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Magnon band structure and magnon density in one-dimensional magnonic crystals

Rong-ke Qiu [a,*], Te Huang [a], Zhi-dong Zhang [b]

[a] Shenyang University of Technology, Shenyang 110870, PR China
[b] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, PR China

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ABSTRACT

By using Callen's Green's function method and the Tyablikov and Anderson–Callen decoupling approximations, we systematically study the magnon band structure and magnon density perpendicular to the superlattice plane of one-dimensional magnonic crystals, with a superlattice consisting of two magnetic layers with ferromagnetic (FM) or antiferromagnetic (AFM) interlayer exchange coupling. The effects of temperature, interlayer coupling, anisotropy and external magnetic field on the magnon-energy band and magnon density in the K_x-direction are investigated in three situations: a) the magnon band of magnetic superlattices with FM interlayer coupling, b) separate and c) overlapping magnon bands of magnetic superlattices with AFM interlayer coupling. In the present work, a quantum approach is developed to study the magnon band structure and magnon density of magnonic crystals and the results are beneficial for the design of magnonic-crystal waveguides or gigahertz-range spin-wave filters.

1. Introduction

It is interesting to investigate the energy band (if an energy gap exists) and the density for different particles and quasiparticles, such as photons [1], electrons [2] and phonons [3,4] in a periodic medium. Yablonovitch and Gmitter [1] have identified the photonic crystal that actually has a band gap and describes the behavior of electromagnetic waves in 3D periodic face-centered-cubic (fcc) dielectric structures. Periodically modulated magnetic materials have been explored to form magnonic crystals, a magnetic analogue of photonic crystals, in which the information carriers are spin waves (SWs). Due to particular properties of SW spectra, magnonic devices should offer important functionalities that are different from those of photonic and electronic devices. For example, magnonic devices can easily be controlled by an applied magnetic field. In magnonic crystals, the SW band spectrum consists of bands of allowed magnonic states and forbidden-frequencies gaps (in which magnonic states are not allowed), which are deterministically dependent on the pattern design [5,6]. 3D magnonic crystals are the least studied objects in magnonics, because of the difficulty of theoretical and experimental investigations [7–9]. Collective SW modes in 3D arrays of ferromagnetic (FM) particles in non-magnetic matrices have been studied [7]. 2D magnonic crystals have been proposed [10,11], consisting of periodically arranged infinitely long FM cylinders embedded in a matrix of a different FM material. An external static magnetic field was applied along the direction of the cylinders and both FM materials were assumed to be magnetized parallel to it. The existence of gaps is related to the physical parameters (spontaneous magnetization M_S and exchange constant A) of the materials involved.

Along the growth direction (or along the array direction for magnetic stripes), superlattices, which consist of a sequence of layers (or stripes) with alternating magnetic properties, can be viewed as 1D magnonic crystals. 1D magnonic crystals have attracted enthusiastic attention in the past few years, due to the fundamental interest and their potential application in magnonic devices [5,12]. Especially, 1D magnonic crystals can be used as magnonic-crystal waveguides or SW filters [13]. A robust magnonic-crystal waveguide structure has been formed, which consists of serial combinations of various width modulations with different periodicities and motifs in planar-patterned thin-film nanostrips composed of a soft-magnetic material. The magnonic-crystal waveguide can be used as an efficient gigahertz-range SW filter that only lets pass magnons of selected narrow band frequencies and filters out magnons with other frequencies [13]. The magnon band structure of magnonic crystals can be affected by an applied magnetic field [14]. Recently, it has been found that the band structure of magnonic crystals with antiferromagnetic (AFM) exchange coupling of the magnetic layers (or stripes) is

* Corresponding author. Tel.: +86 13591494026.
E-mail address: rkqiu@163.com (R.-k. Qiu).

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different from that with FM coupling [15,16]. SW excitations (magnons) have been investigated in a 1D magnonic crystal prepared from $Ni_{80}Fe_{20}$ nanowires. Experiments and simulations have shown that there are two different magnon band structures depending on the magnetic ordering of neighboring wires, i.e. parallel and antiparallel alignments [15].

Different theoretical methods have been used to study the magnon band of 1D magnonic crystals. Within the framework of the long-wavelength Heisenberg model, a simple magnonic monomode circuit has been designed to obtain stop (or pass) bands where the propagation of SWs is forbidden (or allowed). This simple device is composed of an infinite 1D monomode waveguide (the backbone) along which side resonators (symmetric or asymmetric loops) are grafted. This study was performed with the help of Interface Response Theory which permits one to calculate the Green's function of any composite material [17]. The magnonic band structures for exchange SWs propagation in 1D-magnonic-crystal waveguides of different material combinations have been investigated by means of micromagnetic simulations, which calculate the dynamics of the magnetization by solving the Landau–Lifshitz–Gilbert equation. The waveguides are periodic arrays of alternating nanostripes of different FM materials. The widths and center frequencies of the band gaps are controllable by the component materials, the stripe widths, the applied magnetic field and the exchange interaction [18,19]. The magnon dispersion for two FM layers has been calculated in the pure exchange limit, in the pure dipolar limit and in the presence of both exchange and dipolar interactions. It was shown that the derived magnon-energy gaps mainly result from the exchange interaction [20,21]. A magnon-energy gap has also been computed to exist in layered composite materials [22].

In order to design magnonic-crystal waveguides or SW filters, a study of the various magnon-band structures and magnon densities of 1D magnonic crystals is necessary and one has to further develop some theoretical approaches. Most of the earlier work has mainly used the classical method of the Landau–Lifshitz equation (or based on the Landau–Lifshitz equation), while quantum methods have seldom been used [23–27,30]. The classical method ignores the effect of quantum fluctuations, whereas the quantum method is more accurate and touches the essential physics [23]. Furthermore, to discuss the magnon band structure and magnon density, one needs to study short-wavelength cases in the Brillouin zone. In order to consider both the discrete effect (related to a short wavelength) and the quantum effect, a discrete quantum spin Heisenberg model can be applied to study the magnon band structure and magnon density [23]. The SW spectra of infinite, semi-infinite and finite FM superlattices have been analyzed in the exchange-dominated region within the transfer-matrix formalism [24,25]. These studies were devoted to the important investigation of magnon spectra, but did not focus on the magnon-energy gap and magnon density. Deng et al. [23] have studied the magnon-energy band of a periodic anisotropic two-layer magnetic superlattice by using local coordinates and a spin-Bose transformation quantum approach. Here, in the energy-gap vs applied-field diagram three phases have been derived from quantum fluctuations. The temperature dependence of the magnetization and the optical magnon gap in an AFM YBaCuO bilayer has been obtained by employing the Green's function technique and the Callen decoupling approximation [26]. The magnonic band gaps, in the terahertz frequency range, in periodic and quasiperiodic (Fibonacci sequence) magnonic crystals formed by layers of cobalt and permalloy, have been investigated, using a magnetic Heisenberg Hamiltonian in the exchange regime, together with a transfer-matrix treatment within the random-phase approximation [27]. This previous work, using quantum methods, was only focused on the study of the width of the magnon band gaps, but did not deal with the magnon density and the total band structure.

The magnon density is an important quantity to measure the excitation probability of a propagating SW in a passband. The SW density of states for spin-1/2 Heisenberg ferromagnets has been calculated by means of the quantum Green's function method [28,29]. Thus far, there is no report on the magnon density of magnonic crystals using the quantum method (we define the number of magnons with a certain frequency in a frequency interval of one frequency unit as the magnon density at this particular frequency). The magnon band structure and magnon density of a 1-D magnonic crystal can be significantly affected by an applied magnetic field [18,23,30], by the interlayer exchange coupling [18,25,30] and by the magnetic anisotropy [23,30], while also the temperature should have influence. However, studies on these issues are rare.

The theoretical studies mentioned above are mainly focused on magnonic crystals with FM interlayer coupling, while there is not much theoretical work for AFM coupling. Earlier, we have studied the magnon band gap in a superlattice composed of two alternating FM materials with AFM interlayer coupling by means of Callen's Green's function method and the Tyablikov decoupling approximation [30]. Only the magnon band gap was studied and the Tyablikov decoupling approximation was applied for the single-ion anisotropy term. However, it is believed that the Anderson–Callen decoupling approximation is more accurate for the single-ion anisotropy term [31,32] and that the use of different decoupling procedures for the exchange and anisotropy contributions is an important detail [33]. Therefore, in the present work, the Anderson–Callen decoupling approximations will be used to treat the single-ion-anisotropy term.

In this work, we study systematically the magnon band structure and magnon density of SWs propagating along the direction perpendicular to the superlattice plane by using Callen's Green's function method, the Tyablikov approximations (for the exchange coupling term) and the Anderson–Callen decoupling approximations (for the single-ion anisotropy term). The periodic anisotropic magnetic superlattice is formed by two alternating FM layers with FM or AFM interlayer coupling. The effects of temperature, anisotropy, interlayer coupling and external magnetic field on the magnon band structure and the magnon density are investigated. Especially, we report an overlap of the magnon density of two energy spectra in the magnon band of a magnetic superlattice with AFM interlayer coupling. Our study shows the existence of a diversity of magnon band structures and magnon densities and provides a theoretical basis for the design of magnonic-crystal waveguides or SW filters with different frequency bands and magnon densities.

The outline of the paper is as follows: in Section 2, we describe the model and the calculation procedure. Section 3 presents the effects of temperature, anisotropy, interlayer exchange coupling and external magnetic field on the magnon band structure and magnon density in a two-layer superlattice with FM or AFM interlayer coupling. In Section 4, conclusions are presented.

2. Model and calculation procedure

The superlattice, investigated in the present paper, is composed of two kinds of periodically arranged FM thin films with different anisotropies. We consider a Heisenberg model with single-ion anisotropy for a two-layer simple cubic magnetic superlattice. A schematic representation of the two-layer superlattice is shown in Fig. 1.

The two magnetic layers (representing two coupled thin films) lie in the y–z plane, the superlattice structure is stacked