Review Report on PhD Thesis

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

Academic year: **2019/2020**

Student: **Ing. Lukáš Flajšman**

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

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

Supervisor: **prof. RNDr. Jiří Spousta, Ph.D.**

Co-supervisor: **Ing. Michal Urbánek, Ph.D.**

Reviewer: **prof. Dr. Andrii Chumak**

PhD thesis title: **Magneto-optical study of the dynamic properties of magnetic nanostructures and nanostructured metamaterials**

Topicality of doctoral thesis:

Spin waves propagate in magnetic materials with wavelengths down to the nanometer range and can be used as data carriers in novel low-power magnetic data processing systems. The quanta of spin waves – magnons – gave the name magnonics to this field of modern science. Magnonics is a relatively new field but demonstrates a fast growth and a large potential. The development of new and energy-efficient methods to guide and control spin waves in two dimensions is one of the most actual tasks in the field. Particularly this challenge is addressed by Mr. Flajšman in his thesis in a unique and pioneering way. The topic of the thesis is staying at the cut edge of modern advanced materials and nanosciences and a set of breakthroughs are presented in the thesis.

Meeting the goals set:

I would say that Mr. Flajšman defined three main objectives in his work. The first objective was to explore the possibilities to control saturation magnetization and uniaxial magnetic anisotropy of novel ion beam phase transition material based on $Fe_{78}Ni_{22}$. This aim was achieved to the full extent: The control of the saturation magnetization of the material was demonstrated all the way from the nonmagnetic state up to the fully ferromagnetic state with high saturation magnetization. Moreover, the local control of the orientation of the uniaxial magnetic anisotropy axis was demonstrated modifying the direction of focused ion-beam (FIB) writing. These two phenomena were comprehensively investigated and demonstrated in a variety of different structures. The smallest feature size of the developed structures is 50 nm which is the smallest size of a magnonic structures reached until now.

The second goal defined in the thesis was the utilization of the FIB direct writing for the re[illegible] the magnonic waveguides and conduits. First, the micromagnetic model of the system was de[illegible]

Second, a comprehensive characterization of the developed structures was performed using Kerr microscopy and micro-focused Brillouin light scattering (BLS) spectroscopy. All required parameters were subtracted and analysed. Finally, phase-resolved BLS was used to demonstrated and characterize propagating spin waves in the FIB-written waveguides. Thus, this goal was reached to the full extent.

The final goal of the thesis was to use the developed technology and knowledge on spin-wave properties to realize complex magnonic structures. In particular, the tunability in the direction of the uniaxial magnetic anisotropy was used to realize 90-degree spin-wave turns and the possibility to create structures with engineered saturation magnetization was used to fabricate the prototypes of graded-index magnonic waveguides. It was shown that the magnetization in both arms of the 90-degree turn is stabilized in the desired direction. Nevertheless, the bending element between the arms causes a huge distortion of the wave-front disturbing the spin-wave propagation and only a part of spin-wave energy passes the turn. In the case of graded-index waveguides, the spin-wave spectra, as well as the spin-wave propagation, were investigated in positive and negative profiles of the magnetization gradients. Although the possibility to control the spin-wave properties in such a way was demonstrated, the effect requires further enhancement in its efficiency. Nevertheless, in spite of the fact that not all of the ideas proposed by Mr. Flajšman gave the expected results, he has performed all required in-depth and systematic investigations to define the strong and weak sides of the proposed approach. Taking into account the large scientific and technological complexity of the tasks and the truly-pioneering nature of the research, this objective can also be considered as fulfilled.

Problem solving and dissertation results:

The main scientific problems which Mr. Flajšman defined and solved during his PhD studies are described in the previous section "Meeting the goals set". To sum up the main achievements, I would underline the following results: (1) A novel directly-written nano-scaled material with engineered magnetization and anisotropy was proposed, tested, and utilized for the tasks of magnonics. (2) This material was used for the realization of the magnonic conduits of the width down to 50 nm. (3) Complex two-dimensional structures like 90-degree spin-wave turn and element with graded-index magnonic properties were realized and tested.

All the goals formulated by the applicant are at the cut-edge of modern magnonics. The performed investigations satisfy the highest-level international standards. The scientific results are systematic, comprehensive, and address the formulated goals to the full extent.

Importance for practice or development of the discipline:

With no doubts, the obtained results make a valid next step in the developing fields of magnonics and spintronics. A completely new and powerful approach for the realization of even very complex two-dimensional magnonic circuits is proposed and tested. The approach is original and, in addition, opens doors to new functionalities never explored before. Thus, it is probable that the set of pioneering results presented by Mr. Flajšman in his PhD thesis will open a new research direction and will place a solid base for future studies.

Formal adjustment of the thesis and language level:

When speaking about the PhD thesis of Mr. Flajšman itself, the first that attracts attentio broad scope of scientific and technological problems that are covered by this work. The invest performed by the applicant start with studies in the frames of material science and fa technologies, involving such advanced modern technologies like focused ion-beam writing. The fabricated nano-structures were investigated using a broad spectrum of complex modern techniques, including magneto-optical Kerr effect and micro-focused Brillouin light scattering spectroscopies. The experimental results are supported by analytic models and by the results of numerical simulations. The second pronounced characteristic of the thesis is its truly academic nature. All the background information, methods, as well as analysis of the original results are discussed very systematically and carefully. The applicant shows a broad in-depth academic education. The structure of the thesis is clear and all results are properly analysed. All conclusions made in the thesis are justified. The thesis itself is well-written in good English.

The study is fully completed by a state doctoral examination and the dissertation's defence, which proves the ability and readiness for independent research activity. The dissertation includes original and published results.

Questions and comments:

Taking into account the high scientific level of the PhD thesis of Mr. Flajšman and his very academic approach to the presenting of information, I have just few questions:

- In his PhD studies, Mr. Flajšman investigated spin waves in the Damon-Eshbach geometry to achieve the longest spin-wave propagation lengths. But what would be the estimated spin-wave propagation length in the backward volume geometry for the investigated material?
- What was the exchange stiffness of the developed on $Fe_{78}Ni_{22}$ material? Is it possible to use the frequency of the first perpendicular standing spin-wave mode measured in BLS experiments to determine the exchange constant of the material?
- Did Mr. Flajšman take into account the possible formation of the caustic beams while analysing the spin-wave propagation through the 90-degree turn (see e.g. Fig. 5.2)?
- A question about the outlook. Would it be possible to use the proposed approach of the engineering of the saturation magnetization and/or magnetic anisotropy for the excitation of short-wavelength exchange spin waves?

Conclusion:

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

I am glad to evaluate the thesis of Mr. Flajšman entitled "Magneto-optical study of the dynamic properties of magnetic nanostructures and nanostructured metamaterials" with the grade "A" – Excellent.

In Vienna, date 23.03.2020

prof. Dr. Andrii Chumak