# Review Report on PhD Thesis

Faculty: **Central European Institute of Technology**
**Brno University of Technology in Brno**

Academic year: **2020/2021**

Student: **Ing. Marek Vanatka**

Doctoral study program: **Advanced Materials and Nanosciences**

Field of study: **Advanced nanotechnologies and microtechnologies**

Supervisor: **Ing. Michal Urbánek, Ph.D.**

Reviewer**:** **Prof. Sebastiaan van Dijken**

PhD thesis title: **Static and dynamic properties of nanostructured magnetic materials**

**Topicality of doctoral thesis:**

Marek Vanatka's doctoral thesis focuses on the behavior of magnetic vortices, a topical subject in the field of nanomagnetism, and spin-wave characterization methods, the experimental cornerstone of magnonics. The results are original and relevant for the development of magnetic memories, wave-based computing devices, and scalable microwave components. Chapter 1 provides a solid background on micromagnetic theory, ferromagnetic resonance (FMR), and the properties of magnetic spin waves. Chapter 2 discusses the experimental techniques used for the imaging and electrical detection of vortices in magnetic disks as well as other experimental techniques (BLS) and sample fabrication methods. Hereafter, the main findings of the doctoral study are described in four result chapters.

Chapter 3 reports on a detailed study of vortex nucleation states in magnetic NiFe disks with diameters ranging from 500 nm to 4 µm and thicknesses ranging from 20 nm to 100 nm. After classifying the different vortex states by performing micromagnetic simulation in open-source OOMMF software, experimental data are discussed in detail. Two complementary techniques are used: Lorentz transmission electron microscopy and electrical measurements of anisotropic magnetoresistance. The experiments convincingly demonstrate that the evolution of magnetization from the fully saturated state to the vortex state proceeds via different nucleation states.

Chapter 4 provides an overview of vector-network-based techniques for the characterization of FMR and propagating spin waves. A good introduction to the measurement of S-parameters is given and the excitation spectra of different antenna structures are compared. Hereafter, FMR data as a function of magnetic bias field for 100 nm thick NiFe, CoFeB, and YIG films and an epitaxial Fe film on MgO(001) are presented (flip-chip measurement). The saturation magnetization and field offset for epitaxial Fe are extracted by fitting the experimental data to the Kittel formula. Moreover, extraction of the exchange constant from perpendicular standing spin-wave modes and the damping parameter from the frequency dependence of FMR line broadening are demonstrated. The dynamics of vortices in NiFe disks is also briefly discussed. At the end of the chapter, a detailed description of propagating spin-wave spectroscopy is given, including good discussions on the effect of microwave excitation power, the choice of microwave antenna, and the spin-wave propagation distance.

Chapter 5 introduces a new method for the extraction of spin-wave dispersion relations using all-electric propagating spin-wave spectroscopy. The method is based on the measurement of the spin-wave phase as a function of frequency and propagation distance. It therefore requires parallel antennas to be patterned with different gap sizes. Results are subsequently presented for NiFe, CoFeB, and YIG films. For CoFeB films an interesting hybridization effect between propagating spin waves and perpendicular standing spin waves is reported. The chapter also discusses propagating spin-wave spectroscopy data on a FIB-fabricated NiFe magnonic crystal, a magnetic metamaterial that allows the manipulation of spin-wave signals.

In Chapter 6, a new concept of exciting spin waves by freestanding antennas is reported. This method replaces the need for patterning microwave antennas on top of magnetic samples, saving time and providing flexibility in the selection of probing locations. The freestanding antenna is implemented on a transparent thin glass cantilever, allowing it to be used in Brillouin light scattering (BLS) and other optical characterization techniques. Application of the freestanding antenna in BLS experiments on YIG (FMR characterization) and CoFeB is convincingly demonstrated. I also find the reported phase-locking of spin Hall nano-oscillators to the Oersted field of a freestanding antenna of great interest. To date, the application of a freestanding antenna in VNA-based FMR experiments or propagating spin-wave spectroscopy suffers from weak signal strengths. If this drawback can be circumvented in future designs, it would provide an intriguing measurement option.

**Meeting the goals set:**

The doctoral thesis reports on a wide variety of experiments and methods. Marek Vanatka successfully addresses key issues in nanomagnetism. His work on spin-wave characterization is original. As key outcomes, a new approach for all-electrical measurements of spin-wave dispersion relations and excitation/probing of spin waves by a cantilever-based freestanding antenna are demonstrated. The extent of the results in the doctoral thesis is impressive.

**Problem solving and dissertation results:**

The main results of the doctoral thesis are summarized under “Topicality of doctoral thesis“. The methods applied are appropriate for solving problems related to magnetic vortex nucleation. The magnonics related topics (Chapters 4-6) are more technical, offering original measurement solutions for the characterization of FMR and propagating spin waves. These results will stimulate other researchers in the field to adopt similar characterization methods.

**Importance for practice or development of the discipline:**

Nanomagnetism, spintronics, and magnonics are important for the development of new magnetic storage devices, wave-based analog computers, and tunable microwave components for information and communication technology. The results in the doctoral thesis provide a better understanding of magnetic vortices, a non-collinear spin structure that is of interest as a spin-wave emitter. The new methods for spin-wave characterization will inspire researchers in the field of magnonics. The freestanding microwave antenna is of interest for fundamental research and may also be suitable for fast non-intrusive characterization of magnonic devices.

**Formal adjustment of the thesis and language level:**

The doctoral thesis is detailed and well written. While it is apparent that the thesis is written by a non-native English speaker, the descriptions of the theoretical background, experimental methods, and results are very clear. The results are original and have been published in several journal publications. The thesis provides much more details than the published articles, signifying independent writing by the doctoral candidate. I have a few suggestions for adjustments, which are given under “Questions and comments“.

**Questions and comments:**

I suggest the following changes and clarifications:

- Section 4.5 focuses on propagating spin-wave spectroscopy. Results for 30 nm CoFeB are shown. Unfortunately, the measurement data is not used to extract physical parameters. It would be nice to extract the spin-wave group velocity from Re$\Delta S_{12}$ or Im$\Delta S_{12}$ and add a description on how this is done.

- On page 74, non-reciprocity in propagating spin-wave spectra is briefly discussed. The origin of non-reciprocity is ascribed to the surface character of the DE mode. However, if the film thickness is much smaller than the wavelength of the spin waves, the wave profile across the film becomes nearly uniform and the non-reciprocity diminishes (see e.g. Appl. Phys. Lett. 105, 232403 (2014)). This seems to be the case for the 30 nm thick CoFeB film under study here. The non-reciprocity in the propagating spin-wave spectra more likely originates from the excitation geometry (see e.g. J. Appl. Phys. 124, 243901 (2018)). I suggest changing the discussion of the measurement data.

- On page 82, the theoretical spin-wave propagation length is given as $\Lambda = v_g\tau$. While this is correct, it is not clear how the theorical curves in Figs. 5.6, 5.9, 5.11, and 5.12 are calculated. It would be good to clarify the calculations and the parameters that are used in the calculations.

- In section 5.5, and propagating spin-wave spectroscopy measurement on a NiFe magnonic crystal is presented. Details of the structure such as stripe width, crystal period, and thickness modulation are not given. More details could be provided. Also, to prove that the suppression in the transmission signal corresponds to an actual bandgap, it would be good to show that its frequency corresponds to a Bragg scattering condition of the magnonic crystal. This requires an analysis of the NiFe spin-wave dispersion relation.

**Conclusion:**

In my opinion, the reviewed thesis fulfills all requirements posed on theses aimed for obtaining PhD degree. This thesis is ready to be defended orally, in front of respective committee.

In Espoo, Finalnd

Date 11-3-2021

Prof. Sebastiaan van Dijken