# Review Report on PhD Thesis

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

Academic year: **2023/2024**

Student: **Ing. Ondřej Wojewoda**

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

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

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

Reviewer: **Dr. Ping Che**

**PhD thesis title:** Brillouin light scattering characterization of nanoscale spin waves

**Topicality of doctoral thesis:**

In this thesis, Ing. Ondřej Wojewoda addresses the detection of nanoscale spin waves with wavevectors exceeding 100 rad/μm in metallic magnetic thin films. He employs the lab-based Brillouin light scattering (BLS) technique alongside a proposed design of individual or array-shaped silicon-based Mie resonators. Additionally, he develops semi-analytical models to interpret the observed phenomena, achieving excellent agreement with experimental results. This research is timely and highly relevant to the field of magnonics, particularly in the context of developing nanoscale devices based on magnons. Such advancements hold promise for novel computing and logic devices utilizing exchange-dominated spin waves with wavelengths below 100 nm and high group velocities.

**Meeting the goals set:**

The research objectives in this thesis are thoroughly achieved through robust experimental and modeling work. The methods are well-developed, and the data analysis is meticulously conducted, resulting in a clear narrative of achieving high-k magnon detection using the proposed Mie resonator.

**Problem solving and dissertation results:**

In this thesis, Ing. Ondřej Wojewoda designed Mie resonators and tested their effect on extending the accessible region of k-space for the micro-focus BLS setup. In thermal magnon measurements, significant broadening of **k**-space was observed, particularly in the Damon-Eshbach mode. The array design of the Mie resonators further enhanced the detection of propagating short-wavelength spin

waves, a crucial element for miniaturized magnonic devices, as stated above. Additionally, Ing. Ondřej Wojewoda developed a semi-analytical model to calculate micro-focused BLS spectra, effectively utilizing the detected BLS spectra to extract magnetic material properties and gain insights into magnon dispersion relations. This approach is well demonstrated and shows excellent agreement with experimental results.

Besides, Ing. Ing. Wojewoda adeptly managed various methods and collaborative efforts, including nanofabrication, finite-difference time-domain simulations, micromagnetic simulations, and COMSOL. The methods were carefully selected based on their suitability for addressing the specific questions in this thesis, and the consistent results strongly support the underlying physics discussed.

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

The combined experimental and modeling work presented in this thesis demonstrates that Mie resonators are a reliable method to access the high-k regime of magnon dispersion relations in magnetic thin films using lab-based techniques. This approach is particularly important for developing devices with easily accessible lab techniques, rather than relying on complex synchrotron-based methods. The full-phase reconstruction of nanoscale spin waves in periodic Mie resonator arrays, presented in Chapter 6, illustrates how to fully utilize the potential of the BLS technique and extend its boundaries for magnonic research.

However, the magnetic material systems in this thesis are somewhat limited to metallic magnetic materials, which may influence the audience size and acceptance of the work. Due to the limitations of damping parameters, insulating garnets are essential for magnonic research. It is somewhat unfortunate that the integration of Mie resonators with garnet-based systems is not too much discussed. Nevertheless, this project is still developing, and the work presented in this thesis is an excellent start.

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

(4) The study is duly completed by a state doctoral examination and the defense of a dissertation, which proves the ability and readiness for independent activity in research or development or for independent theoretical and creative artistic activity. The dissertation must include original and published results or results accepted for publication. )

This thesis is well-structured, with all aspects of the introduction, methods, results, and discussions organized clearly for readers with relevant backgrounds. Additionally, the level of English in this thesis is proficient.

Some minor typos or format issues could be corrected: In page 98, the first paragraph "30thick"; the units of rad/μm are in different format, for example, in page 112, the last second paragraph; some features in the figures are not explained in the legend, e.g. the shadowed regions in Fig. 4.15.

**Questions and comments:**

General questions:

1. This thesis presented how to use Mie-resonator to access existing high-*k* magnons, would it be possible to use the Mie-resonator for exciting high-*k* magnons?
2. Is the anti-Stokes spectra being investigated, especially when the BLS laser is on the edge of the Mie-resonator? When the laser spot is only partially on incident on the surface of the magnetic thin films, part of the **k** access would be lost. Here the laser spot is not fully covered but still influence.
3. In Chapter 5, the periodic Mie-resonators are presented to detect high-*k* magnons with selected frequencies corresponding to the designed periodicities. The similar effect has also been observed in the BLS measurements using magnonic grating couplers (e.g. J. Chen, et al., Phys. Rev. B 100, 104427 (2019)). How would you comment on the pros and cons of this methods compared with the Mie-resonators arrays?
4. What type of design, including materials, shape, dimensions and so on, for developing such Mie-resonators to access high-k magnons in insulating garnets, such as yttrium iron garnet?
5. Could there by any naturally formed nanostructure, especially arrays, working as the Mie-resonators? The nanofabrication of periodical structures below 100 nm is still challenging for a lot of labs without state-of-art Ebeam lithography (EBL) setups.

Besides, there are some more detailed questions:

1. Fig3.2: The laser power seems to have more fluctuations (around 6mW) after the mode filter (around 3mW before), what is the reason?
2. In Fig.4.4 (c), there seems to be peaks between 10 GHz to 20 GHZ in the bare film data (black circles), what are their origins?
3. The AFM shows the "ears" of the nanodots in Fig.4.6, and likely to be caused by some process during the nanofabrication, which could be the choice of the double-layer resist thickness, development time after EBL writing, sputtering process. And among them, sputtering process can easily cause this issue. Could the Ph.D. candidate describe the sputtering process used here?
4. Fig.4.6, the diameters of (a) looks more likely to be 100 nm instead of 200 nm, and (b) 250 nm instead of 450 nm. Could the author check the labelling?
5. What is the boundary conditions used in calculating the wavelength of the PSSW mode in section 4.4.2?
6. The difference for low and high magnetic field presented in Fig.4.10 seems to be too large to be caused only be overestimation and underestimation. Could there be any field dependent effect in the system?
7. In Fig. 4.15, the k distribution of the electric field generated by the Mie-resonator seems to be periodical along x direction, but the broadening of the BLS spectra towards shows no features of multiple peaks, why?
8. What is the electric field distribution of the silicon disk of 1500 nm-diameter, like the one used in Fig. 4.17?
9. The SEM image of the periodical stripes in Fig. 5.1 shows a bit broadening of the size in the center of the array. Is there any proximity effect correction during the EBL process?
10. Why there is a big drop of the BLS signal at about 8 GHz? Too much compared to like 7 GHz or above 8 GHz.
11. What is the reason of choosing 8 degree of the array fabrication in chapter 6?

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**Conclusion:**

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

In .....Palaiseau.., date...14.06.2024.....

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**Dr. Ping Che**

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