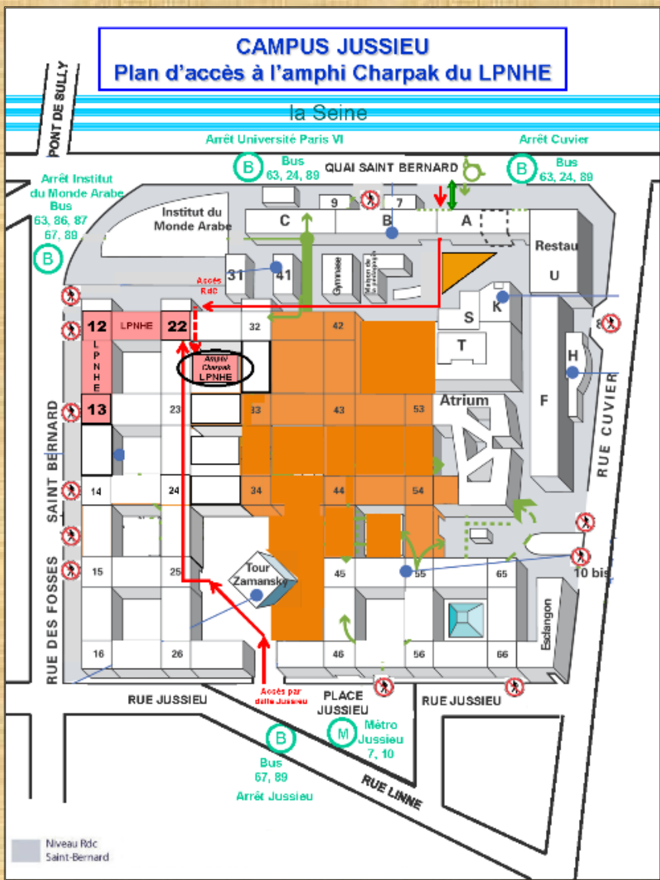
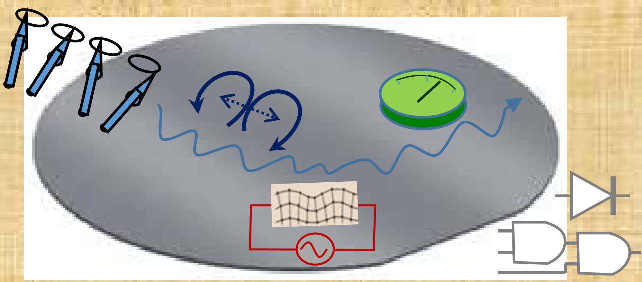
Second SWING workshop

Spin Waves for Advanced Signal Processing

May 20th -21st 2025
Amphithéâtre Charpak,
campus Jussieu



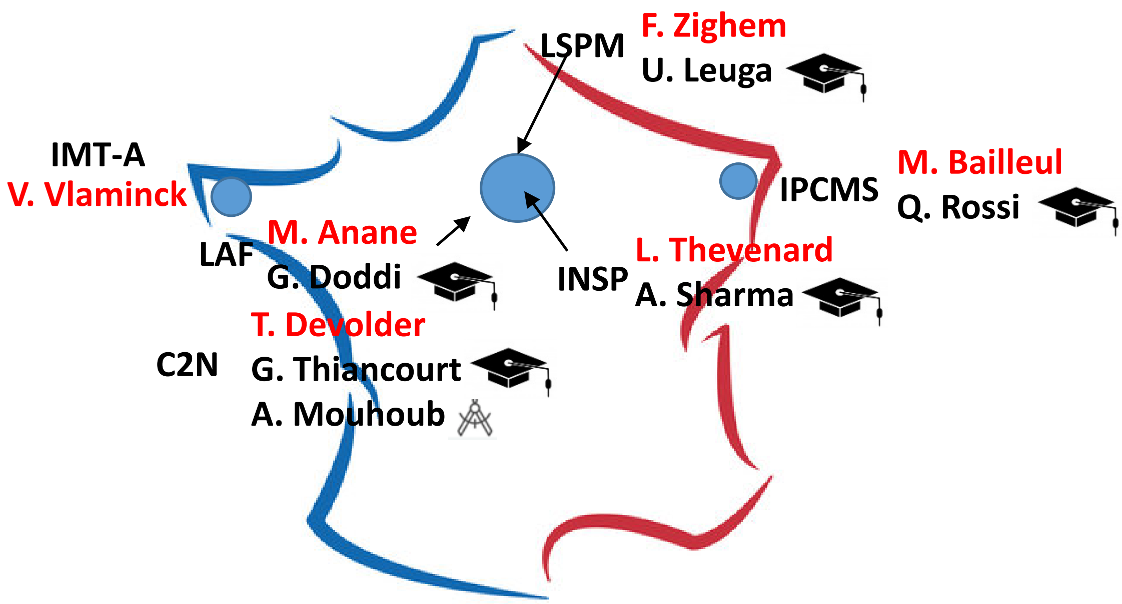


UFR Physique

SWING CONSORTIUM

IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom | laboratoire Albert Fert | LSPM | C2N | INSP | IPCMS

Local SWING contact in each partner lab and
PhD student/engineer hired by the PEPR SPIN



Program at a glance

		Tuesday 20/05
<14h00		**Coffee**
14h00 – 15h50	14:00	Introduction
	14:20	Gael Thiancourt (C2N)
	14:40	Salama Sali (C2N)
	15:00	*Olivier Klein (SPINTEC)*
	15:40	Roméo Beignon (LCC)
16h00 – 16h30		**Coffee break**
16h30 – 17h30	16:30	Ping Che (LAF)
	16:50	Julien Berthomier (LAF)
	17:10	Nessrine Benaziz (C2N)
17h30-18h30		**Posters**
19h	*for those who registered*	Diner at « Le Temps des Cerises »

Wednesday 21/05		
Rafael Lopes Seeger (C2N)	09:00	**9h – 10h**
Anupam Sharma (INSP)	09:20	
Maya Khelif (LSPM)	09:40	
Coffee break		**10h – 10h30**
Gyandeep Pradhan (IPCMS)	10:30	**10h30 – 12h**
Sarah Mantion (LAF)	10:50	
Gyorgy Csaba (TUM)	11:10	
Discussions	11:40	
Lunch at « l'Ardoise »	*for those who registered*	**12h**
Silvia Tacchi Univ. of Perugia, Istituto Officina dei Material		**14h**
Philip Pirro RPTU Kaiserslautern-Landau		

Program
Tuesday 20th

14:00 **Introduction** : Matthieu Bailleul

Session 1: Nanomagnonics & devices

#CHAIR Mathieu Bailleul (IPCMS)

14:20: « *Modelling of frequency spectra and impulse responses of multi-nature spin waves* »
Gaël Thiancourt (Centre de Nanosciences & Nanotechnologies, Orsay)

14:40: « *Nonlinear spin waves processes in a 500nm Bi:YIG* »
Salama Sali (Centre de Nanosciences & Nanotechnologies, Orsay)

15:00: «*Orbital Angular Momentum of Azimuthal Spin-Waves* »
Olivier Klein (SPINTEC, Grenoble) **INVITED**

15:40: « *Spatially Resolved Investigation of Spin Wave Frequency Multiplication* »
Roméo Beignon (Laboratoire Charles Coulomb, Montpellier)

16h-16h30: **COFFEE BREAK**

Session 2: Spin wave non-linearities

#CHAIR Thibaut Devolder (C2N)

16:30: « *Observations of Bubble Dynamics in a Magnetic Insulator via Time-Resolved Scanning Transmission X-ray Microscopy* »
Ping Che (Laboratoire Albert Fert, Orsay)

16:50: « *Unravelling spin-wave propagation regimes using NV magnetometry* »
Julien Berthomier (Laboratoire Albert Fert, Orsay)

17:10: «*Method of analysis of the spectra obtained by microfocused BLS* »
Nessrine Benaziz (Centre de Nanosciences & Nanotechnologies, Orsay)

17:30-18:30: **POSTER SESSION**

18:30 *For those who signed up*, departure for **dinner** at
Le Temps des Cerises, 18 rue de la the Butte aux Cailles
(Métro Place d'Italie, line 5)

19:00: DINNER

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Program
WEDNESDAY 21st

Session 3: Magnetoacoustics & Straintronics
#CHAIR Fatih Zighem (LSPM)

9:00: « *Experimental observation of vortex gyration excited by surface acoustic waves* »
Rafael Lopes Seeger (Centre de Nanosciences & Nanotechnologies, Orsay)

9:20: « *Tuning the Interaction between Surface Acoustic Waves and Spin Waves in Fe thin films via N-implantation* »
Anupam Sharma (Institut des Nanosciences de Paris)

9:40: « *Influence of Stress Gradient on Micromagnetic Configurations in Nano-Objects*»
Maya Khelif (LSPM, Villetaneuse)

10:00-10:30: **COFFEE BREAK**

Session 4: Novel techniques for magnonics
#CHAIR Madjid Anane (LAF)

10:30: « *Spin wave dynamics in curved magnets* »
Pradhan Gyandeep (IPCMS, Strasbourg)

10:50: « *RF magnonic devices: modelling, experiment and integration* »
Sarah Mantion (Laboratoire Albert Fert, Orsay)

11:10: «*Wave-based processing using magnons: use cases and real-world constraints* »
Gyorgy Csaba (TUM School of Computation Munich, Germany) **INVITED**

11:40: Discussions

12:00: **lunch at l'Ardoise** *[for those who signed up]*

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Oral presentations

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INVITED

Wave-based processing using magnons: use cases and real-world constraints

Adam Papp[1], Maucha Levente[1], Farkas Domonkos[1] Laszlo, Kovacs Tamas Istvan[1], Robert Erdelyi[1] Markus Becherer[2], Gyorgy Csaba[1]*

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Wave interference is a powerful way of doing computing – as it is well known from the literature of optical computing [1] and also SAW devices [2]. Figure 1 exemplifies this principle via three building blocks: Fig 1a shows a magnonic Joint Transform Correlator, which is similarly to its optical analog, takes two input patterns that are projected through a magnonic lens, where their interference pattern is recorded. The resulting wave intensity is then used as the amplitude input for a second lens. Correlation signals emerge at the back focal plane of this second lens. The intensity of the resulting correlation peaks serves as a basis for shape classification. Convolution may also be done in the time-domain, as shown in Fig 1b: here two counter-propagating spin waves form a standing wave to yield convolution output. Finally, Fig 1c shows a holographic processing device where an inverse-designed [3] magnetic landscape performs classification.

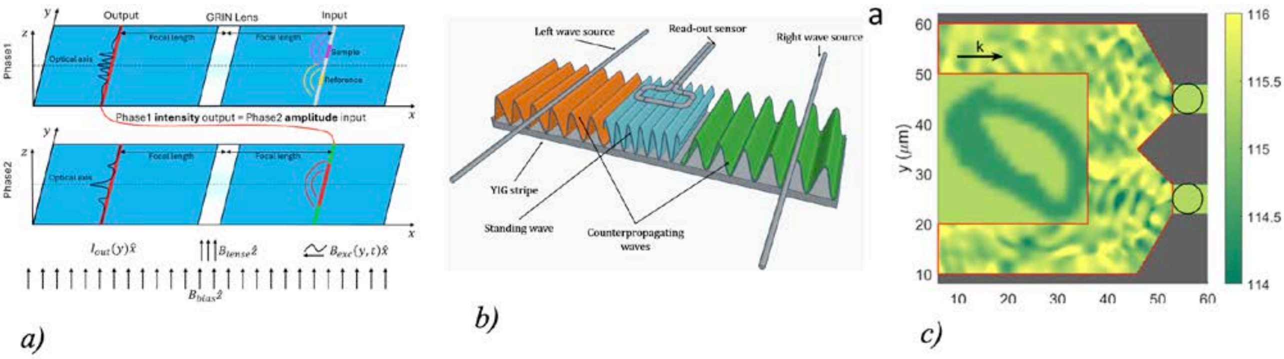

Fig. 1 (a) is a magnonic joint transform correlator (b) is a time-domain convolver (c) is a holographic pattern classifier

In my talk I will explore, where magnonic processing may offer competitive advantages compared to electronic signal processing. While processing in the magnetic domain is fast and ultra-low-power, there are limitations. For example, magneto-electric transduction efficiency becomes very low for submicron-size devices - we will show calculations addressing tradeoff between size and energy efficiency [4]. Also, magnonic nonlinearity is a two-edged sword: nonlinearity is essential in signal processing, but decreases dynamic range, which is critically important in signal processing. I will show simulations characterizing nonlinearity in magnonic devices. Despite these tradeoffs, we believe that magnonic wave processors have the potential to revolutionize computing units in microwave and millimeter-wave edge devices.

References

[1] Goodman JW. Introduction to Fourier optics. Roberts and Company publishers; 2005.
[2] Campbell, C. Surface acoustic wave devices and their signal processing applications. Elsevier, 2012.
[3] Papp, Á., Porod, W., & Csaba, G. Nature communications, 12(1), 6422. . (2021)
[4] Erdélyi, R. et. al. "Design rules for low-insertion-loss magnonic transducers." Scientific Reports 15, no. 1 (2025): 9806.

INVITED

Orbital Angular Momentum of Azimuthal Spin-Waves

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[2] *ASRC, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*

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There has been an increasing realization in recent decades of the fundamental importance of the angular momentum carried by wave fields, which can be in certain cases separated into spin (SAM) and orbital (OAM) components. The latter is a universal feature of waves in uniform continuum media represented by helical or rotational wavefronts, and can potentially encode a large amount of information for mode multiplexed communication channels or multi-level registers of quantum states. Efficient detection method of OAM states is still lacking, however, hindering further progress in the field.

It turns out that different OAM states of spin waves (SW) can be distinguished by their eigenfrequency splittings caused by the ubiquitous dipole-dipole interactions acting as a type of spin-orbit interactions (SOI) for magnons. We experimentally prove this prediction by a magnetic resonance force microscopy on a YIG microdisk [1] (see FIG.1. This leverages on the broken time-reversal symmetry of magnetic excitations for which there is no reason for the modes with counter-rotating wavefronts to be degenerate. The assignment of OAM to spectral peaks, however, requires its unambiguous definition for linear SW dynamics. We have thus in parallel developed a general formulation of magnon AM that clarifies its relation to azimuthal SW eigenstates in any axisymmetric geometry [2]. Agreement with the experiment is quantitative, and establishes a spectroscopic measurement of OAM. Our findings lay a foundation for reading OAM states not only for SWs but also for phonons or photons that can hybridize with SWs, and thereby open a new research direction in the study of general wave angular momentum.

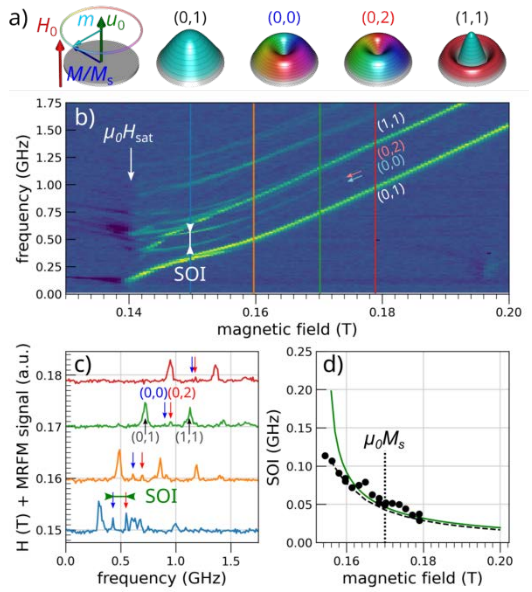

FIG 1. a) Precession pattern for SW modes (n_R, n_J). b) Magnetic Resonance Force Microscope spectrum as a function of normal magnetic field on a YIG disk. c) Line cuts at fixed field values. The split between the (0,2) and (0,0) peaks defines the SOI. d) Magnetic field dependence of the SOI. The dots are the experimental points, while the solid and dashed lines are theoretical predictions, respectively assuming perfect alignment and a misalignment of 0.7°.

This work was partially supported by the EU-project HORIZON-EIC-2021-PATHFINDER OPEN PALANTIRI-101046630; the French Grants ANR-21-CE24-0031 Harmony; the PEPR SPIN - MAGISTRAL ANR-24-EXSP-0004; the French Renatech network; and the REIMEI Research Program of Japan Atomic Energy Agency.

References

[1] T. Valet, K. Yamamoto, B. Pigeau et al. "Orbital Angular Momentum of Azimuthal Spin-Waves" (aXiv 2025)

[2] T. Valet, K. Yamamoto, B. Pigeau et al. "Field Theory of Linear Spin-Waves in Finite Textured Ferromagnets and Applications to Axisymmetric Systems" (aXiv 2025)

Experimental observation of vortex gyration excited by surface acoustic waves

R. L. Seeger[1,2], F. Millo[1], G. Soares[2], J.-V. Kim[1], A. Solignac[2], G. de Loubens[2], T. Devolder[1]

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One particularly interesting example of magnetization dynamics in found in magnetic vortices. These structures are an inhomogeneous magnetic texture that can be formed in magnetic nanosdisks, featuring in-plane magnetization curling along the disk's perimeter and out-of-plane magnetization at the center, which defines the vortex core [1]. At remanence the vortex core is localized at the center of the disk. Resonant excitation by a microwave field induces gyrotropic dynamics of the vortex core [2]. Recently, it has been proposed by simulations that surface acoustic waves (SAWs) can excite the gyrotropic mode of the vortex state in a magnetic disk [3].

Here we report on experiments utilizing a magnetic resonance force microscope to investigate magnetization dynamics in CoFeB sub-micrometer disks in the vortex state, grown on a Z-cut $LiNbO_3$ substrate [4]. Our device design enables excitation of the gyrotropic mode either inductively, using an antenna on top of the disks, or acoustically via SAWs launched from an interdigital transducer (IDT) (Fig. 1, left). These experiments demonstrate the clear excitation of the vortex gyrotropic modeby magneto-acoustic excitation. Our modelling indicates that the lattice rotation ω_{xz} generates a localized magnetoacoustic field that displaces the vortex from the disk center (Fig. 1, right). It allows driving the vortex gyrotropic mode.

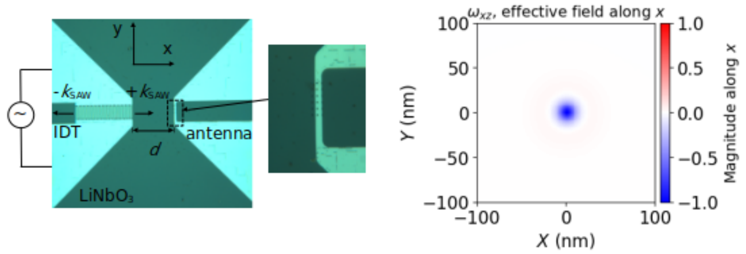

Fig. 1: (left) Optical image of the experiment to detect the vortex gyration induced by SAWs. An IDT excites SAWs on a piezoelectric substrate towards a disk in the vortex state. The setup includes a top antenna for inductive excitation. (right) Normalized magnetoacoustic field distribution over the vortex due to the rotation ω_{xz} at zero applied field, with color coding indicating the x-direction field.

References

[1] R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, M. E. Welland, and D. M. Tricker. Single-Domain Circular Nanomagnets. Phys. Rev. Lett. 83, 1042–1045 (5 1999).

[2] V. Novosad, F. Y. Fradin, P. E. Roy, et al. Magnetic vortex resonance in patterned ferromagnetic dots. Phys. Rev. B 72, 024455 (2 2005).

[3] A. Koujok, A. Riveros, D. R. Rodrigues, et al. Resonant excitation of vortex gyrotropic mode via surface acoustic waves. Applied Physics Letters 123, 132403 (2023).

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Spatially Resolved Investigation of Spin Wave Frequency Multiplication

Roméo Beignon[1,*]*, Chris Körner*[2] *, Rouven Dreyer*[2]*,Georg Woltersdorf*[2]*,Vincent Jacques*[1]*, and Aurore Finco*[1]

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Interactions between spin waves (SW) and magnetic textures offer a nice playground to study non-linear phenomena, as well as promising tools for designing magnonic devices. Among new developments, a frequency multiplication phenomenon has been observed in Permalloy (Py) microstructures [1]. Magnetic resonance measurements on NV center ensembles reveal SW generation with frequencies at more than 60 times the excitation frequency. While micro-magnetic simulations point towards the involvement of spatial variations of the magnetization, the mechanism for the harmonic generation is yet to be demonstrated experimentally. Our goal is to address this question by imaging the SW harmonic generation and the magnetic texture to study the possible correlations.

Here, we rely on NV-center scanning microscopy to image the microwave field emitted by the SW (see **Figure a**). With this method, we can image both the magnetic state of the material and the SW with a spatial resolution of about 50 nm [2]. We detect the SW at a specific frequency close to 2.87 GHz by performing electron spin resonance on the NV center. On **Figure b**, we observe several resonances corresponding to different SW harmonics matching the detection frequency. We can detect up to the 15^{th} harmonic with a single NV center.

Furthermore, we imaged the distribution of the SW generated in Py microstructures directly at the excitation frequency. The interference of the SW field with the excitation field reveals the phase of propagating SW as presented in **Figure c**. It is possible to image selectively SW propagating in different directions. We can observe that the SW propagating to the right (left) are stronger on the left (right) edge of the rectangle. This method thus offers a way to locate where the SW are generated. We now want to apply this technique to SW generated by frequency multiplication to locate their generation areas. By comparing these measurements to the static stray field maps, we aim to conclude on the role of the magnetization texture in this frequency multiplication phenomenon.

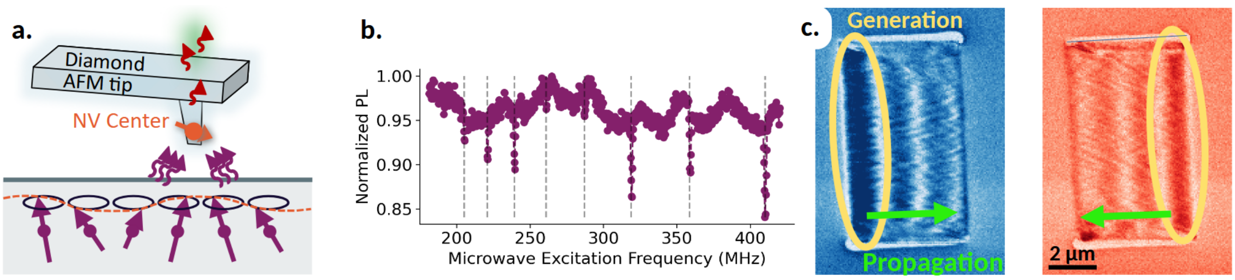

Figure a. Schematic of the experiment. Placed at the apex of an AFM tip, an NV center is sensitive to the microwave stray field generated by SW. **Figure b.** ESR spectrum featuring replicas of the NV center resonance. Each resonance correspond to a different harmonic of the excitation frequency to reach the NV resonance (≈ 2.87 GHz). **Figure c.** Maps of the amplitude of the SW stray field in interference with the excitation. The two maps show SW with different propagation directions.

References

[1] Chris Koerner *et al*, *Science*, **375** 1165-1169 (2022)

[2] Aurore Finco and Vincent Jacques, APL Materials, **11** 100901 (2023)

Method of analysis of the spectra obtained by microfocused Brillouin light scattering

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One popular technique to characterize the spinwave is the Brillouin light Scattering (BLS) [1]. BLS can be used in two modes, in the k-resolved or in the microfocused mode. In microfocused Brillouin light scattering (μ-BLS), the light is focused into the sample through a high numerical aperture lens. This allows to map a wide range of in-plane SW wavevectors in a single acquisition contrary to the k-resolved BLS where one specific SW in probed. This results in complex spectra that need to be analyzed and interpreted. Here, we develop a physically transparent method to help interpret the μ-BLS signal as only a few models have been reported [2]. The key assumption in our analysis is that scattering of photons in directions other than back-scattering can be disregarded. We consider that a spectrum collected in microfocused mode is just the sum of all back-scattering events that lie inside the numerical aperture of the microscope objective. The model takes into account the full complexity of the magnetic response expressed in the reciprocal space. This includes the dispersion relations of all spin wave families present in the sample, as well as their exact spatial profile within the thickness of the magnetic film, and their population. The model is written for systems whose equilibrium magnetization lies in the plane of the sample. The model also takes into account the main optical properties of the sample, and for the specificity of the experimental set-up (numerical aperture of the microscope objective, spectral resolution of the interferometer). By isolating the role of optical absorption, of precession ellipticity, and of the dispersive or non-dispersive character of spin waves, our model provides guidelines that can be used to interpret experimental microfocused BLS spectra. We test our model on a 50 nm-thick $Co_{40}Fe_{40}B_{20}$ film that comprises four families of spin waves contributing to the μ-BLS signal in the 50 GHz-wide frequency range.

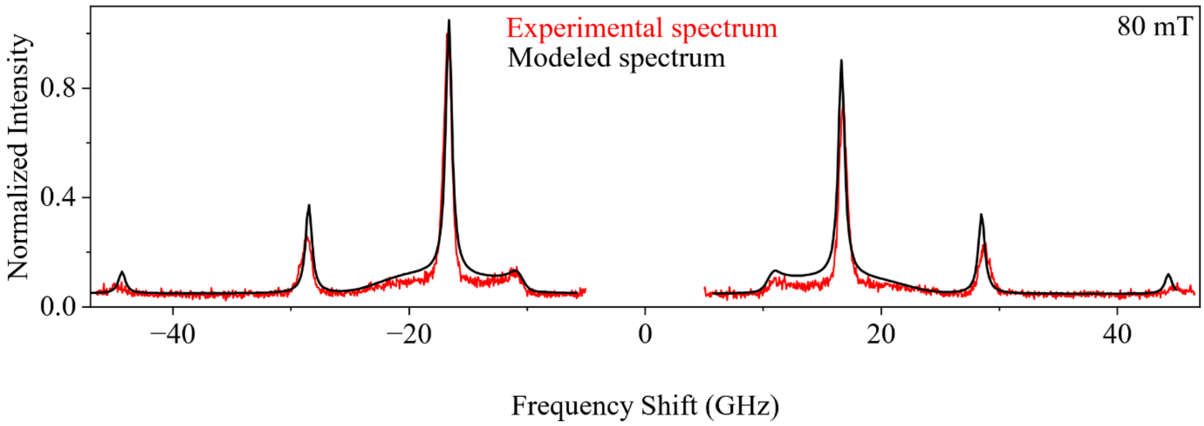

Fig. Comparison between the experimental μ-BLS spectra (red lines) and our model (black lines). The experimentally determined noise floor was added to the theoretical spectra. Spectrum recorded for an applied field of 80 mT.

References

[1] Sebastian, Thomas, et al. "Micro-focused Brillouin light scattering: imaging spin waves at the nanoscale." *Frontiers in Physics* 3 (2015): 35

[2] Wojewoda, Ondřej, et al. "Modeling of microfocused Brillouin light scattering spectra." *Physical Review B* 110.22 (2024): 224428.

Observations of Bubble Dynamics in a Magnetic Insulator via Time-Resolved Scanning Transmission X-ray Microscopy

P. Che[1], S. Wintz[2,3], T. Srivastava[4], N. Reyren[1], D. Gouéré[1], A. El Kanj[1], S. Mantion[1], S. Finizio[5], M. Weigand[2], A. Mucchietto[6], Tim A. Butcher[7], D. Grundler[6,8], G. Schütz[3], I. Boventer[1], R. Lebrun[1], V. Cros[1], J.-V. Kim[4], A. Anane[1]

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Magnetic skyrmions and bubbles are of great importance in magnonics due to their non-trivial magnon band structures [1] and the predicted skew scattering [2]. However, these systems typically host bubbles and skyrmions either at cryogenic temperatures or with significantly increased damping parameters, making spin-wave-driven motion difficult to observe experimentally at room temperature. Here, we stabilized magnetic skyrmions and bubbles in 20 nm-thick Bi-doped yttrium iron garnet (Bi-YIG) films with perpendicular magnetic anisotropy (PMA) while maintaining low damping down to 10^{-4}. Time-resolved scanning transmission X-ray microscopy (STXM) was used to image bubble dynamics and magnon-driven bubble motion. We distinguished between bubbles exhibiting both rotational and breathing modes and those displaying only a second-order rotational mode below 0.1 GHz. This indicates the presence of both skyrmionics and type-II bubbles, which can be tuned via the magnetic field configuration, as shown in Fig. 1(a). Above 0.1 GHz, magnons excited by an antenna propagate through resonating magnetic bubbles, and spin-wave-driven bubble movement was experimentally observed with a speed of 175 m/s (Fig. 1(b)), an order of magnitude faster than current-driven bubble motion in garnet. Our observations provide direct evidence of magnetic bubble manipulation using magnons and pave the way for bubble-based magnonic device designs.

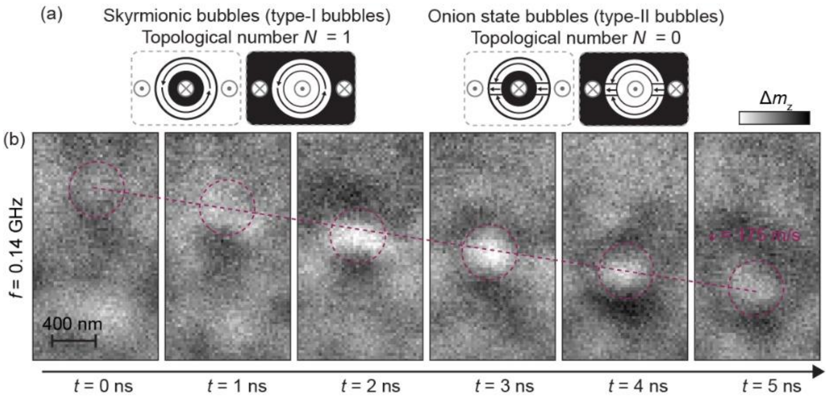

Fig. 1 (a) Sketch of skyrmionic and type-II bubbles in magnetic thin films with PMA. (b) Magnon-driven magnetic bubble motion with moving speed of 175 m/s at f = 0.14 GHz with external field $\mu_0 H$ = 10 mT applied with 1 degree tilted from the axis normal to the thin film.

References

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[2] C. Schütte and M. Garst. *Phys. Rev. B* **90**, 094423 (2014)

Unravelling spin-wave propagation regimes using NV magnetometry

Julien Berthomier[1], Romain Lebrun[1], Karim Bouzehouane[1], Vincent Cros[1], Marie-Pierre Adam[2], Jean-François Roch[2], Jamal Ben Youssef[3], Abdelmadjid Anane[1]

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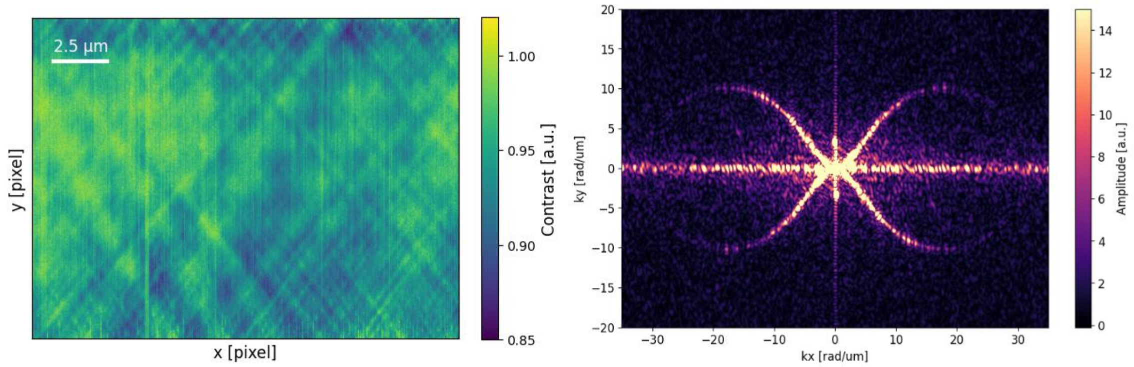
Studying and controlling spin wave propagation and (non-)linear magnon-magnon interactions require the development of fast and efficient 2D imaging techniques of nanostructured magnonic devices. Until recently, the laboratory techniques have solely relied on magneto-optical effects (such as Kerr microscopy and micro-Brillouin light scattering (μ-BLS)).

With the emergence of NV centers as ultrasensitive quantum sensors of magnetic fields, new approaches are being developped to image magnonic transport through their oscillating stray field [1] [2].

Following this approach, we develop NV microscopy techniques to image spin-waves in various garnet films (YIG, BiYIG) with thicknesses ranging from 20 to 500 nm. In these sytems, we could first image the expected highly anisotropic dispersion relation of spin waves in both real and k spaces (Fig. 1). We also evidence the presence of a standing wave pattern arising from multi-magnons scattering processes. Our approach paves the way for the study of nonlinear spin-waves dynamics in complex geometries in presence of topology and potential quantum phenomena.



(a) Image of a spin-wave in real space in Damon-Eschbach configuration for a YIG thin films.

(b) Spatial Fourier transform of the figure 1.a (k-space).

Figure 1. The image are obtained through the spatial ESR contrast of a single NV center mounted on an atomic force microscope (AFM). It shows spin wave propagating from the top to the bottom excited by a stripline antenna (not shown). We observe secondary spin waves propagating diagonally (a). Its Fourier transform reveals shifted dispersion relation contour of spin waves at NV frequency (b).

This work has benefited from a government grant operated by the French National Research Agency as part of the France 2030 program, reference ANR-22-EXSP-0004 (SWING).

Ce travail a bénéficié d'une aide de l'État portant la référence ANR TACTIQ project, Grant No.23-CE47-0009

Ce travail a bénéficié d'une aide de l'État au titre de France 2030 (QuanTEdu-France) portant la référence ANR-22-CMAS-0001.

[1] I. Bertelli et al., Science Advances 6 46 (2020) eabd3556
[2] B. Vindolet, PhD thesis University Paris Saclay (2021)

Nonlinear spin waves processes in a 500nm Bismuth Yttrium Iron Garnet disk

Sali Salama[1], Maryam Massouras[1], Ping Che[2], Jamal Ben Youssef, [3] Joo-Von Kim,[1]
Abdelmadjid Anane[2] and Jean-Paul Adam[1]

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One of the interesting properties of spin waves, the elementary excitations of magnetic material, is their nonlinearity, which can be reached with moderate radio frequency RF excitation fields. The nonlinear interactions between spin waves attract increasing attention in neuromorphic computing and magnonic logic devices. This study presents micro-focused Brillouin light spectroscopy (uBLS) of nonlinear processes in a 500 nm Bismuth Yttrium Iron Garnet (BiYIG) disk [1]. Such material is a soft ferrimagnet with moderate cubic anisotropy and has one of the lowest dampings among all the magnetic materials. The spin waves are excited with out-of-plane RF excitation generated by the Ω-shaped antenna. An in-plane static magnetic field is applied, resulting in an in-plane magnetized disk. We vary three parameters to investigate the nonlinear dynamics: the in-plane static field, the rf power (ranging from -15 dBm to 10 dBm), and the rf frequency. We focus on three magnon splitting, where one magnon at f splits into two magnons around $f/2$. By sweeping the in-plane field between 5 and 25 mT at 5 dBm power, we excite the mode denotated by f in Fig. 1(a). In the field range of 13–17 mT, a doublet appears around $f/2$ (denoted f_A and f_B) indicating the occurrence of three magnon splitting. Time-resolved BLS measurements show that f_A and f_B appears after f, with the intensity of f, reaching a minimum when f_A and f_B reach their maximum values as shown in Fig. 1(b). The presence of different channels around $f/2$ creates different possibilities for conserving the energy of the split magnons. At higher excitation frequencies, a cascade of three magnon splitting was observed which leads to the generation of three pair of modes around $f/2$. Time resolved BLS measurements show a sequential appearance of these modes: the mode closest to $f/2$ appear first followed by pairs with progressively larger frequency separations.

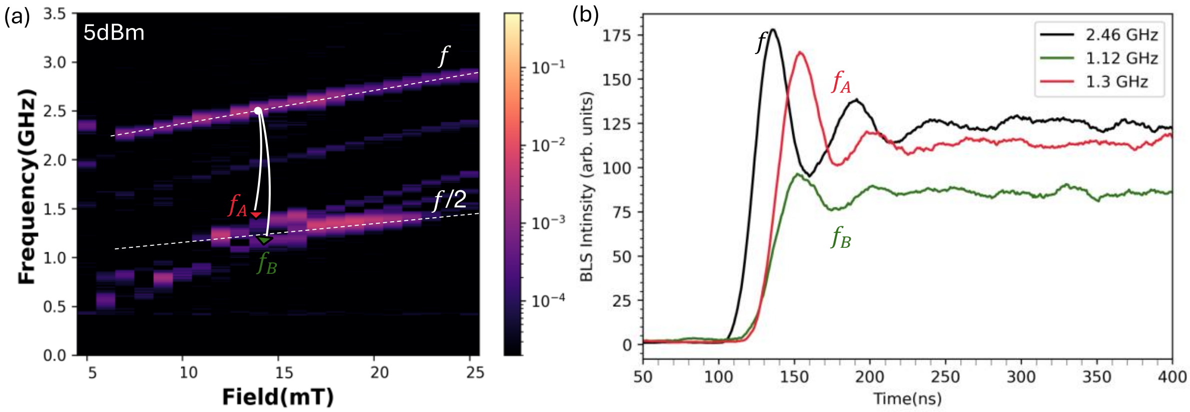

Figure 1 a) BLS spectra for an in-plane static field swept from 5 to 25 mT, while the excitation frequency varied for each field at a constant power of 5 dBm. The excited mode is denoted as f. b) Temporal dependance of the modes f, f_A and f_B.

This work was supported by the French National Research Agency (ANR) [under a public grant overseen as part of the Investissements d'Avenir program (Labex NanoSaclay, reference: ANR-10- LABX-0035), SPICY, and a research contract No. ANR-20-CE24-0012 (MARIN)].

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Tuning the Interaction between Surface Acoustic Waves and Spin Waves in Fe thin films via N-implantation

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Spin waves (SWs) are propagating spin excitations in magnetic materials, with magnons as their quanta. For future magnonic devices, local and selective excitation of SWs is crucial to enable the control of SW propagation. One of the ways to achieve this is by using Surface Acoustic Waves (SAWs) i.e., elastic waves traveling on the surface of piezoelectric materials, to locally excite SWs and tune the magnetic parameters of the magnetic material by doping with foreign atoms to selectively excite SWs.

In this work, we study the evolution of SAW-SW interaction as a function of N-doping in Fe thin films.

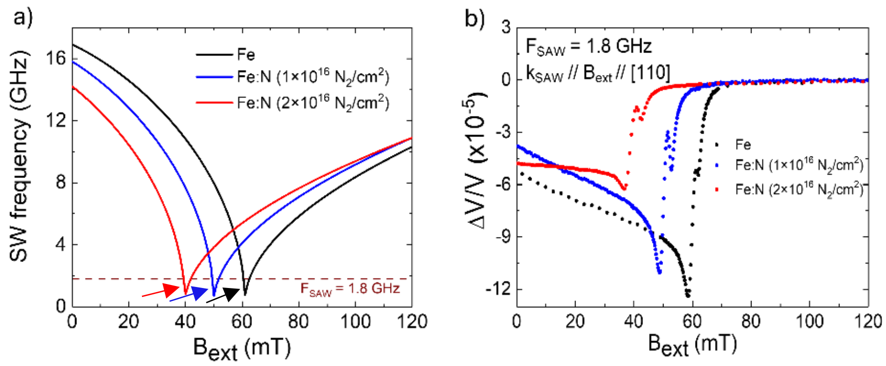

Figure 1. (a) Calculated shift in the SAW-SW resonant field, based on magnetic anisotropy measurements of the epitaxial Fe thin film and, (b) Experimental relative SAW velocity vs applied field, for three different N doping levels

It has been established that SAW-SW interaction is governed by magnetoelasticity and magnetorotation [1, 2]. The softening of SW precession frequency allows it to couple resonantly with the SAW frequency as experimentally demonstrated in ref. [3]. The N-implantation slightly modifies the magnetocrystalline anisotropies of Fe, resulting in controlled variation of its dispersion, while maintaining the initial epitaxy of Fe, i.e., Fe (001) // GaAs (001), and Fe [100] // GaAs [100].

We found that the resonant magnetic field of the SAW-SW coupling shifts to lower fields with increasing N-doping levels in Fe [see Fig. 1(a)]. We also study the relative SAW velocity variation after its interaction with the magnetic film doped with different concentration of N atoms. We find that the SAW-SW interaction, which depends on the depth of $\frac{\Delta V}{V}$, decreases with doping and also shifts towards lower fields [see Fig. 1(b)], corresponding to the shift seen in Fig. 1(a). This implies that SAW-SW coupling can be tuned out of resonance for different doping levels at a given external field which has the potential to selectively excite SWs. Finally, we anticipate to control N-implantation locally using a Focused Ion Beam technique.

Acknowledgement: The authors acknowledge the support of the ANR-22-CE24-0025 SACOUMAD, PEPR SPIN projects ANR 22 EXSP 0008 and ANR 22 EXSP 0004.

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Spin wave dynamics in curved magnets

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Recent studies have focused on spin waves in reduced dimensions, such as thin films, nanotubes, and 2D materials [1]. Theoretical work shows that surface curvature and magnetic charges can break symmetry, leading to anisotropies and magnetochiral interactions, including curvature-induced spin wave nonreciprocity in vortex-state ferromagnets [2–5]. In this communication, we report on the fabrication and characterization of ferromagnetic nanoscale crescent half-tube structures. The process resulted in the formation of the half-pipe structures, as illustrated in Fig. 1(a). SQUID magnetometry measurements revealed an easy axis along the length of the half-pipes, and a semi-hard axis transverse to the half-pipes, as shown in the inset of Fig. 1(b). Complementary measurements using cavity FMR techniques (X-band and Q-band) revealed additional resonance peaks (inset of Fig. 1(c)), which we attribute to the strongly inhomogeneous magnetic landscape developing under the applied field. Propagating spin wave spectroscopy (PSWS), shown in Fig. 1(d,e), revealed multiple oscillating spin wave modes whose frequencies are sensitive to the waveguide geometry and antenna positioning. The observed frequency nonreciprocity, dependent on the wavevector and mode index, is attributed to mode hybridization.

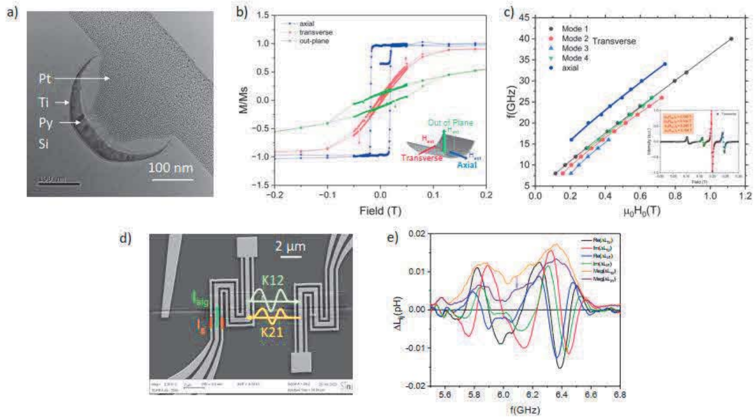

Fig: a) TEM image of crescent half tube. b) Magnetic hysteresis in different orientation of external field. c) Broad-band FMR frequency vs field. Inset: Cavity FMR at X band. d) Microwave antenna for PSWS measurement. e) Mutual inductance spectrum for counter-propagating spin-waves.

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RF magnonic devices: modelling, experiment and integration

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We present our works towards the development of magnonic analog microwave devices. We will first present our strategy to optimize their microwave properties, taking the example of magnonic delay lines. Via a combination of analytical models [1], numerical models and measurements via propagative spin wave spectroscopy (PSWS) using Vector Network Analyzers (VNA), we can successfully optimize their frequency operation, bandwidth and insertion losses.

In a second part, we present a strategy to achieve reconfigurable on-chip delay lines based on MEMS (Micro-Electro-Mechanical Systems) technology [2]. For this purpose, we developed a process allowing the monolithic integration of magnetic MEMS on a YIG delay line (Fig. 1). The magnetic MEMS membrane is suspended above the magnonic delay line in the form of a "bridge". By applying a voltage between the magnetic MEMS membrane and an electrode placed onto the surface of the magnonic delay line, one can move the magnetic MEMS closer to the magnonic medium. The stray field experienced by the YIG is hence locally modified by a few mT, thus changing the spin wave group velocity. First characterization of such effect was performed by PSWS, effectively demonstrating propagation delay tunability with virtually zero stand-alone power. Such approaches hold promising opportunities for the optimized development of reconfigurable, integrated and low-power magnonic devices.

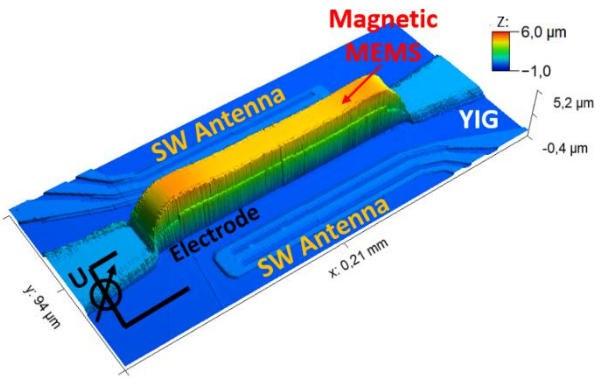

Fig. 3D optical profilometer image of a YIG magnonic delay line combined with a magnetic MEMS membrane placed above the magnonic medium (in-between the spin wave antennas) at a certain height of about 4.7 µm.

The financial fundings from the European Union's Horizon research and innovation programme under grant agreement No 101070536 (M&MEMS), and No 101070417 (SPIDER), and from a government grant operated by the French National Research Agency as part of the France 2030 program, reference ANR-22-EXSP-0004 (SWING) are gratefully acknowledged.

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Modelling of frequency spectra and impulse responses of multi-nature spin waves

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Spin waves (SWs) offer unique properties which offer new ways for the fabrication of signal processing devices. In order to use SWs to transport information, the sample is usually patterned into different shapes. This modified the behaviour of SWs which results on a complex signal. This study will address the case of SWs confined in magnetic stripes. We treat the case of SWs propagation in a patterned CoFeB of $t_{\text{mag}} = 60$ nm under an in-plane applied field $\vec{H}_x$. The field is applied perpendicularly to the direction of propagation to selectively excite SWs in the so called Damon-Eshbach configuration (DE). In this configuration SWs frequencies increases rapidly for a small range of wavevectors (k). This leads to highly dispersive SW where a low k SW has a much higher group velocity than high k SW.

To better understand the response of this system, we model the SW spectra and their impulse responses for a stripe with a variable width ($w_{stripe} = 0.1, 1, 5, \ldots$ μm) using [1]. We consider that SWs are excited by the rf-field produced by a line-shape antenna and their responses is the magnetic susceptibility which depends on the dispersion relation. In the saturated state, we can approximate the dispersion relation of DE SWs as [2],

$$\omega_{\text{DE}}(k_y) = \gamma_0 \sqrt{\left(H_0 + M_s \frac{e^{-kt_{\text{mag}}} - 1}{kt_{\text{mag}}}\right)\left(H_0 + M_s \frac{k_y^2}{k^2}\left(1 + \frac{e^{-kt_{\text{mag}}} - 1}{kt_{\text{mag}}}\right)\right)} \tag{1}$$

where $H_0 = H_x - H_{\text{ani}}$ the internal field and $k^2 = (\frac{\pi}{w_{\text{stripe}}})^2 + k_y^2$. Fig. 1.(b) shows the dispersion relation for the different stripe width while considering the same internal field $H_x - H_{\text{ani}} = 12$ mT. It is noticeable that wider the stripe is more dispersive is the dispersion relation. We plot the variation of the group velocity as a function of the wavevector in Fig. 1.(c) and it shows that the group velocity evolves very abruptly for low k whereas for high k it stabilises at a low value of speed. Therefore, in this configuration we expect to observe a separation of the wavepackets in the time domain. We first modelled the frequency spectra which is shown in Fig. 1.(a). In the spectra we can see that we excite more frequencies for the largest waveguide and the phase change all along the frequencies, indicating a continuous change of SWs velocities. From this it is possible to obtain the impulse responses for the different widths and therefore from the more dispersive to the less dispersive SWs.

It is therefore possible to study the shape of the frequency spectra and the impulse response as a function of various parameters. This allows us to gain information on SW propagation and an understanding of the measured signal after performing SW propagation.

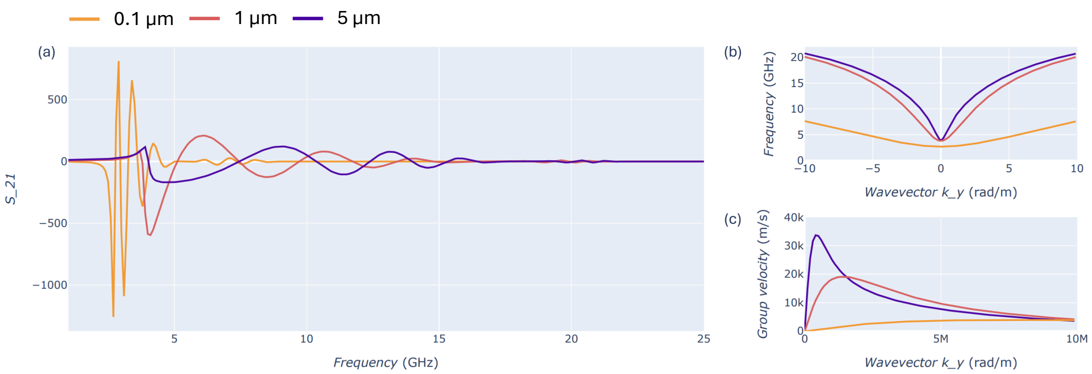

Figure 1: (a) Real part of the modeled frequency spectra ($\tilde{S}_{21}$) for different waveguide widths. (b) Analytical dispersion relation of spin waves in a magnetic waveguide (c) Analytical calculation of the group velocity of spin waves in the magnetic waveguide

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Influence of Stress Gradient on Micromagnetic Configurations in Nano-Objects

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Magneto-mechanical effects have gained renewed interest, particularly in nanomagnetism. These effects are explored in flexible magnetic devices, often consisting of magnetic systems on polymer substrates, with applications in everyday items and microelectronics. A key focus is how geometry, such as curvature, influences magnetic properties and generates new phenomena. Central to this research is stress-gradient magnetism, which impacts magnetic behavior, enabling the development of flexible, stretchable magnetic systems. In this study, we used a micromagnetic code coupled with solid mechanics, developed within our team using Comsol Multiphysics® [1,2], to study the effects of stress gradients on the static and dynamic properties of ferromagnetic nano-objects. As an example, we started with a self-supported nanobar, which we subjected to a mechanical bending test. This generates a stress gradient (Fig. 1) in the thickness direction. When the material is non-magnetostrictive, only shape effects come into play, which ties into the concept of curvilinear magnetism, where magnetic textures can emerge in curved objects [3]. On the other hand, when the material is magnetostrictive, we demonstrate a significant influence of these stress gradients on both the static and dynamic properties (through changes in magnetic modes, including their energies and shapes). More specifically, dynamic properties are much more sensitive to the stress gradient. Indeed, we show that the distribution of magnetic moments remains fairly uniform as long as the gradient of the induced magnetoelastic field does not exceed a certain threshold (by increasing the saturation magnetostriction coefficient), while the magnetic modes undergo significant changes in both their energy and shape once the stress gradient reaches the first curvature value. A complete study of these effects will be presented during this talk.

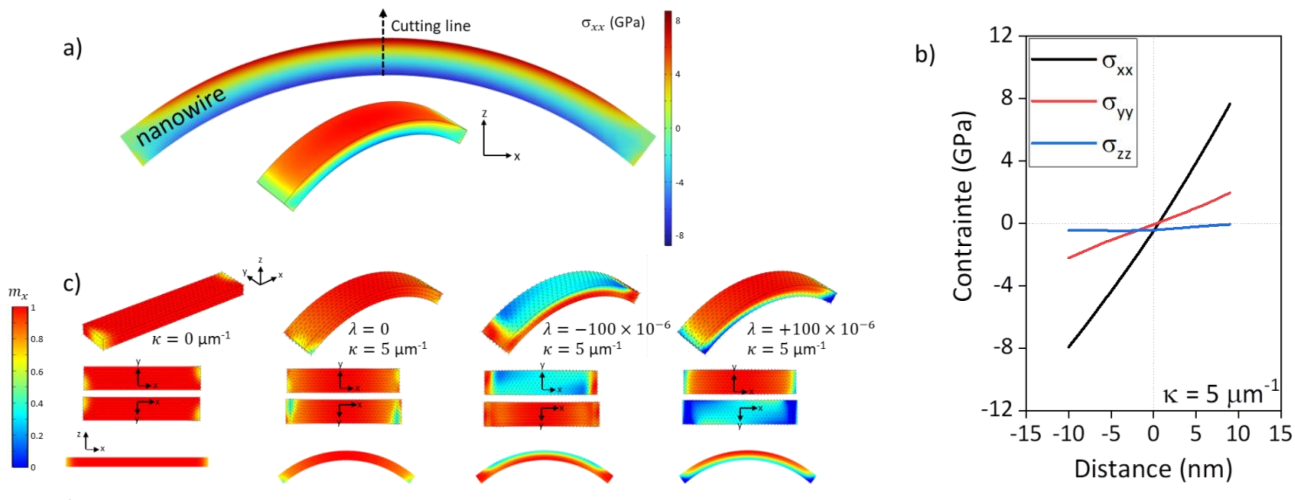

Fig. (a) Mechanical response of a nanowire under strain. (b) Stress distribution along the cutting line of the nanowire. (c) Magnetic configurations under varying curvature and magnetostriction coefficients.

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Poster presentations

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Spin waves involved in three-magnon splitting in synthetic antiferromagnets

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An important nonlinear effect in magnonics is the 3-magnon splitting (3MS) where a high frequency magnon splits into two magnons of lower frequencies. Here, we study 3MS in spin wave conduits made from synthetic antiferromagnets (CoFeB 17nm / Ru / CoFeB 17nm). The dc field is tuned to naturally satisfy energy conservation in 3MS between the optical spin waves and the acoustic ones (Fig. 1a). A parallel pumping inductive scheme is used to populate selectively the sole optical family such that every detected acoustic spin wave can be traced back to a 3MS event. Spin wave detection is done using a spectrum analyzer after propagation to a receiving antenna(Fig. 1b). The splitting is most often non-degenerate and its result appears as a well-defined frequency doublet (Fig. 1c-d). Several splitting channels, with different quantization signatures are possible, depending on the system size and related quantization conditions. An elementary model based on conservation laws reproduces the main experimental trends. Its clarifies why the magnons generated by 3MS have effective wavevectors that are neither collinear to each other nor to the initial optical magnon. When in addition, the SWs are confined in a narrow conduit, the split acoustic spin waves have a standing wave character in the direction transverse to the conduit and a plane wave character in the direction of the conduit.

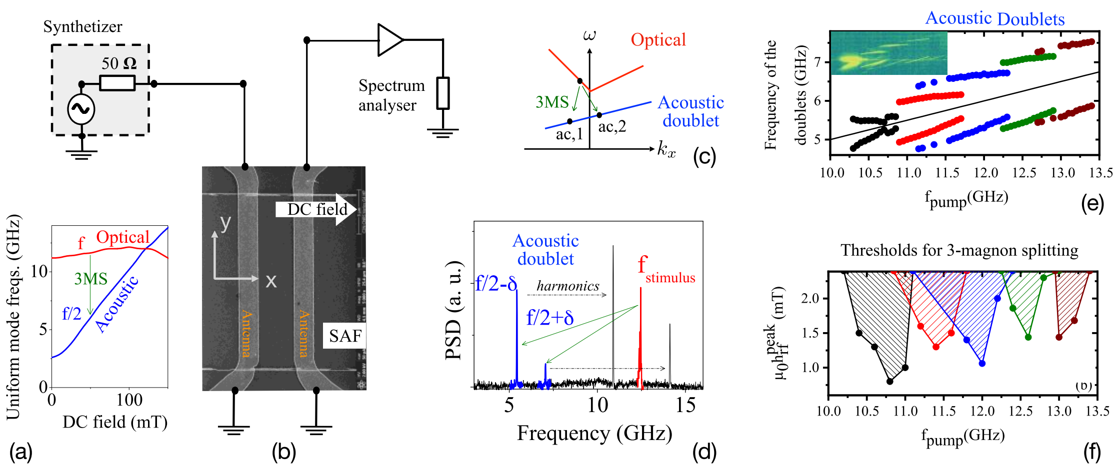

Figure 1. (a): Frequencies of the uniform acoustic and optical modes on a SAF. The green arrow sketches the field required to get energy conservation in 3 magnon-splitting. (b) Set-up and sample. (c): Illustration of the three magnon scattering process in SAFs: a spin wave from the optical branch splits into two spin waves belonging to the acoustic branch. (d) Typical spectral signature of this process as seen with spectrum analyzer. (e) Frequencies of the doublets of acoustic spin waves versus pump frequency for an rf field of 2.7 mT.
A line is at fpump/2 was superimposed. Inset: power spectral densities from which the frequencies are extracted. (f) doublet-resolved 3MS thresholds forming the Arnold tongues.

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Quantum teleportation via a two-qubit Heisenberg XXX chain with presence of DM interaction

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Abstract

This paper examines thermal entanglement and teleportation in a thermally mixed entangled system using a two-qubit Heisenberg XXX chain with the x-component Dx of the Dzyaloshinskii–Moriya interaction. We find that the factors of temperature, spin coupling constant, and Dx influence the entanglement of output states, which impacts teleportation protocols. The study highlights that effective entanglement requires low temperatures, weak Dzyaloshinskii–Moriya interactions, or an antiferromagnetic chain. Ultimately, the establishment of entanglement in the channel makes teleportation protocols feasible and practical.

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Mapping the magnetic response of materials on a local scale using magneto-resistive sensors

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The characterization of the magnetic properties of materials at the local scale is important for applications such as in situ monitoring, non-destructive testing or nanometrology. Indeed, for some materials that exhibit a magnetic response and in particular steels, mechanical and magnetic properties are correlated via the microstructure. The measurement of magnetic properties at the local scale could therefore allow access to the mechanical properties of materials in a non-destructive way and a better understanding of their microstructure.

Two magnetic mapping tools, at two scales, submillimeter and submicrometer, are developed in the laboratory by combining magnetoresistive magnetic sensors [1] and a scanning system. The use of the giant and tunnel magnetoresistance effect (G-TMR), based on spin electronics, allows the development of very sensitive magnetic sensors whose size can be submicron. These sensors allow to detect magnetic fields emitted by the sample surface in a quantitative way, with a detectivity of the order of $\mathrm{nT}/\sqrt{Hz}$, in a topography-decolored way, and on a large frequency range (DC to the hundred MHz).

In order to achieve micrometer and submicrometer resolution, the GMR sensor is integrated into a flexible cantilever (Figure 1 left) and combined with a local probe microscope. On a larger scale, the tool working with sub-millimeter resolution is composed of a 3D probe integrating GMR sensors mounted in Wheatstone bridge and gradimeter to eliminate temperature and environmental drift, and positioned on a pyramidal support (Figure 1 right), and a motorized stage. The three components of the field can be extracted and allow a 3D mapping of the fields emitted by the material surface.

In order to obtain additional contrasts, it is possible to map the frequency response of the material to the application of an alternating magnetic field. The idea is to adapt these scanning setups by optimizing the sensors, electronics and excitation to measure magnetic susceptibility and detect spin waves with MR higher-frequency measurements [4, 5, 6].

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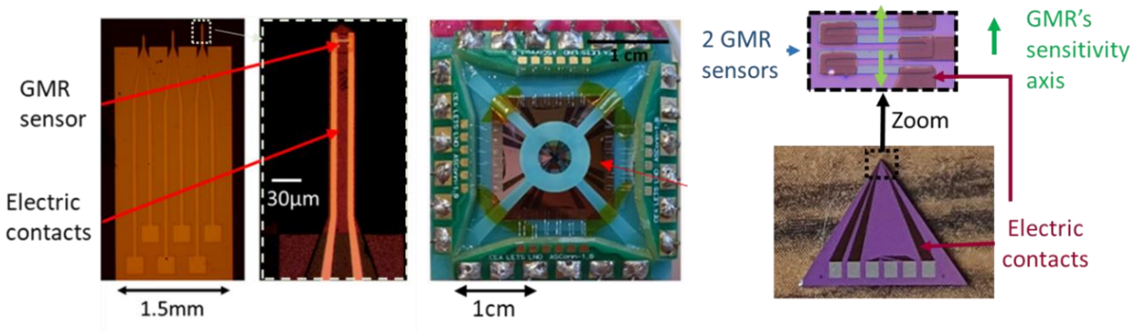

Figure: (Left) Atomic force microscope (AFM) support composed of 3 flexible cantilivers (1µm Si3N4) on which are integrated a GMR sensor. (Right) 3D probe composed of 4 GMR dies positioned on a pyramidal support.

Neuro-Inspired Computing in k-Space: Harnessing Spin Wave Dynamics in YIG Microdisks

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Neuromorphic devices promise new perspectives for the next generation of hardware technologies. Bypassing conventional CMOS architectures and exploiting nontrivial physical effects may offer lightweight and energy-efficient computation solutions. We explore nonlinear spin wave interactions in Yttrium Iron Garnet (YIG) microdisks as a versatile platform for computation and classification tasks. Unlike conventional neuromorphic systems based on hardwired neurons and synapses, our approach utilizes intrinsic interconnectivity in the reciprocal (k-) space of spin wave excitation spectra, as demonstrated in prior work [1].

Finite-size effects in a 1 µm YIG disk impose quantization, leading to a discrete spin wave spectrum. Parametric excitation of the corresponding eigenmodes [2] exhibits a threshold behavior crucial for neuromorphic applications. Mode interactions enable population shifts, effectively modeling the system as a recurrent neural network (RNN), where spin wave modes act as neurons and nonlinear interactions as synapses. An illustrative example of such a network is shown in Figure 1. A programming signal composed of a small number of sinusoids is used to dynamically adjust neuron interactions, enabling reconfigurable network behavior.

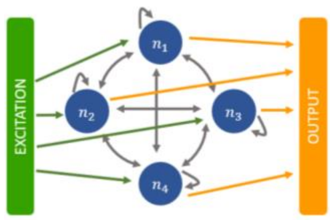

Figure 1. Recurrent neural network of interacting magnon modes in k-space.

Our experimental setup consists of 20 YIG disks, each 55 nm thick, with their magnetization saturated by an in-plane static magnetic field. Spin waves are then excited through a coplanar waveguide at a 45° angle to the static field. An arbitrary waveform generator shapes the input signal, while a spectrum analyzer measures the frequency-resolved magnetization response. By optimizing input and programming parameters using algorithms such as Differential Evolution and Powell's method, we demonstrate a binary threshold function with three input variables, achieving 94% accuracy. While our long-term objective is to extend this approach to more complex tasks, such as speech classification, our immediate focus is on constructing a model of the neural network and characterizing its fundamental properties and capabilities. Specifically, we aim to explore nonlinear multi-variable functions for binary classification and investigate how the excitation of specific spin wave modes can be selectively enhanced or suppressed. As the network complexity grows, this foundational model will serve as a starting point for optimizing parameters in higher-dimensional tasks.

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Propagation of spin waves in non-uniform magnetic textures

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Yttrium iron garnet (YIG) has been the main material platform for magnonics because of its ultra-low magnetic damping $\alpha \approx 10^{-5}$ [1]. It has been shown that perpendicular magnetic anisotropy (PMA) induced by Bismuth doping can stabilize magnetic textures such as worm-like domains or magnetic bubbles [2], making Bi-YIG an ideal candidate for reconfigurable magnonic devices [3]. In this work, we investigated the propagation of spin waves (SW) in Bi-YIG films with a thickness of ~ 20nm, combining Magneto-Optical Kerr effect (MOKE) imaging and all electrical propagating spin wave spectroscopy (PSWS) between two radio-frequency antennas. A simultaneous in-plane ($\mu_0 H_{ip}$) and out-of-plane ($\mu_0 H_{oop}$) fields were applied and controlled independently to tune the magnetic phases.

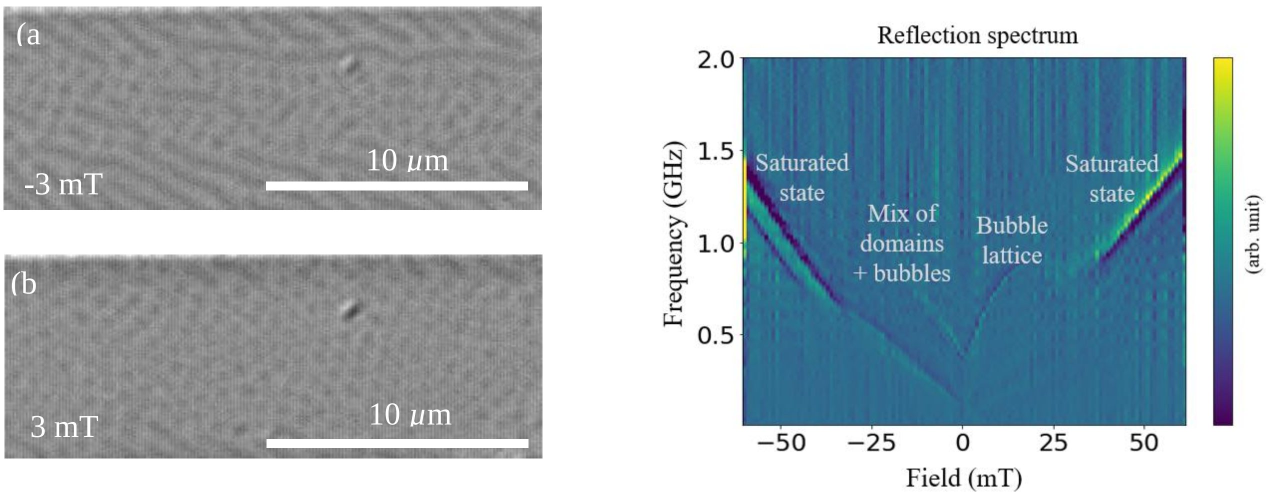

Figure 1. (a) and (b) Magneto-optical imaging of Bi-YIG at different in-plane fields $\mu_0 H_{ip}$ = -3 mT and 3 mT respectively with fixed out-of-plane field $\mu_0 H_{oop}$ = 3mT. The white bar represents 10 μm. (c) Reflection spectrum for $\mu_0 H_{ip}$ scanned from -60 mT to 60 mT with $\mu_0 H_{oop}$ = 3mT. The color bar represents the intensity of the reflection spectrum.

Different magnetic textures were observed including magnetic bubbles, stripe-shape domains and a mixture of both, depending on the strengths of the $\mu_0 H_{ip}$ and $\mu_0 H_{oop}$. The interplay between PMA and dipolar energy stabilizes these phases which were observed via both MOKE imaging (Fig. 1 (a) and (b)) and the spin wave spectrum (Fig. 1 (c)). With $\mu_0 H_{ip}$ above 37 mT and below -34 mT, Zeeman energy dominates to form fully saturated states, which exhibit a single spin wave mode following Kittel formula. When $\mu_0 H_{ip}$ was swept from 29 mT down to 0 mT, bubble lattice was formed. They turned into a mixed state consisting of bubbles and stripe-shaped domains when we further decreased the $\mu_0 H_{ip}$ until -18 mT. When $\mu_0 H_{oop}$ increases, a wider range of $\mu_0 H_{ip}$ for stabilizing the bubbles is observed. MuMax^3 simulations have been conducted to investigate the dynamic behavior of the textures corresponding to these different phases. We acknowledge the financial support from SWING (Project- ANR-22-EXSP-0004) and DEMURGE (Project-ANR-22-CE30-0014).

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Vortex light beams for probing asymuthal spin-waves by BLS

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Magneto-optics (MO) is a very convenient and versatile way to probe and possibly manipulate the magnetic order in a huge number of systems [1]. In particular, the inelastic Brillouin light scattering (BLS) is a powerful and non-invasive tool to study spin waves (SW) eigen modes thanks to a selection in wavevector (the difference of the incident and scattered light wave vectors select the SW mode wave vector). Even if planar-wave Gaussian-beams are preferred for simpler implementation and understanding of MO, other more exotic waves can propagate in isotropic media such as vortex-beams [2] with a phase nonuniform in the phase-plane non-perpendicular to its wave-vector (as shown Fig.a). The azimuthal variation of these beams phase has two main effects: the phase singularity emerging at the center of the beams leads to a so called doughnut intensity profiles, and the emergence of a significant optical orbital-momentum, much larger than the usual optical spin-momentum carried by usual Gaussian-beams (related to their circular polarization).

Thus, we propose to use vortex light beams to push MO beyond the unusual planar-wave configurations. In particular, we propose to use them to measure azimuthal SW modes [3] by BLS (usually not possible because of the *k*-selectivity). In such configuration, the azimuthal SW modes order can be selected thanks to the azimuthal order of the vortex beams.

Preliminary results have already demonstrated the possible generation of such vortex beams thanks to optical grating with singularities (as shown in Fig.b). The frequencies and the structure of azimuthal SW modes have been explored in nano- and micro-structures thanks to analytical calculations and micro magnetic modeling (Fig.c). Finally, their MO interaction with vortex beams occurring during the BLS have been simulated.

Such approach allows to push the BLS to non-planar magnonics. In the future, others properties of vortex beams could lead to the measurement and the manipulation of more exotic properties of magnetic systems [1].

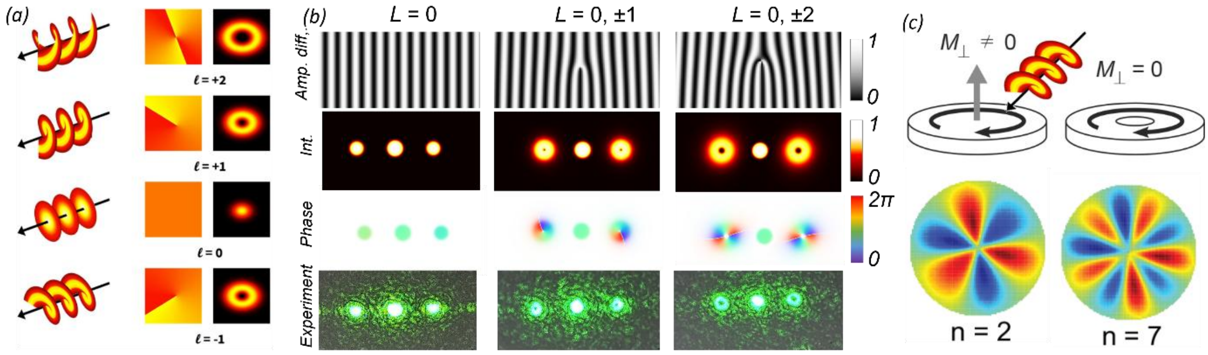

Fig. (a) Examples of vortex beams of different orders *l*. From right to left: zero-phase quasi-plane, phase and amplitude of the *E*-field in the polarization plane (normal to the k-vector). *l*=0 corresponds to the usual Gaussian beam. (b) Simulated (intensity and phase) and experimental intensity of vortex beams generated by amplitude singularities of different orders *L*. (c) Magnetic state in a disk or ring and the resulting azimuthal circular SW modes.

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Spin wave propagation in weak stripe structures

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Magnetic thin films exhibiting low perpendicular magnetic anisotropy, insufficient to stabilize out-of-plane magnetization, can develop weak stripe structures. This work focuses on the study of spin-wave propagation in $Ni_{80}Fe_{20}$ thin films with thicknesses of 400 nm and 720 nm, using Brillouin light scattering (BLS) spectroscopy. Measurements are conducted in two magnetic configurations: saturated, with uniform magnetization, and non-saturated, where a periodic modulation of magnetization appears (stripe structures). Each configuration is investigated under two spin-wave propagation geometries: Damon-Eshbach and Backward Volume. The objective is to analyze the influence of stripe presence and periodicity on the dispersion relations of the various spin-wave modes observed in our systems.

Interference effects in the parametric excitation of spin waves in YIG disks

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In the context of unconventional computing using spin waves [1], it is essential to understand how modes influence the generation of other modes and the role of transients dynamics. We examine this question using the MUMAX3 code [2] for 1-µm-diameter 50-nm-thick YIG disks at 300 K under parallel pumping [Fig. (a)]. Using mode-filtering method projected onto precomputed eigenmode profiles [3,4], we can monitor both population and power spectrum of any mode. Figure shows the main features for modes $\kappa = 11, 18$, first when excited individually [Figs. (b-c)]. Pumping at $2\nu_{11}$, targeted mode ψ_{11} is populated along with satellite modes ψ_{17} and ψ_7. Pumping at $2\nu_{18,}$ targeted mode ψ_{18} is populated along with mode ψ_{19}. After having characterized their detuning ranges [Figs. (d-f)], we study whether modes from a second pump can be populated when modes preexist with toggled sequences [Figs. 1(g-h)]. When $2\nu_{11}$ is pumped first, additional pump $2\nu_{18}$ populates mode ψ_{18} and inhibits mode ψ_{19} while preexisting modes carry on. When the sequence is reversed, additional pump $2\nu_{11}$ populates all modes affiliated while preexisting mode ψ_{18} maintains its value and mode ψ_{19} is annihilated, accompanied by the transient mode creation of modes $\kappa = 12, 29$. While mode power spectra can account for mode creations ($\nu_{11}+\nu_{29}=2\nu_{18}$ and redshift of mode ψ_{12}), the presence/absence of modes associated with the added pump can be explained by the mutual nonlinear frequency shift imposed by the first pump. When pumping at $2\nu_{11}$, modes $\kappa = 18, 19$ undergo frequency redshifts, detuning the associated populations at ν_{18}: non-zero and below thermal level respectively. This explains why mode ψ_{18} is populated while mode ψ_{19} is inhibited with the preexisting $2\nu_{11}$ pump. Pumping at $2\nu_{18}$, mode $\kappa = 11$ undergoes a frequency redshift yielding non-zero value at ν_{11} explaining why it is populated with the preexisting $2\nu_{18}$ pump. The strong bearing on overall dynamics goes beyond the example of mode selection: full inhibition, annihilation and coexistence depending on pumps, sequence and supercriticality suggesting potential computing applications.

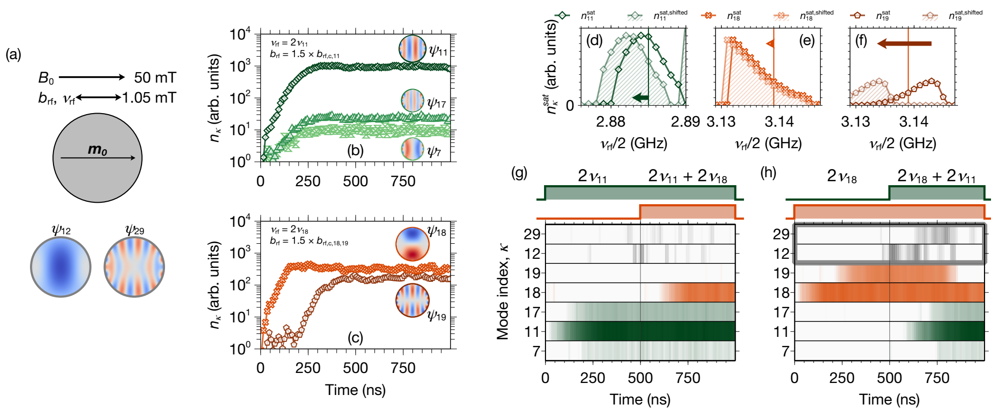

Fig. (a) Geometry and eigenmode profiles. (b-c) Populated modes with single pump. (d-f) Evolution of saturation values with detuning and when undergoing frequency shifts (solid and shaded filling respectively (g-h) Populated modes manifold when excitations are toggled (g) $2\nu_{11}$, $2\nu_{11}+2\nu_{18,}$ and $2\nu_{18}$, $2\nu_{18}+2\nu_{11}$.

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Micromagnetic simulations combining magnonic, straintronic and curvilinear magnetism consideraration

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Information technologies are increasingly turning toward magnetic-based alternatives, where information is carried by spin, to envision future devices. This broad field offers numerous possibilities, each capable of meeting specific needs. Emerging branches are focusing on magneto-mechanical couplings or the use of materials with unconventional geometries. These studies can be grouped under fields such as straintronics, which relies on mechanical stress to control magnetization; flexomagnetism, which explores the influence of stress gradients; and curvilinear magnetism, which investigates magnetism in curved objects. While these areas are being increasingly explored experimentally, their numerical study remains limited due to the constraints of existing simulation tools such as MuMax or OOMMF. The aim of my work is to propose a numerical model devolopped in Comsol Multiphysics capable of overcoming these limitations and simulating all types of magnetic objects with complex shapes and/or under mechanical constraints. This research also builds on experimental studies conducted on deformed thin films, magnonic crystals, and curved nanowires. [1-3]

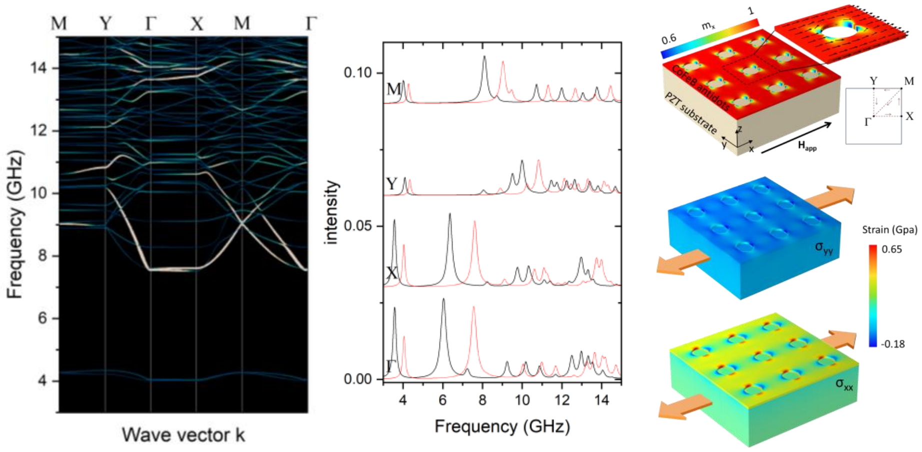

Figure 1: (left) Simulation of spin wave dispersion in a square lattice of holes in $Co_{40}Fe_{40}B_{20}$ under 0.2% strain. (middle) Simulated spectra at 0% strain in black and 0.2% strain in red. (right) Simulated profiles of the static magnetization configuration and the σ_{xx} and σ_{yy} components of the stress tensor.

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Magneto-resistive detection of spin-waves

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Spin-waves are conventionally detected by magneto-optical imaging (magneto-optical Kerr effect, micro Brillouin light scattering [1]) or by inductive microwave measurements [2]. These methods are now reaching their limits in terms of signal sensitivity and spatial resolution, which constitutes a technological bottleneck for the miniaturization of magnonic devices [3] and for the exploration of the fundamental physics of spin-waves. In this work, we demonstrate a novel detection method based on a standard element of spintronics, a giant magneto-resistive (GMR) sensor [4]. The sensor is directly integrated below a ferromagnetic slab guiding spin-waves. It is electrically insulated from the track, but located close enough to dipole couple to it. When the spin-wave passes over the sensor, it generates an oscillating dipole field which induces a precession of the magnetization of the free layer. This translates in an oscillation of the impedance of the sensor, which, for a given current bias, results in a voltage that can be accessed via suitable microwave measurements [5].

The fabricated device includes a coplanar waveguide which, upon injection of a microwave current, generates spin-waves with wavelength of about 1µm in the nearby Permalloy slab. Its magnetization is saturated along the width using an external static field H_0 (so-called Damon-Eshbach configuration). The microwave voltage is measured at the output of a second coplanar waveguide connected to the 300x600nm² rectangular GMR sensor [3]. The measurements are performed for two polarities of the DC current flowing in the sensor, which allows one to separate the magneto-resistive contribution from the inductive one related to the magnetic flux across the second waveguide. These experiments show an increase of the signal by a factor of 50 when going from inductive detection to magneto-resistive one [5]. We will discuss these results in the light of micromagnetic simulations addressing directly the coupling at play, and show that the favorable scaling law expected upon miniaturization makes it a game changer for the implementation of several advanced computing architectures proposed in the field of magnonics [4].

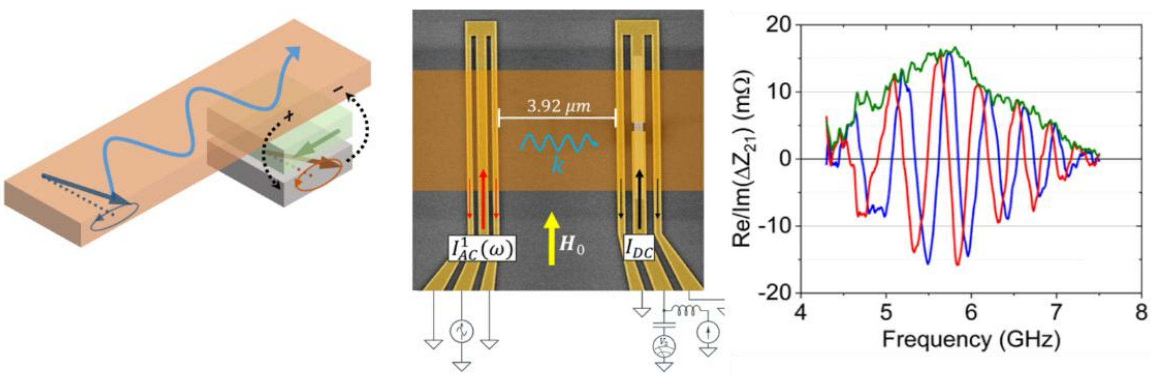

Fig. (left) Principle of the magnetoresistive detection of a spin-wave. (middle) Scanning electron microscope picture of the device. (right) GMR contribution of the microwave transmission signal, for an external magnetic field of 20mT and a bias current of 2.5mA.

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Shaping non-reciprocal spin wave beams in thin magnetic films

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Spin waves constitute the building blocks of novel wave computing methods such as spectral analysis [1], and neuromorphic computing [2], which are all interference-based techniques. Recently, basics concepts of optics applied to spin waves demonstrated the possibility to shape and steer spin wave beams, suggesting prominent performance in particular tasks such as image processing and speech recognition [3].
Here, we present several approaches that allows exciting non-reciprocal spin wave beams in thin magnetic films such as curvilinear antennas [4], grating of nanomagnets, and sharp constrictions. We first present a near-field diffraction model (NFD) that benchmarks spin wave beamforming in thin films for any geometry [5]. Then, we experimentally test our predictions using both spin wave spectroscopy and micro-focused Brillouin light spectroscopy to map diffraction patterns in the 2D plane. We will show in particular how a sharp constriction in an antenna can directly excite non-reciprocal caustic beams in an extended film when the suitable conditions of field and frequency meets an inflection point in the dispersion relation [6]. These findings have important implications for the development of switchable spin wave splitters, passive spin-wave frequency-division demultiplexers, and magnonic interferometry.

This work has benefited from a government grant operated by the French National Research Agency as part of the France 2030 program, reference *ANR-22-EXSP-0004 (SWING)*, as well as the ANR project *MagFunc/ANR-20-CE91-0005*, and the Transatlantic Research Partnership, a program of FACE Foundation and the French Embassy.

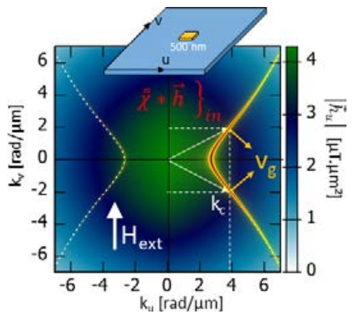

Figure 1: in-plane Fourier component of the magnetization at 7.9 GHz for a 50 nm thick YIG film magnetized along v-axis under a bias field of 200mT.

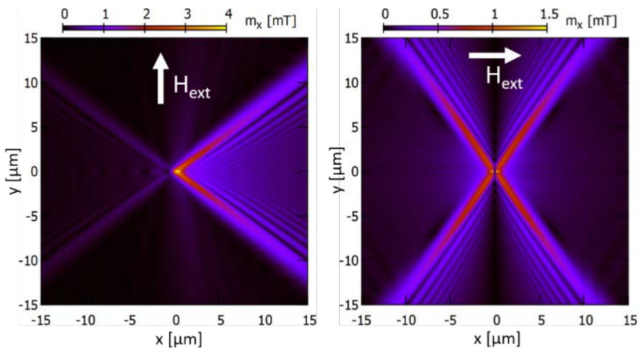

Figure 2: Corresponding NFD simulations for both field orientations.

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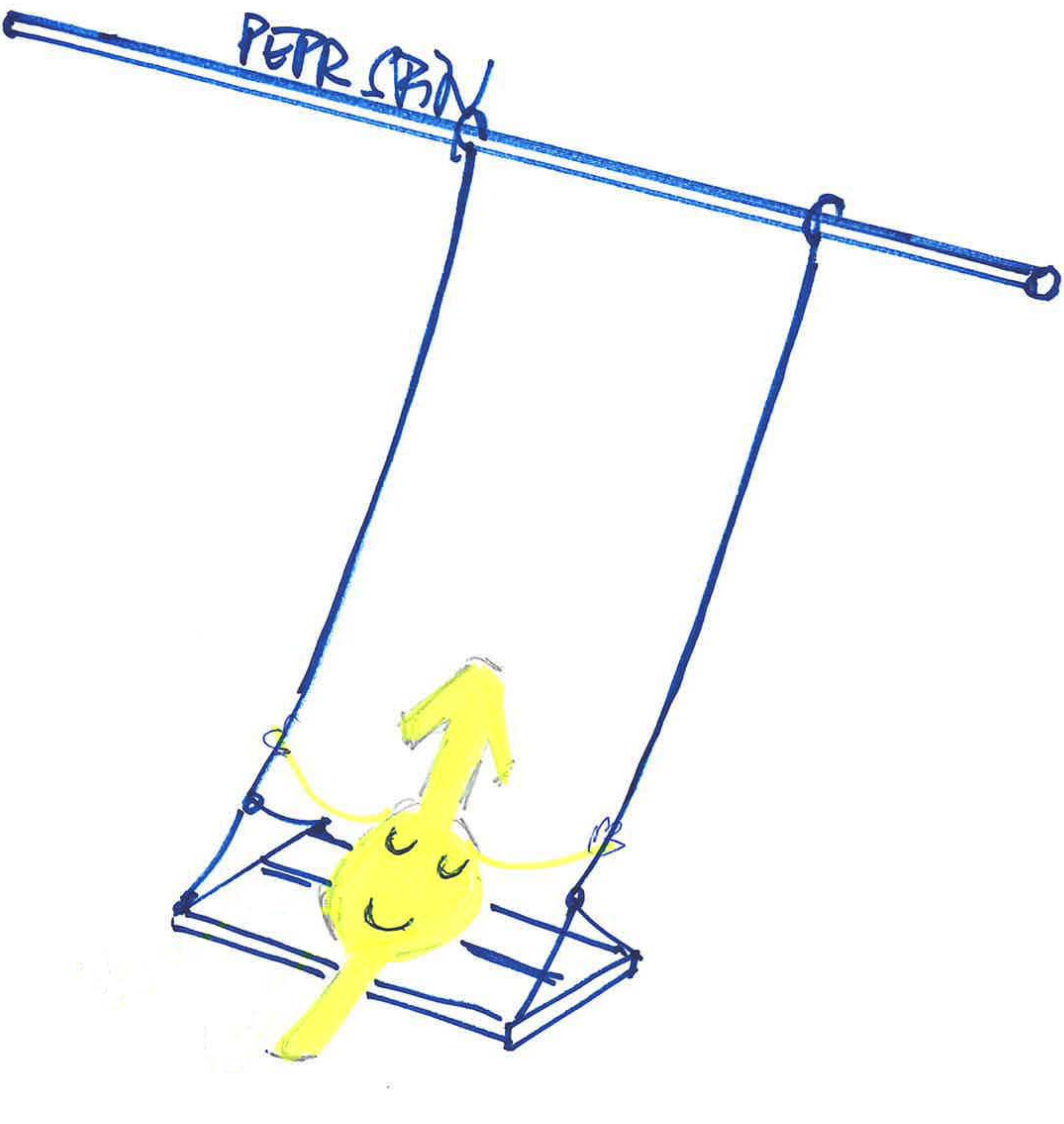

** 1 free beer to the PhD/Post-doc who can turn this sketch into something nicer*