Spin-wave modes and band structure of rectangular CoFeB antidot lattices

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We present an investigation of rectangular antidot lattices in a CoFeB film. Magnonic band structures are numerically calculated, and band gaps are predicted which shift in frequency by 0.9GHz when rotating the external field from the long to the short axis of the unit cell. We demonstrate by time-resolved experiments that magnonic dipolar surface modes are split in frequency by 0.6GHz which agrees well with the theoretical prediction. These findings provide the basis for directional spin-wave filtering with magnonic devices.

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The use of spin waves opens up routes to new computing devices with advantages over today’s CMOS-based technology. Although magnetic damping is comparably high (requiring small-scale devices), Joule’s heating caused by electron currents is avoided [1]. Much research has been devoted to interferometer-like structures [2], inspired by the possibility of (local) spin-wave phase manipulation by Oersted fields [3]. On the other hand, effective spin-wave filters can be designed on the basis of ferromagnetic stripes with modulated widths [4,6]. One concept of spin-wave excitation and detection is based on rf-antennas which, however, cannot be put in arbitrary proximity, due to inductive coupling. If, instead, the excitation was achieved by intense light pulses as implemented in heat-assisted recording in modern hard disc drives [7,8], only one antenna would be needed for detection. Hence, effective mechanisms for spin-wave selection from the broad-band (laser) excitation are required. It has been shown that magnonic crystals inhibit the necessary features: two-dimensional antidot lattices show Bloch-like modes with distinct wave vector, which is in turn tunable by the magnonic lattice parameter [9]. These modes propagate in the Damon-Eshbach (DE) geometry, i.e. with the wave vector \( \mathbf{k} \) perpendicular to the external magnetic field \( H_{\text{ext}} \) [10]. They have for example been used for spin-wave imaging [11].

A transition between different magnonic crystals may allow the scattering of one magnonic mode into another. In particular, when propagation takes place across a (one-dimensional) interface, spin-wave tuning or filtering is viable, if the magnonic lattices in question are of similar character. This can be achieved in rectangular lattices, i.e., if the orthogonal unit vectors of the antidot lattice \( a_1 \) and \( a_2 \) differ in length. In such magnonic materials we demonstrate experimentally how the lattice anisotropy can be employed to change the spin-wave characteristics. A rotation of the magnetic field from along the long axis of the rectangular lattice to the short axis allows to decrease the spin-wave frequency by \( \approx 0.6\text{GHz} \) rerouting the spin wave by \( 90^\circ \). Namely, we observe spin-wave splitting at the Brillouin zone boundary which opens routes to magnonic spin-wave filter devices tunable by rotating the magnetic field.

In order to develop a theoretical understanding, band structure calculations are performed, the numerical formalism of which has been presented in detail in Ref. [12]. In brief, the Landau-Lifshitz-Gilbert (LLG) equation of motion is solved by a plane-wave method as developed by Puszkarski and co-workers [13]. For the case of a thin ferromagnetic film, dynamic magnetic modes can be – under neglect of the exchange interaction – assumed to be uniform across the film thickness [15]. In the lateral direction, the periodic modulation of the sample’s magnetization between film and antidots is achieved by a Fourier synthesis [13]

\[ M_S(r) = \sum_G M_S(G) e^{iGr}, \]  

where \( G \) is a two-dimensional vector of the reciprocal lattice. The profile of \( M_S \) which has been used in the calculations is plotted as a black line in Fig. 1(a) [14]. The constituting reciprocal lattice vectors are shown in Fig. 1(b) [15]. These provide a compromise between a desirably high approximation of the stepwise magnetization profile on the one hand, yet fulfilling the initial assumption of mode uniformity (\( A \gg t \), with spin-wave length \( A \) and thickness \( t \)) on the other hand.

Other parameters in the calculations were \( \mu_0 M_S = 1.6\text{T} \), \( \mu_0 H_{\text{ext}} = 130\text{mT} \), and \( g = 2.04 \). An antidot lattice with \( a_1 = 3.5\mu\text{m} \) and \( a_2 = 2.5\mu\text{m} \) was the basis for both the calculations as well as the experiments to be discussed later in

FIG. 1: Uniform mode analysis in rectangular antidot lattices. (a) Calculated magnetization profile using Eq. (1) along a high-symmetry direction (solid black line). The lattice parameter \( a_1 = 3.5\mu\text{m} \) is depicted as well as the idealized profile (blue dashed line). In (b), the respective reciprocal lattice vectors in Fourier space are plotted (black points). The Brillouin zone boundary is given by the solid red line, high symmetry points \( \Gamma, X, S, \) and \( X' \) are marked in white. Reciprocal lattice unit vectors (gray arrows) are \( b_1 = 2\pi/a_1 \) and \( b_2 = 2\pi/a_2 \), respectively.
the Damon-Eshbach dispersion into the first Brillouin zone is found as expected from solid state theory (orange line). The external field was applied parallel to structures for a non-vanishing radius band structures shown in experimentally observed in an altered population of spin-wave modes. For the experiments, a Co substrate and passivated with 3nm of ruthenium. With a focus of the very broad band, neither frequency- nor states (DOS). According to general solid state theory, the flat-
vation as stated above, and \( H_s = H_{ext} \cos \phi \) is the projection of the canted external field onto the film plane (\( \phi = 30^\circ \) for the experiments presented here). Therefore, as the only free parameter the wave vector \( k_{DE} \) remains.
Given by the solid green and orange lines is the fit of the Damon-Eshbach dispersion to the experimentally determined dispersion $f_{DE}(H_{ext})$. In both cases of $H_{ext} \perp a_i$ ($i = 1, 2$) the fits yield the Damon-Eshbach wave vectors $k_{DE,1} = 0.87(7)\mu m^{-1} = 0.97 \times \pi/a_1$ and $k_{DE,2} = 1.23(7)\mu m^{-1} = 0.98 \times \pi/a_2$. Hence, not only can one single magnonic mode be defined in the structures. Instead, merely changing the relative orientation between external field and antidot lattice by $90^\circ$ is sufficient to excite a different magnonic spin-wave mode. This is accompanied by a frequency shift further detailed in which contains the Fourier spectra of the TRMOKE measurements performed at $H_{ext} = 150\,mT$. The shift of the magnonic mode’s frequency is marked by the black arrows and accounts to $0.55 \pm 0.04\,GHz$, which is similar to the value expected from the calculations in Fig. 2.

The bosonic character of spin waves becomes apparent in the condensation-like excitation in the TRMOKE experiment. As a consequence, selected spin-wave excitation is possible and processing schemes which employ the spin-wave propagation for manipulation purposes on top of mere transport can be applied. In view of the results presented in this manuscript, the interplay between the intrinsic anisotropy of the dipolar modes’ dispersion $\omega|_{LM} \neq \omega|_{M}$ and the (rectangular) anisotropy stemming from the magnonic crystals can further be employed. Namely, frequency splitting of spin waves becomes feasible, with the direction of the applied magnetic field as the external control parameter. By means of the magnetic field, the propagation direction of the spin waves is changed, accompanied by the frequency shift described above.

In conclusion, we expect from numerical calculations the opening of magnonic band gaps in the Damon-Eshbach geometry and verify this with TRMOKE results that show the optical excitation of dynamic modes with wave vectors at the Brillouin zone boundary. Thus, a controlled excitation of selected spin waves can be achieved by rotation of the external field. In a more farsighted view, interfaces between respective magnonic crystals provide interesting perspectives: a reflection of spin waves may be observed due to an abrupt change of the magnonic index of refraction. Similarly, the spin-wave splitting observed here hints towards directional switching devices for spin waves defined by rectangular (i.e. anisotropic) magnonic crystals.

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