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Band structure of collective modes and effective properties of binary magnonic crystals☆

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Abstract

In this paper a theoretical study of the band structure of collective modes of binary ferromagnetic systems formed by a submicrometric periodic array of cylindrical cobalt nanodots partially or completely embedded into a permalloy ferromagnetic film is performed. The binary ferromagnetic systems studied are two-dimensional periodic, but they can be regarded as three-dimensional, since the magnetization is non uniform also along the z direction due to the contrast between the saturation magnetizations of the two ferromagnetic materials along the thickness. The dynamical matrix method, a finite-difference micromagnetic approach, formulated for studying the dynamics in one-component periodic ferromagnetic systems is generalized to ferromagnetic systems composed by F ferromagnetic materials. It is then applied to investigate the spin dynamics in four periodic binary ferromagnetic systems differing each other for the volume of cobalt dots and for the relative position of cobalt dots within the primitive cell. The dispersion curves of the most representative frequency modes are calculated for each system for an in-plane applied magnetic field perpendicular to the Bloch wave vector. The dependence of the dispersion curves on the cobalt quantity and position is discussed in terms of distribution of effective ''surface magnetic charges'' at the interface between the two ferromagnetic materials. The metamaterial properties in the propagative regime are also studied (1) by introducing an effective magnetization and effective ''surface magnetic charges'' (2) by describing the metamaterial wave dispersion of the most representative mode in each system within an effective medium approximation and in the dipole-exchange regime. It is also shown that the interchange between cobalt and permalloy does not necessarily lead to an interchange of the corresponding mode dispersion. Analogously to the case of electromagnetic waves in two-dimensional photonic crystals, the degree of localization of the localized collective modes is expressed in terms of an energy concentration factor.

Keywords: Magnonic crystals; Band structure; Binary magnetic systems; Effective properties; Metamaterials; Energy concentration factor

1. Introduction

During the last decade much attention has been devoted to the study of magnonic crystals (MCs) for their challenging properties like, for example, the control of spin wave propagation and also for their potential applications (see e.g., [1,2]). This kind of studies is similar to the ones carried out for studying light propagation and electromagnetic bands in photonic crystals (PHCs) [3].

Several theoretical and experimental investigations have been carried out for characterizing collective

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modes and for determining the magnonic band structure in one-dimensional (1D) and two-dimensional (2D) MCs (see e.g., [4,5]). Among them, very recently, a 1D binary MC consisting of arrays of nanostripes made by alternating permalloy ($Ni_{80}Fe_{20}$, Py) and cobalt (Co) materials and exhibiting allowed minibands and frequency gaps was experimentally investigated [6]. Moreover, a micromagnetic study of magnonic band structures of exchange spin waves propagating in 1D binary MCs made by arrays of alternating cobalt and nickel stripes was carried out [7]. On the other hand, band structure of 2D MCs consisting of different magnetic materials was studied theoretically as a function of the filling fraction and of the lattice parameter [4]. Moreover, micromagnetic simulations were performed to study spin wave propagation in binary MC waveguides [8,9].

The recent works on 2D binary ferromagnetic systems (BFMSs) deal either with time-domain analysis of spin wave dynamics [10] or with modelling of dispersion and opening of band gaps (BGs) at edges of Brillouin zones (nBZs with $n = 1, 2, \ldots$) based on analytical approaches confirming Brillouin light scattering (BLS) measurements [11]. More specifically, the experimental BLS dispersion was measured for a BFMS consisting of Co cylindrical dots partially embedded into a Py continuous film and was theoretically determined by using an analytical approach, called plane wave method (PWM) [12]. The PWM is a powerful and general analytical approach based on the Fourier expansion of the dynamic magnetization and formulated to determine the band structure of different types of binary 1D, 2D and three-dimensional (3D) MCs. In particular, in [11] it was applied to study the band behaviour and BGs of collective modes of binary 2D MCs under the assumption that Co cylindrical dots were completely etched into the Py film. Recently, the PWM was also applied to study the dispersion of binary periodic ferromagnetic systems formed by Co rods arranged in sites of a 2D square lattice and completely embedded in an iron matrix [13] and to explain, when used in combination with the empty lattice model, the mechanism responsible for the shaping of different parts of the corresponding magnonic spectra [14]. On the other hand, spin-wave mode frequencies in Py/Co binary systems (with Co nanodisks partially etched into the Py film) were also determined as a function of the external magnetic field and for vanishing Bloch wave vector both experimentally and according to micromagnetic simulations [15].

The main limitation of the PWM is the fact that it can be applied only to 2D BFMSs without introducing a non-uniformity of the magnetization arising from the contrast of the two ferromagnetic materials along the z direction. In this paper we overcome this restriction introducing magnetization non-uniformity along the z direction by taking into account the magnetization contrast along the thickness of the BFMS. This extension allows us to study the band behaviour of four different BFMSs depending on both the Co volume (V_{Co}) and the relative position of Co cylindrical dots with respect to Py continuous film within the primitive cell. Indeed, to the best of our knowledge, a general analysis of the effect of the quantity and of the relative position of Co cylindrical dots on collective mode band structure still lacks in the literature. In this respect, the dynamical matrix method (DMM), recently developed and applied to periodic 2D and one-component MCs [16], was extended to study systems composed by F ferromagnetic materials (multi-component MCs) and applied to BFMSs ($F = 2$) with one material periodically included into the matrix of the other material. The DMM is a finite-difference method representing an eigenvalue/eigenvector problem. According to this method, the frequencies and profiles of the collective spin-wave modes in a purely conservative regime associated to the eigenvalues and the eigenvectors, respectively, of a dynamical matrix are found. The eigenvalue/eigenvector problem derived from the Hamilton equations of motion can be set as a complex generalized Hermitian Eigenvalue problem. The method presents several advantages: a single calculation yields the frequencies and eigenvectors of all modes of any symmetry, it is applicable to a particle of any shape (within the nanometric range) and the computation time is affordable. It is thus possible to determine, after a single iteration, the frequencies and the profiles of all collective modes, independently of the ground-state magnetization. The main restriction of the method is its applicability to laterally confined periodic systems under the assumption of a purely precessional spin dynamics. The BFMSs studied are 2D periodic (in the x–y plane), but they can be regarded as 3D, since the magnetization is assumed non uniform not only in the x–y plane, but also along z. The non uniform magnetization along the thickness which is mainly due to the contrast between the two ferromagnetic materials is taken into account by subdividing in the simulations the systems into a stack of layers along z. A study of BG behaviour up to the 5th Brillouin zone (BZ) for the two most representative families of magnonic modes according to DMM is also given. By using the notion of effective magnetization and effective field and by studying the BFMS as an effective medium [17], interesting effective properties in the propagative