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Effects of point defect shapes on defect modes in two-dimensional magnonic crystals

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ABSTRACT

Based on the plane-wave expansion method, the effects of point defect shapes on defect modes of spin waves in two-dimensional magnonic crystals are numerically investigated. The considered point defect bodies include square defect, circular defect and rectangular defect. For both cases of square defect or circular defect, the defect modes vary obviously as the shape of the defect body only for a bigger defect filling fraction. However, for the case of rectangular defect, the defect modes show a dependence on its shape even if the defect filling fraction is smaller, and the double degeneration of rectangular defect mode will split into two nondegenerate modes when the ratio of edge widths of the rectangular defect reaches a certain value. Besides, whether square defect or rectangular defect, the defect modes change with the orientation of the point defect localizing in the cell only for a bigger defect filling fraction. Such an approach of changing shape of point body may open up a new scope for engineering defect modes and band gaps of spin waves in two-dimensional magnonic crystals.

1. Introduction

Since the magnetic superlattices become the research focus in the 1980s, the propagation of spin waves in the magnonic crystals (MCs) was investigated experimentally [1,2] and theoretically [3–5]. Some comprehensive reports on MCs can be found in the review papers [6,7]. Such periodic magnetic composite materials can exhibit magnonic gaps, in which, the spin waves are forbidden completely to propagate in any direction of the periodic structure. Moreover, the existence of the spin-wave gaps makes the MCs possess many potential engineering applications, such as the design of microwave filters [8], waveguides [9,10], spin switching [11], current controlled delay lines [12], sensors [13], and so on.

Although most of researches devoted into searching the optimal conditions of the existence of spin-wave band gaps [4,5,14–18], a few works have been devoted to localization phenomena [19–23] of defects in MCs. Kruglyak and Kuchko et al. [20,21] have studied the properties of defect states in one-dimensional (1D) MCs, and found that spin waves were localized around defects. Recently, we have paid attentions to defect states of two-dimensional (2D) MCs with point defects or line defects [22,23], and found the point defect modes are very well localized in the vicinity of the defect body, furthermore, the spin waves with certain frequencies can be propagated along the arrangement direction of defects for multi-point defects and line defects. Such properties can be used as the fabricating materials of spin-wave filters or waveguides.

However, the defect bodies in previous works mentioned above are almost formed by changing the size of one or several scatterers embedded in matrix, and the shapes and arrangement orientations of defect bodies are same as other perfect scatterers. In this work, we try to study the effects of the shape and the orientation of the defects on the properties of defect modes in 2D MCs.

2. Model and method

Now, we consider a point defect in the 2D MCs composed of Fe (with exchange constant $A = 2.1 \times 10^{-11}$ Jm^{-1} and spontaneous magnetization $M_s = 1.752 \times 10^6\ Am^{-1}$) square rods with a square array embedded in a EuO ($A = 0.1 \times 10^{-11}$ Jm^{-1}, $M_s = 1.910 \times 10^6\ Am^{-1}$) matrix. The cross sections of the 9×9 supercell of the 2D MCs with three different shapes of point defect are sketched into Fig. 1, where a is the lattice constant and θ is the rotational angle. The point defect can be introduced by changing the edge width and the rotational angle of the square rod located at the center of the supercell shown in Fig. 1(a), or by replacing the square defect with a circular one shown in Fig. 1(b) and with a rectangular one in Fig. 1(c).

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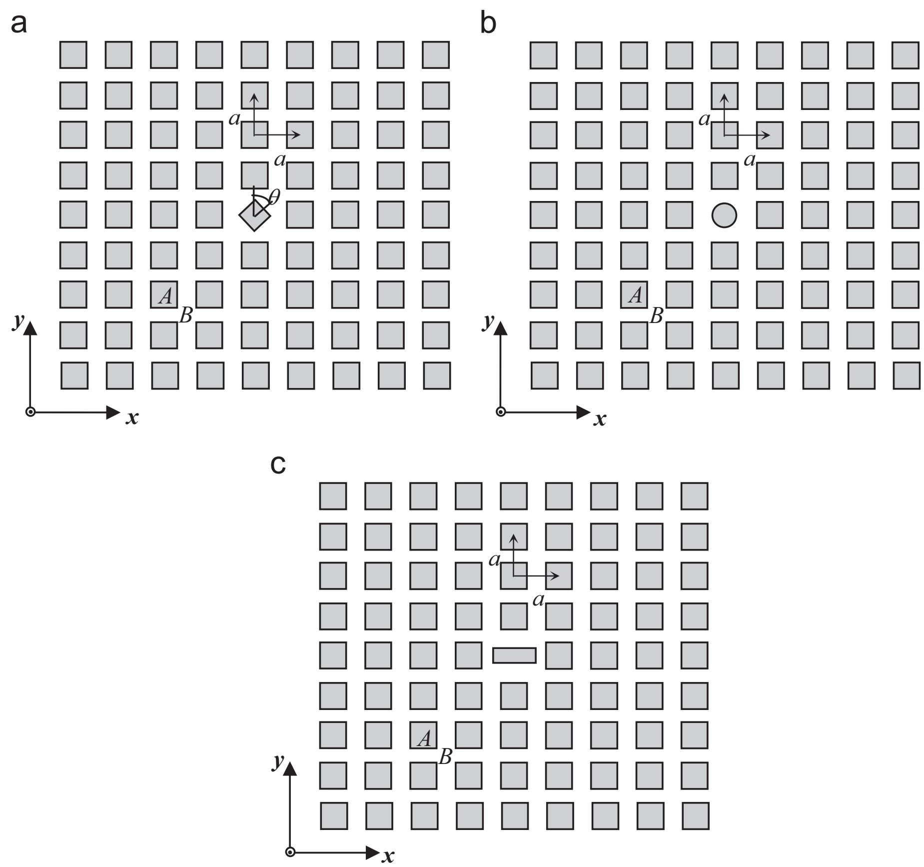

Fig. 1. The transverse cross section of 2D MCs with different shapes point defects. (a) Square defect, (b) circular defect, and (c) rectangular defect.

The propagation of spin waves in homogeneous isotropic ferromagnetic materials can be described by the Landau–Lifshitz equation without a damping term [5]

$$\frac{\partial}{\partial t}\boldsymbol{M}(\boldsymbol{r},t) = -g\boldsymbol{M}(\boldsymbol{r},t)\times\boldsymbol{H}_{eff}(\boldsymbol{r},t), \tag{1}$$

where g is the gyromagnetic ratio ($g>0$) and $\boldsymbol{H}_{eff}$ is an effective magnetic field acting on the magnetization $\boldsymbol{M}(\boldsymbol{r},t)$. When considering short-wavelength perturbations, the magnetostatic term can be neglected as compared to the exchange term [24], and so the effective magnetic field can be described as

$$\boldsymbol{H}_{eff}(\boldsymbol{r},t) = H_0\boldsymbol{z}+\frac{\partial}{\partial \boldsymbol{r}}\left(\alpha_0\frac{\partial}{\partial \boldsymbol{r}}\boldsymbol{M}(\boldsymbol{r},t)\right), \tag{2}$$

in which, $\alpha_0 = 2A/\mu_0 M_s^2$. M_s and A are the spontaneous magnetization and the exchange constants of ferromagnetic material, respectively. Both of ferromagnetic materials are assumed to be sufficiently magnetized parallel to the applied magnetic field $\boldsymbol{H}_0$ along the z-direction shown in Fig. 1. Magnetization $\boldsymbol{M}(\boldsymbol{r},t)$ can be written as

$$\boldsymbol{M}(\boldsymbol{r},t) = M_s\boldsymbol{z}+\boldsymbol{m}(\boldsymbol{r},t), \tag{3}$$

where $\boldsymbol{m}(\boldsymbol{r},t)$ is the dynamic component of the magnetization in the x–y plane as shown in Fig. 1, and $|\boldsymbol{m}(\boldsymbol{r},t)| \ll M_s$.

In the process of calculation, we use the usual linear-magnon approximation of neglecting, in Eq. (1), the small terms of second order in $\boldsymbol{m}(\boldsymbol{r},t)$. After some algebraic operations from Eqs. (1)–(3), the eigen equation of the system can be easily obtained with a plane-wave expansion method (PWM) [18,25], and the eigen equation is written as follows:

$$\Omega m_{\pm\omega}(\boldsymbol{G}) = \sum_{\boldsymbol{G}'}[\mu_0 H_0\delta(\boldsymbol{G}-\boldsymbol{G}')+(\boldsymbol{k}+\boldsymbol{G})(\boldsymbol{k}+\boldsymbol{G}')\alpha(\boldsymbol{G}-\boldsymbol{G}')]m_{\pm\omega}(\boldsymbol{G}'), \tag{4}$$

where $\Omega=\mu_0\omega/g$, $\alpha = 2A/M_s$, and $\delta(\boldsymbol{G}-\boldsymbol{G}') = \begin{cases} 1 & \boldsymbol{G}=\boldsymbol{G}', \\ 0 & \boldsymbol{G}\neq\boldsymbol{G}'. \end{cases}$

One can easily obtain the magnon band structure $\Omega(\boldsymbol{k})$ by numerical solving the Eq. (4). The lattice constant $a=100$ Å and the applied magnetic field $\mu_0 H_0 = 0.1\ T$ are chosen in the whole calculation process. It is notable that the supercell approximation will be employed in the numerical calculations, and 3249 reciprocal vectors are used in the following computations for a good convergence.

3. Results and discussions

In our previous work [22], we have investigated the properties of point defect in 2D MCs when $f=0.60$ and $f_d=0.006$ for nonrotating the square defect rods ($\theta=0^\circ$), where f and f_d are regular and defect filling fraction, respectively. Now, to study the effects of the orientation of the square defect on the defect modes, the band structures with different rotational angle θ are calculated. Fig. 2 shows the case of $\theta=30^\circ$ for $f=0.60$ and $f_d=0.006$, in which, one can clearly see that a band gap lies in the range of (1.1584–1.6663) ($\mu_0\omega/g$), and three flat defect modes (the uppermost defect mode is a double degenerate mode) can be found in the gap. Meanwhile, five sets of numerical results corresponding with other five rotational angles $\theta=5^\circ, 15^\circ, 25^\circ, 35^\circ, 45^\circ$ are given in Table 1, and we also can immediately find that these results are almost the same as the case of $\theta=0^\circ$. Moreover, the results for the circular defect are exhibited in Table 1 when $f=0.60$ and