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Report on the dissertation submitted by Mr. Mathieu MOALIC
For the degree of Doctor of Philosophy at the Adam Mickiewicz University of Poznan
Title: "Numerical Investigations of Collective Spin-Wave Dynamics in Complex Magnetic Textures and Patterned Ferromagnetic Films"

The study of spin waves in magnonic crystals and structured magnetic nanomaterials is a rapidly expanding field that continues to attract significant interest, in particular due to their potential applications in high frequency, low-power consumption information processing. The propagation of magnons in tailored magnetic materials can be controlled through the engineering of their dispersion curves. In this context, the theoretical and simulation work of Mathieu Moalic has presented several original and topical results on the dynamics of spin waves in nanoscale structured ferromagnetic films. These findings have been published in several high-quality physical journals and five of them are selected for the presentation in the thesis dissertation. They include the investigations of spin waves and magnon-magnon coupling in thin films of antidot lattices with inhomogeneous perpendicular magnetic anisotropy (PMA), the possibility and efficiency of generating second harmonics in such films, the proposition of Sierpinski-triangle networks to explore the hierarchical confinement of spin waves, and finally a theoretical support to the experimental study of magnonics in 1D YIG hole-based nanocrystals. In addition, during his thesis, Mathieu Moalic has developed new tools for micromagnetic simulation and data post-processing that can be very helpful for other researchers in the future.

The thesis is divided into 5 chapters but all the new physical results are gathered in Chapter 4 by the reproduction of five published papers (as sections 4.1 to 4.5).

Chapter 1 gives a brief introduction on the foundation of magnetism. Then, chapter 2 presents the basis of micro-magnetism simulations. First, the different components of the magnetic Hamiltonian (exchange, dipolar, Zeeman and anisotropy terms) are described, followed by the introduction of the Landau-Lifshitz-Gilbert (LLG) equation and the presentation of the magnetization configurations (magnetic domains, walls and vortices). The last part of this chapter is devoted to the discussion of spin-waves in magnetic structures and some applications of magnonic crystals for controlling and manipulating wave propagation by tailoring their dispersion curves. To be complete, this chapter would have benefited from including a number of illustrations of the spin-waves dispersion curves associated with various magnetic interactions, as well as in different magnonic crystals reported in the literature. Nevertheless, the chapter and the references cited may prove very useful as a starting point for future PhD students.

Chapter 3 describes certain technical aspects of the custom software developed by Mathieu Moalic, that were designed to enable the efficient computation and analysis of the magnetic structures studied in chapter 4. Two main components of this software are the "Amumax" simulation tool and the "Pyzfn" data post-processing package designed to handle the spatial and temporal analysis of large datasets. The development of these tools is extremely valuable, especially since they are made available to other researchers as open access resources. What is missing from this chapter is a brief overview of the mathematical methods underlying Mumax3, which enables to solve the LLG equation and provide the eigenvalues and eigenvectors or the scattering coefficients in the frequency domain, or the evolution of wave propagation in the time domain, including boundary conditions.

Chapter 4 collects the five core publications of Mathieu Moalic in well-recognized physics journals. Section 4.1 [paper: M. Moalic et al, J. Appl. Phys. 132, 213901 (2022)] explores the spin-wave excitations in thin magnetic films with perpendicular magnetic anisotropy (PMA) that are patterned with antidots surrounded by rims with reduced PMA. The local inhomogeneity of the PMA can be used to tailor the spin-waves spectra which are sensitive to the anisotropy contrast and rim's width. The magnetic film is a multilayer constituted by very thin (below nm) alternate layers of Co and Pd and described as an effective medium. Typical geometrical dimensions are period of 500 nm, antidot radius of 200 nm and rims width of 50 nm. Micromagnetic simulations are used to calculate the spin waves at the wavevector k=0 as a function of the model parameters, namely the ratio between rims and bulk anisotropies, the antidot diameter and the thickness of the rims. The spectra display a set of bulk and edge modes (localized in the rim area) and some possible hybridization when varying the parameters. The hybridization of the fundamental bulk and rim modes is attributed to magnetostatic interaction, while local exchange interaction should dominate the coupling between the fundamental bulk and higher radial rim modes. Indeed, the latter couplings are suppressed by inserting a thin spacer between the rim and the bulk.

In continuation of the preceding work, the phenomenon of magnon-magnon coupling in antidot lattices is more deeply investigated in section 4.2 [paper: M. Moalic et al, Scientific Reports, 14, 11501 (2024) and continued in S.S. Kunnath et al, Small Structures, 2400627 (2024)]. Considering an antidot lattice (ADL) with modified rim (MR), this section explores the different behaviors of bulk and rim modes as a function of the strength of the external magnetic field. A thorough analysis of the spectral evolution is presented, in particular by comparing the trends of full ADL-MR with those of two complementary subsystems, a square lattice of rings (RL) without PMA and a simplified ADL utilizing PMA but without rims. This comparison shows that the interactions between the subsystems significantly modify the spin-waves spectrum and its dependence on the magnetic field. The coupling between bulk and rim modes were studied in different frequency ranges. One main finding is the demonstration of a strong magnon-magnon coupling between the fundamental bulk mode and the second-order radial rim mode which is visible in the spectrum of ferromagnetic resonance even in the presence of a realistic damping coefficient. It is shown that the origin of this coupling is the exchange interaction between bulk and rim, mediated by the domain wall.
Overall, the phenomena studied in these sections are expected to be generic and to occur in other structured films exhibiting locally induced anisotropy. However, It would have been helpful to supplement the published papers with a discussion of a few potential applications of the structures studied.

Building on the above concepts, the object of section 4.3 [paper: M. Moalic et al, Arxiv 2509.07705v1] is to propose a design for an efficient generation of second harmonic of propagating spin waves in a thin ferromagnetic film with perpendicular magnetic anisotropy (PMA). The objective of generating high frequency magnons and exploring the non-linearity of the patterned structures is of great interest due to its several potential applications. It would have been useful to give some explanations about the non-linear coupling mechanism in the Hamiltonian and how the micromagnetic simulation tools work in this regime.
The structure is constituted by the Co/Pd multilayer containing two regions differing by their PMA: an excitation region (ER) with in-plane magnetization constituting a magnonic nanocavity and the propagating region with PMA; the two area are connected via a 90°domain wall. The excitation is generated by a microwave magnetic field *b* oriented in the perpendicular direction. The simulations are performed in both 1D (plane wave generation) and 2D (thin disk containing a central antidot surrounded by a rim). In both cases, the excitation frequency of the nanocavity f_0 falls below the lowest ferromagnetic resonance of the propagating region (at 13.9 GHz) and is then evanescent in this area while the higher harmonics nf_0 are above and can propagate. The signal is in general dominated by the second harmonic $2f_0$, whose efficiency increases non-linearly with the pump amplitude. Other higher harmonics can also appear when increasing the field *b*. The emission frequency can be tuned continuously by two parameters in the system, the bias field B_0 and the ER width w. The emission is significantly enhanced for a particular value of w, where the frequency $2f_0$ matches the frequency of a higher order mode in the nanocavity.

Overall, the above results on the nonlinear generation of propagating higher harmonics are very valuable, even though the limitations associated with the use of realistic damping values will still need to be addressed in the future.

Section 4.4 explores the spin-wave dynamics and their tunability in Sierpinski triangular lattices which are deterministic fractal structures. [paper: R. Mehta, M. Moalic et al, J.Phys.: Cond. Matter 35 (2023) 324002]. By investigating the rich spectral features of such self-similar structures and their sensitivity to the magnitude and orientation of the applied magnetic field, the aim is to propose new pathways for the design of reconfigurable aperiodic magnonic crystals.
The parameters of the magnetic material used in this study are those of Permalloy $Ni_{80}Fe_{20}$ (Py). The successive iterations of Sierpinski triangles (labelled TRI_0 to TRI_6) are obtained by starting with a complete triangle with sides measuring 2.85 microns and creating each subsequent generation from triangles whose size is halved. The spectra of the spin-wave modes and the spatial distribution of their power and phase are calculated for each generation. As a matter of comparison and discussion, similar calculations are made for individual homogenous triangles (labelled TR_0 to TR_6) and for periodic triangular arrays (P_0 to P_6). The magnetization dynamics changes significantly from individual triangles to Sierpinski arrangement, and also from generation to generation. This results in a rich and complex spectral feature including the existence and number of bandgaps, and a variety of spatial distributions. For example, a wide frequency gap is observed for a structure with an iteration number exceeding some value and a plenty of mini-frequency bandgaps at structures with high iteration numbers. The difference between periodic and Sierpinski arrangements is attributed to different inter-triangular magnetostatic interactions. The specral features are demonstrated to be sensitive to the strength and orientation angle of the applied magnetic field resulting in tunable frequency gaps and the existence of minigaps that are characteristic of the fractal structure. Despite the complexity of the spectral features, this chapter shows the variety and tunability of situations that can be obtained.
Given that the manuscript points to "*the possible applications of Sierpinski triangles as a novel multi-functional nano-magnonic devices"*, it would have been helpful to also elaborate further on this point.

Section 4.5 reports a publication [paper: K.V. Levchenko et al, Appl. Phys. Lett. 127, 172401 (2025)] on spin waves in a 1D YIG hole-based magnonic nanocrystal. This work was done in collaboration with the experimental group of Pr. A.V. Chumak and the contribution of Mathieu Moalic is dealing with the simulations of band structures and transmission spectra and the interpretation of experimental results. The magnonic crystal studied in this paper is a monomode waveguide of width 320 nm and thickness 100 nm, which is modulated by an array of holes with diameter d=150 nm and period a=1 micron. The spin wave transmission is studied in Damon-Eshbach configuration under a bias magnetic field by means of propagating spin-wave spectroscopy, supported by the dispersion curves calculation, and by microfocused Brillouin light scattering.
The simulations are based on Tetrax and Amumax softwares, respectively for the unstructured and structured waveguides. In the former, the first two modes (n=0 and 1) are edge modes that arise from nonuniform internal fields and dipolar interactions in finite-sized structures. The first resonance in the width of the waveguide is the mode n=2 whose symmetry allows an efficient excitation. There are two anti-crossings between modes n=2 and 3 where most of the spin-wave energy is efficiently transported by n=2 mode. The calculation of the dispersion curves in the magnonic crystals reveals well-defined passbands and bandgaps with a high rejection efficiency due to the Bragg scattering. The spin-wave dispersion enables the estimation of the relative positions of the band gaps within the magnonic spectrum, in good agreement with TetraX dispersion calculation.
As in the previous sections, a more pedagogical presentation that stands on its own, separate from the publication in a journal, would have been preferable.

In conclusion, the dissertation presents a large number of original results on the topical field of magnonic crystals and nano-patterned magnetic structures. The results are based on rigorous and complex simulation methods. Mathieu Moalic has clearly demonstrated his in-depth knowledge and understanding of physical phenomena and modeling on magnetic nanostructures, as well as his advanced computational skills. Several publications in high-impact journals that go beyond those developed in the dissertation attest to the quality of his work. Finally, it is worth highlighting his contribution to the development of new open-access tools for micromagnetic simulations and data processing.

In my opinion, the submitted dissertation entitled "Numerical Investigations of Collective Spin-Wave Dynamics in Complex Magnetic Textures and Patterned Ferromagnetic Films", fulfills the requirements set for doctoral dissertations under the applicable regulations. In particular, it demonstrates the candidate's general theoretical and computational knowledge in the discipline, confirms the ability to conduct independent scientific research, and constitutes a set of original contributions and solutions to a topical scientific field.

Therefore, I give a positive assessment of the dissertation and support its admission to the subsequent stages of the doctoral procedure / to the public defense of the doctoral dissertation at Adam Mickiewicz University, Poznań.

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