, and is a function of $\boldsymbol{M}(\boldsymbol{r}, t)$.

The micromagnetic simulations of magnetic spectra are performed in two steps. Firstly, the equilibrium magnetization configuration of element is obtained by the minimization of total energy density function:

$$E = E_{exchange} + E_{demag} + E_{anisotropy} + E_{Zeeman}$$

Secondly, a small exciting magnetic field with the form of $\boldsymbol{H}(t)=\boldsymbol{H}_0 \exp(-10^9 t)$ [33] was applied, and the time evolution of magnetic configuration under the exciting field is obtained by solving LLG equation.

2.2. Simulation

The magnetic spectra of antidot array film and isolated single antidot were investigated by dynamic micromagnetic simulation, respectively. The antidot array film was obtained by using 2DPBC extension. Same magnetic configurations of repeating element will be infinite repeated for two directions, i.e., x and y axes. The micromagnetic simulations are performed using typical permalloy parameters: saturation magnetization $M_s=8.6\times10^5$ A/m, exchange stiffness constant $A=13\times10^{-12}$ J/m, and magnetocrystalline anisotropy constants $K_1=K_2=0\,\mathrm{J/m^3}$. Since our material has no magnetocrystalline anisotropy, the total energy includes exchange, demagnetization and Zeeman energy. Gilbert damping constants α are 0.5 and 0.025 [1] for the equilibrium magnetization configuration and the dynamic response with small exciting field, respectively. The uniform time interval is 1 ps and the mesh sizes are $5\times5\times5\,\mathrm{nm^3}$ [34].

In order to study the magnetic spectra of the system, the system were relaxed without external field [6,8,33] and the magnetization configuration of equilibrium states was obtained first. Then, a small exciting magnetic field with the form of $\boldsymbol{H}(t)=1000\exp(-10^9 t)$ [33] (t in s, $\boldsymbol{H}(t)$ in A/m) was applied to the equilibrium state and parallel to the x direction. The amplitude of exciting magnetic field is small enough to remain in the linear response region. The small exciting magnetic field $\boldsymbol{H}(t)$ and the magnetization distribution $\boldsymbol{M}(\boldsymbol{r}, t)$ were transformed to the frequency domain [$\boldsymbol{H}(\omega)$, $\boldsymbol{M}(\omega)$] by using the fast Fourier transform (FFT) method, respectively. Complex magnetic susceptibility ($\boldsymbol{\chi}=\boldsymbol{\chi}'-j\boldsymbol{\chi}''$) can be calculated by $\boldsymbol{\chi}(\omega)=\boldsymbol{M}(\omega)/\boldsymbol{H}(\omega)$. The imaginary part of susceptibility ($\boldsymbol{\chi}''$) can be obtained by dividing the FFT of the response [$\boldsymbol{M}(\omega)$] and the FFT of the excitation [$\boldsymbol{H}(\omega)$].

3. Results and discussion

Geometry dimensions of repeating element of antidot array are characterized by thickness $t=20$ nm, inner radius $r=25$ nm and inter-hole distance $d=50$ nm firstly. An isolated single antidot, which has same dimensions parameters as one the repeating element of the antidot array, is also investigated for reference. Fig. 1(a) demonstrates the equilibrium magnetization of repeating element of permalloy antidot array. It indicates that stripe-shaped domains appear in antidot array film through the hole, which attributes to the shape anisotropy induced by holes and magnetic dipolar interaction of neighboring repeating elements [20]. However, for an isolated single antidot as shown in Fig. 1(b), a vortex-type magnetic configuration can be found due to the edge effects.

Fig. 2 shows the imaginary part of the susceptibility of antidot array film and isolated single antidot. But the resonance frequencies of antidot array film is lower than those of isolated single antidot. The lower resonance frequency for antidot array film can be explained as follows. Due to the magnetic dipolar interaction induced by repeating element, the demagnetization energy of antidot array film is lower than that of isolated single antidot, consequently lower the effective field and the resonance frequencies.

Both resonance peaks 2 and 2′ attribute to spin configuration area with high value of y component of magnetization. While resonance peak 1 comes from four corner regions and strip domain, and resonance peak 1′ from four corner regions [35]. The following are that the resonance frequencies of antidot array film vary as function of antidot array's space parameters.

Evolution of resonance frequencies of antidot array film was investigated as a function of inter-hole distance, as shown in Fig. 3. With increasing inter-hole distance, both resonance frequencies decrease, which shows the same tendency as that in the experiment [23]. The smaller inter-hole distance, the stronger shape anisotropy is induced by periodic holes. That results in the decrease of the effective field.

The evolution of resonance frequencies are also investigated by changing the inner radius of antidot array under same inter-hole distance (50 nm) and thickness (20 nm) (see Fig. 4). The resonance frequency of peak 2 increases with decreasing inner radius. Then the resonance peak 2 disappears until the inner radius decreases to 10 and 5 nm. When the inner radius is much smaller than the

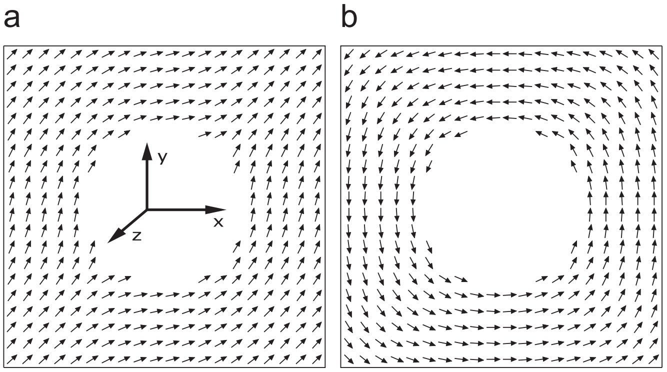

Fig. 1. Equilibrium magnetizations of repeating element of permalloy antidot array film with inter-hole distance $d=50$ nm, inner radius $r=25$ nm, thickness $t=20$ nm (a) and isolated single antidot (b).

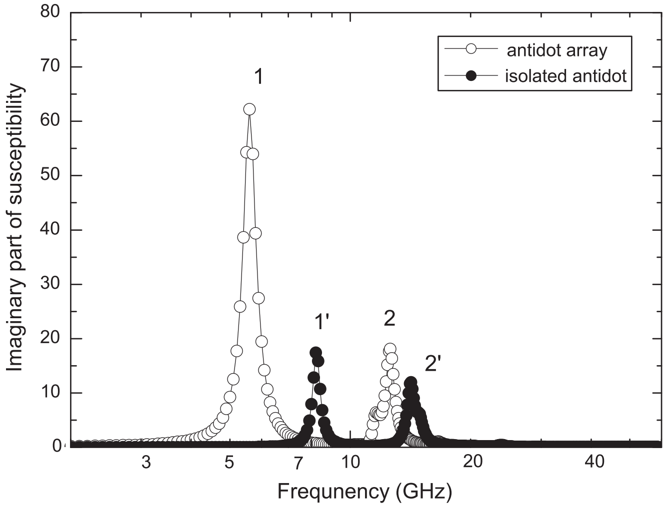

Fig. 2. Calculated imaginary susceptibility of permalloy antidot array with inter-hole distance $d=50$ nm, inner radius $r=25$ nm, thickness $t=20$ nm (open-dot line) and isolated single antidot with same dimensions parameters as one of the repeating element of the antidot array (solid-dot line).