S. N. BOSE NATIONAL CENTRE FOR BASIC SCIENCES

THESIS COLLOQUIUM

SPEAKER

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TITLE OF THESIS

"Development of Nanoscale Systems for Spin-Wave Propagation"

ABSTRACT

It has been proposed that spin–waves, particularly those with frequencies in microwave and submillimeter wave bands, can be used for information transmission and processing. Having shorter wavelengths as compared to electromagnetic waves of the same frequency, spin–wave based devices hold the potential to aid the miniaturization of microwave communication. Designs have been proposed which use nanoscale magnetic systems to create elements which can function as attenuators, filters, phase–shifters, interferometers and logic gates. Here, we study the magnetization dynamics of spin–wave dispersion and magnetic vortex gyration. Both phenomenon are related and have their characteristic frequencies in the microwave frequency band. The nanoscale systems considered here are ferromagnetic thin films, uniform waveguides, magnonic crystals (spatially modulated magnetic systems) and magnetic vortices. Effects like magnetization pinning and mirror symmetry breaking, which alter the spin–wave dispersion characteristic call for greater spatial resolution and precision in fabrication. Thus, we summarize with what needs to be done and the future directions the research needs to take in order to make nanoscale devices technically feasible.

The spectrum of spin–waves propagating in magnetic systems is important from both fundamental and applied points of views. Propagating spin–waves in magnonic crystals will form the building blocks of future microwave data processing and communication. While magnonic modes and band gaps can help in the formulation of filters and attenuators, understanding other phenomena like spin–wave reflection, refraction and interference will help in designing magnonic circuit elements like logic gates and diodes.

The Landau–Lifshitz–Gilbert (LLG) equation has been used in this work to simulate the spin dynamics in different nanoscale magnetic systems. This equation was solved mainly using the finite difference method based Object–Oriented Micromagnetic Framework (OOMMF) or the finite element method based Nmag. In addition to using some existing software packages, we also developed our own LLG equation solver (which can also take spin–transfer–torque terms into account) using MATLAB programming. The combined packages of simulation and post–processing has been named DotMag. DotMag can simulate spin dynamics in two–dimensional systems and can analyse results for any kind of nanoscale system — even those solved using third party packages, such as OOMMF. The results obtained from the newly developed software have been inspected for any magnonic bands and bandgaps using multi–domain discrete Fourier transform. Various issues related to the numerical calculations like aliasing, spectral leakage and scalloping loss have been addressed in Chap. 3. The tools prepared for analysing these magnonic conductors will also allow for the visualization of propagation and power and phase distribution of the spin–wave over the entire region of interest. These tools will be generically designed, so as to accommodate any kind of magnonic conductor.

The newly developed package DotMag was used for the calculations of magnonic band structures of one– and two–dimensional periodic arrays of dots, anti-dots (holes created in continuous magnetic medium) and filled antidots (the holes are now filled with a different magnetic medium). Influence of different structural and material parameters over the spin–wave band structure was studied in these cases. The results obtained using the micromagnetic simulations were also compared with those obtained from the plane wave method (PWM) and any differences were examined. Iso–frequency lines, which are magnonic analogues of the electronic Fermi surfaces were also calculated in the case of two–dimensional antidot arrays. With the knowledge obtained from above we investigated magnonic waveguides embedded with regular and filled antidots to design magnonic filters of tunable bandwidth and bandgaps. Some of the numerically examined magnonic crystals have been fabricated by using different lithography techniques. The low wavevector magnonic modes in some of these magnonic crystals were experimentally investigated by using our TR–MOKE experimental setup.

In Chap. 5, we study the spin–wave spectra in magnonic antidot waveguides (MAWs) versus the surface anisotropy at the ferromagnet/air interface. The MAWs under investigation have the form of a thin stripe of permalloy with a single row of periodically arranged antidots in the middle. The introduction of a magnetization pinning at the edges of the permalloy stripe and the edges of antidots is found to modify quantitatively the spin–wave spectrum. This effect is shown to be necessary for magnonic gaps to open in the considered systems.

Our study demonstrates that the surface anisotropy can be crucial in the practical applications of MAWs and related structures and in the interpretation of experimental results in one- and two-dimensional magnonic crystals. We used three different theoretical methods i.e. PWM, finite difference method and finite element method to validate the results. We showed that PWM in the present formulation assumes pinned magnetization while in micromagnetic simulations special care must be taken to introduce pinning.

In Chap. 6, we theoretically study the spin–wave spectra in magnonic waveguides periodically patterned with nanoscale square antidots and show that structural changes breaking the mirror symmetry of the waveguide can close the magnonic bandgap. But, the effect of these intrinsic symmetry breaking factors can be compensated by a properly adjusted asymmetric external bias magnetic field, i.e., by an extrinsic factor. This allows for the recovery of the magnonic bandgaps occurring in the ideal symmetric structure. The described methods can be used for developing parallel models for recovering bandgaps closed due to an intrinsic defect, e.g. a fabrication defect. The theoretical model developed here is particular to the field of magnonics, a rapidly emerging field combining spin dynamics and spintronics. However, the underlying principle of this development is squarely based upon the translational and mirror symmetries associated with a regular crystal structure. Thus, we believe that this idea of correcting an intrinsic defect by extrinsic means, should be applicable to spin–waves in both exchange and dipolar interaction regimes, as well as to electron, electromagnetic and acoustic waves in general.

In Chap. 7, we present the possibility of tuning the spin–wave band structure, particularly the bandgaps in a nanoscale magnonic antidot waveguide by varying the shape of the antidots. The effects of changing the shape of the antidots on the spin-wave dispersion relation in a waveguide have been carefully monitored. We interpret the observed variations by analysing the equilibrium magnetic configuration and the magnonic power and phase distribution profiles during spin–wave dynamics. The inhomogeneity in the exchange fields at the antidot boundaries within the waveguide is found to play a crucial role in controlling the band structure at the discussed length scales. The observations recorded here will be important for future developments of magnetic antidot based magnonic crystals and waveguides.

In Chap. 8, we demonstrate that the magnonic band structure, including the band gap of a ferromagnetic antidot waveguide, can be significantly tuned by a relatively weak modulation of its structural parameters. We study the magnonic band structure in nanoscale spin-wave waveguides with periodically distributed small antidots along their central line by two independent computational methods, namely, a micromagnetic simulation and a plane-wave method. The calculations were performed with consideration of both the exchange and dipolar interactions. For the exchange dominated regime, we discuss, in details, the impact of the changes of the lattice constant, size, and shape of the antidots on the spin-wave spectra. We have shown that a precise choice of these parameters is crucial for achieving desired properties of antidot waveguides, i.e., a large group velocity and filtering properties due to existence of magnonic band gaps. We discuss different mechanisms of magnonic gap opening resulting from Bragg scattering or anticrossing of modes. We have shown that the dipolar interactions start to assert their role in the spin-wave spectrum when the waveguide is scaled up, but even for a period of few hundreds of nanometres, the magnonic band structure preserves qualitatively the properties found in the exchange dominating regime. The obtained results are important for future development of magnonic crystal based devices.

In Chap. 9, we present the observation of a complete bandgap and collective spin–wave excitation in two–dimensional magnonic crystals comprised of arrays of nanoscale antidots and nanodots, respectively. Considering that the frequencies dealt with here fall in the microwave band, these findings can be used for the development of suitable magnonic metamaterials and spin–wave based signal processing. We also present the application of a numerical procedure, to compute the dispersion relations of spin–waves for any high symmetry direction in the first Brillouin zone. The results obtained from this procedure has been reproduced and verified by the well-established PWM for an antidot lattice, when magnetization dynamics at antidot boundaries is pinned. The micromagnetic simulation based method can also be used to obtain iso–frequency contours of spin–waves. Iso–frequency contours are analogous of the Fermi surfaces and hence, they have the potential to radicalise our understanding of spin–wave dynamics. The physical origin of bands, partial and full magnonic bandgaps has been explained by plotting the spatial distribution of spin–wave energy spectral density. Although, unfettered by rigid assumptions and approximations, which afflict most analytical methods used in the study of spin–wave dynamics, micromagnetic simulations tend to be computationally demanding. Thus, the observation of collective spin–wave excitation in the case of nanodot arrays, which can obviate the need to perform simulations may also prove to be valuable.

DotMag was developed with the ability to excite vortex core gyration by using external magnetic field and spin transfer torque. Magnetic vortex dynamics was investigated in the cases of isolated and coupled vortices. Transducer and transistor like operations were demonstrated based on these results. Transistors constitute the backbone of modern day electronics. Since their advent, researchers have been seeking ways to make smaller and more efficient transistors. In Chap. 12, we demonstrate a sustained amplification of magnetic vortex core gyration in coupled two and three vortices by controlling their relative core polarities. This amplification is mediated by a cascade of antivortex solitons travelling through the dynamic stray field. We further demonstrated that the amplification can be controlled by switching the polarity of the middle vortex in a three vortex sequence and the gain can be controlled by the input signal amplitude. An attempt to show fan–out operation yielded gain for one of the symmetrically placed branches which can be reversed by switching the core polarity of all vortices in the network. The above observations promote the magnetic vortices as suitable candidates to work as stable bipolar junction transistors (BJT).

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TIME - 02:30 PM

VENUE - Silver Jubilee Hall

THESIS SUPERVISOR

Professor Anjan Barman
Department of Condensed Matter Physics and Material Sciences

All are cordially invited to attend the Colloquium.

Refreshments will be served at after the colloquium.