TOPS - Metrology for topological spin structures

Joint Research Project
Newsletter September 2021

Metrology for topological spin structures

Introduction

We are pleased to welcome you to the third newsletter for the "TOPS" Joint Research Project. The project started in June 2018 and will end in November 2021. The underlying goal of TOPS is to develop and establish metrological and scientific tools for the characterization of topological spin structures. This work is expected to contribute to the development of new magnetic storage, spin-logic, and microwave devices in the future well as new quantum standards.

The project is divided into four technical work packages: (i) Towards reliable measurements of key parameters in topological spin structures, (ii) Distinct detection and manipulation of multiple and individual topological spin structures, (iii) Novel dynamical and quantization effects in topological spin structures, and (iv) Materials and simulations.

The aim of this newsletter is to summarize selected work that has been performed across this project over the previous year. More details will be available through further newsletters and on our webpage.

Contact & further information

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(1) DMI quantification in magnonic crystals and isolated nanostructures

In the framework of the TOPS project, researcher operating at Perugia University, in collaboration with colleagues at INRIM-Torino, exploited virtual experiments based on micromagnetic simulations to show that the effect of DMI can be quantified not only in the case of plane films, but also for magnonic crystals consisting, for example, of arrays of interacting Permalloy nanowires deposited over a plane film. In particular, the results of a systematic micromagnetic study, using the GPU-accelerated software MuMax3, of the effect of DMI on the spin wave band structure of two one-dimensional magnonic crystals (MCs), both with the same periodicity *p=300 nm*, but different implementation of the DMI modulation have been presented at JEMS-2020 conference and just published in the Journal of Magnetism and Magnetic Materials [1]. In a first system (Sample A) the artificial periodicity was achieved by modulating the interfacial DMI constant *D*, while in the second system (Sample B) also the sample morphology was modulated. Due to the folding property of the band structure in the dispersion relations of the magnonic crystals it is possible to extend the sensitivity of Brillouin light scattering towards weak DMI strength (*D* in the range from *0* to 0.5 mJ/m^2), by measuring the frequency splitting of folded modes in high-order artificial Brillouin zones, since the splitting increases almost linearly with the band index, as shown in Fig. 1. For relatively large values of the DMI (*D* in the range from *1.0* to *2.0* mJ/m^2), instead, the spin waves dispersion relations present flat modes for positive wavevectors, separated by forbidden frequency gaps whose amplitude depend on the value of *D*. These frequency gaps are more pronounced for the sample with morphology modulation.

In a second study, just published on Applied Sciences [2], the characteristics of spin waves eigenmodes in isolated magnetic nanostructures, such as elliptical dots magnetized in-plane, with lateral dimensions of the order of 100 nm, were analyzed by micromagnetic simulations in presence of a sizeable DMI. It was shown that the eigenmodes spectrum is appreciably modified by the DMI-induced non-reciprocity in spin-waves propagation: the frequencies of the eigenmodes are red-shifted and their spatial profiles appreciable altered due to the lack of stationary character in the direction orthogonal to the magnetization direction. As a consequence, one finds a modification of the expected cross-section of the different

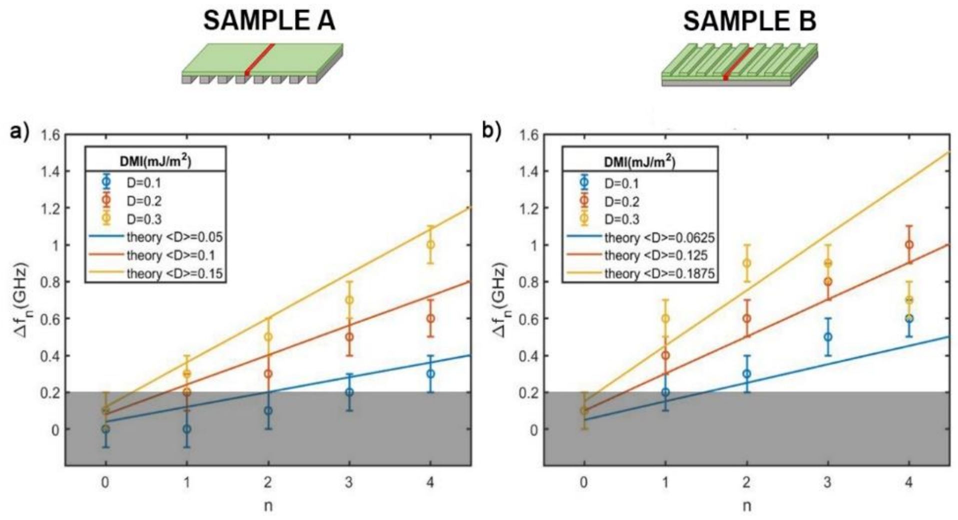

Fig. 1: Frequency asymmetry of spin waves with discrete wavevectors ± k_n (that can be obtained summing or subtracting to the spin wave wavevector $\pm k_0$ an integer number *n* of grating wavevectors $k_G=2\pi/p$) for relatively small value of *D* in sample A (a) and in sample B (b). The points are results of the micromagnetic simulations, while the lines are obtained from the theoretical formula valid for a plain film, assuming an average value of *D*. From Ref. 1.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovations programme and the EMPIR participating states.

modes in either ferromagnetic resonance or Brillouin light scattering experiments, enabling one to detect modes that would remain invisible without DMI. In this respect, the modifications of the spectrum can be directly connected to a quantitative estimation of the DMI constant. Moreover, it is seen that for sufficiently large values of the DMI constant, the low-frequency odd eigenmode changes its profile and becomes soft, reflecting the transition of the ground state from uniform to chiral.

References

[1] R. Silvani, M. Kuepferling, S. Tacchi and G. Carlotti, *"Impact of the interfacial Dzyaloshinskii-Moriya interaction on the band structure of one-dimensional artificial magnonic crystals: a micromagnetic study"*, J. Magn. Magn. Mater. **539**, 168342 (2021)

[2] R. Silvani, M. Alunni, S. Tacchi and G. Carlotti, *"Effect of the interfacial Dzyaloshinskii-Moriya interaction on the spin waves eigenmodes of isolated stripes and dots magnetized in-plane: a micromagnetic study"*, Appl. Sci. **11**, 2929 (2021).

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(2) Tailoring interfacial effect in multilayers with Dzyaloshinskii-Moriya interaction by helium ion irradiation

We show a method to control magnetic interfacial effects in Ta(4.5nm)/[Pt(4.5nm)/Co(1.2nm)/Ta(2.5nm)]$_{20}$ multilayers with Dzyaloshinskii-Moriya interaction (DMI) using helium helium (He$^+$) ion irradiation. We report results from SQUID magnetometry, ferromagnetic resonance as well as Brillouin light scattering on multilayers with DMI as a function of irradiation fluence (IR) to study the effect of irradiation on the magnetic properties of the multilayers. Our results show clear evidence of the He$^+$ irradiation effects on the magnetic properties which is consistent with interface modification due to the effects of the He$^+$ irradiation [1]. As the IR increases, we observe that the perpendicular magnetic anisotropy (PMA) decreases significantly but after the IR reaches a certain level, it approaches saturation (Fig. 2(f)), while a reduction of the DMI is observed at intermediate IR which then stabilises at a constant value at high IR.

The He$^+$ irradiation induces short range atomic displacements, of the order of a few interatomic distances, leading to interface intermixing and hence altering the interface-driven PMA and DMI. This external degree of freedom offers promising perspectives to further improve the control of magnetic skyrmions in multilayers, that could push them towards integration in future technologies.

Reference

[1] A. Sud, S. Tacchi, D. Sagkovits, C. Barton, M. Sall, L. H. Diez, E. Stylianidis, N. Smith, L. Wright, S. Zhang, X. Zhang, D. Ravelosona, G. Carlotti, H. Kurebayashi, O. Kazakova and M. Cubukcu, “Tailoring interfacial effect in multilayers with Dzyaloshinskii-Moriya interaction by helium ion irradiation”, Scientific Reports [submitted] https://arxiv.org/abs/2105.03976

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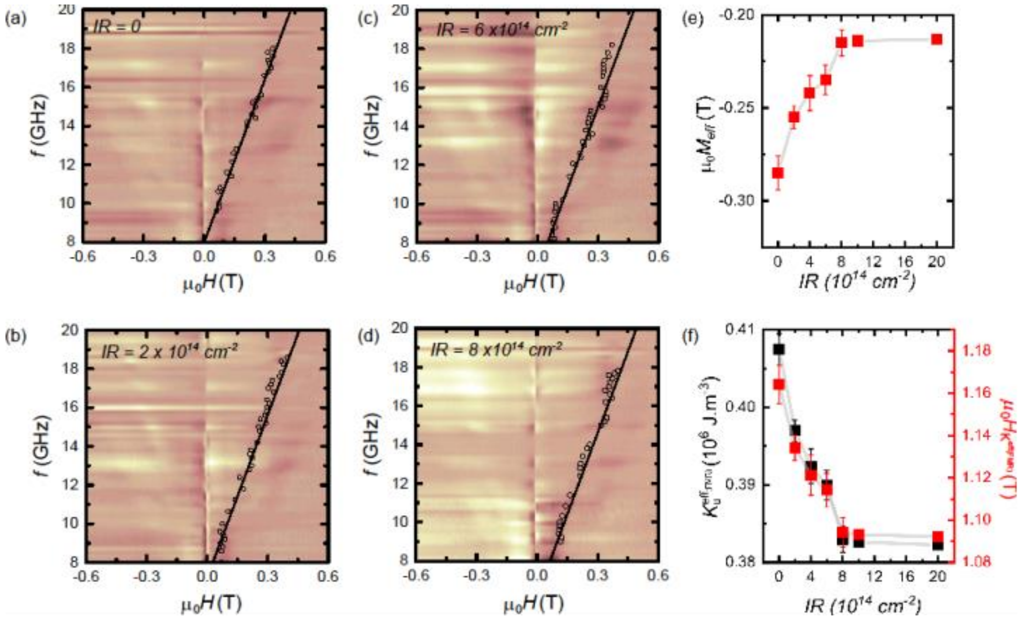

Fig. 2: (a-d) Microwave transmission as a function of frequency for different IR with the magnetic field perpendicular to the film plane. The black hollow markers depict the resonance field obtained by fitting FMR spectra and solid lines are fitting curve. (e-f) The effective magnetisation (e) and the effective uniaxial anisotropy field as a function of IR.

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(3) Study of the Dzyaloshinskii-Moriya interaction and the perpendicular magnetic anisotropy at the $BaTiO_3$(BTO)/CoFeB interface

To date, most of the experimental works on interfacial Dzyaloshinskii-Moriya interaction (*i*-DMI) was focused on heavy metals/ferromagnet systems, where heavy metals was used to induce *i*-DMI. Recently, a sizeable *i*-DMI was observed to arise at the interface between an oxide layer and a ferromagnetic film. Due to the versatility of the oxide materials, featuring peculiar degrees of freedom, such as the terminations in a complex oxide and the polarization in a ferroelectric oxide, these systems are very promising for the design of layered structures with tailored *i*-DMI. In our work, published on Physical Review Letter, we performed a combined experimental and theoretical study of both the perpendicular magnetic anisotropy (PMA) and the *i*-DMI in the $BaTiO_3$(BTO)/CoFeB/Pt system, as a function of the oxide termination (TiO_2 vs BaO). The *i*-DMI was investigated by using Brillouin light scattering (BLS), measuring the frequency difference (Δf) between counter-propagating Damon-Eshbach (DE) spin-waves, induced by the presence of *i*-DMI, as function of the spin-wave wave vector k (Fig. 3). From linear fit to the experimental data, the effective DMI constant D was estimated to be 0.45±0.02 and 0.56±0.02 mJ/m^2, for TiO_2-BTO/CoFeB/Pt and BaO-BTO/CoFeB/Pt structures, respectively. Since the CoFeB/Pt interface gives the same contribution to the DMI of both systems, the different D values can be attributed to the influence of the oxide termination. The experimental results were interpreted by using first principles calculations. We found that *i*-DMI has an opposite sign at the BTO/CoFeB and COFeB/Pt interface, therefore the total *i*-DMI of the system results from the competition of the two interface contributions. In particular, for both the BTO terminations the *i*-DMI has a negative sign indicating that the left-handed chirality is favored by the oxide layer. In addition, theoretical calculations showed that *i*-DMI strength at the TiO_2-BTO/CoFeB interface assumes a higher value than at BaO-BTO/CoFeB one in agreement with the experimental results. This finding was explained on the basis of the different electronic states around the Fermi level at the oxide/ferromagnetic metal interfaces and the different spin-flip process of the two terminations. On the contrary, PMA, investigated by superconducting quantum interference device magnetometry, was found to be larger for the CoFeB films grown on a BaO-BTO substrate.

Reference

W. Lin, B. Yang, A. P. Chen, X. Wu, R. Guo, S. Chen, L. Liu, Q. Xie, X. Shu, Y. Hui, G. M. Chow, Y. Feng, G. Carlotti, S. Tacchi, H. Yang, J. Chen *"Perpendicular magnetic anisotropy and Dzyaloshinskii-Moriya interaction at the oxide/ferromagnetic metal interface"*, Phys. Rev. Lett. **124,** 217202 (2020)

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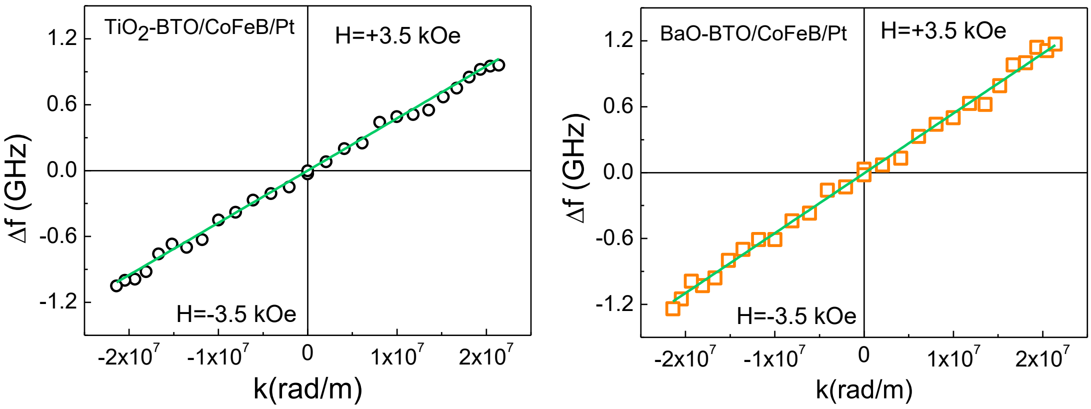

Fig. 3: Measured frequency asymmetry, Δf, as functions of **k** for CoFeB/Pt grown on TiO_2- (left panel) and BaO- (right panel) terminated BTO.

(4) Optically excited collective spin dynamics of skyrmions in $Fe_{1-x}Co_xSi$

So far experimental studies of skyrmion eigenmodes mainly focused on the excitation by microwave magnetic fields and optomagnetical excitation using the inverse Faraday effect. These methods have in common that the dynamics are measured in thermodynamic equilibrium. Little is known on how the skyrmion dynamics change for resonant excitation of charge carriers, which is accompanied by ultrafast thermal gradients in time and space. Only one recently published study on a Néel-type skyrmion hosting material addresses this issue.

In our work we optically excite collective skyrmion eigenmodes in the chiral magnet $Fe_{0.75}Co_{0.25}Si$ and study their dynamics under a strong thermal gradient. The spin excitation is driven by a thermal modulation of magnetic anisotropy by laser heating and is probed by the time-resolved measurement of the magneto-optical Kerr effect (TR-MOKE) using laser pulses with 800 nm center wavelength and 150 fs pulse width. By making use of the cooling history dependence of $Fe_{1-x}Co_xSi$, we study the laser-induced spin dynamics not only in the skyrmion pocket, but also in the metastable skyrmion phase at lower temperatures.

In Fig. 4a the dynamics observed during a field cooling scan (FC+, compare with Fig. 4b) is shown. For the field-polarized and conical phase the observed dynamics are dominated by non-coherent processes, resulting from the laser-induced ultrafast de- and remagnetization. In comparison, for the metastable skyrmion phase we observe GHz oscillations, which are consistent with the breathing mode of the skyrmion lattice (Fig. 4c). These results demonstrate that collective skyrmion dynamics can be excited by the indirect coupling of the laser pulse with the spin system via laser heating in a non-equilibrium situation.

Reference

This work was presented at the Solitons and Skyrmion Magnetism conference (Sol-SkyMag) 2021.

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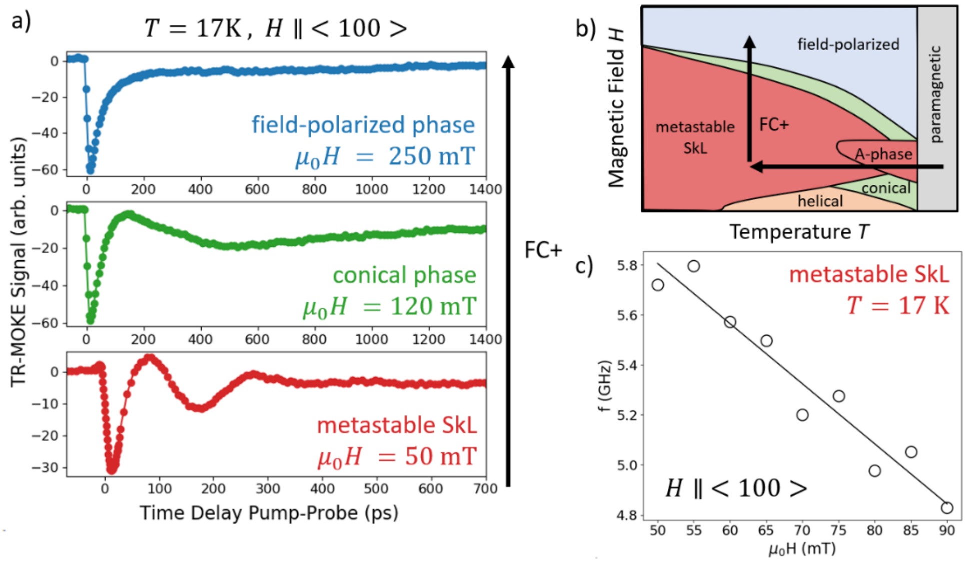

Fig. 4: a) TR-MOKE measurements of the field-polarized, conical and metastable skyrmion phase of $Fe_{0.75}Co_{0.25}Si$, b) Sketch of the magnetic phase diagram under field cooling through the skyrmion pocket (FC+), c) Oscillation frequency of the metastable skyrmion phase (SkL) versus magnetic field.