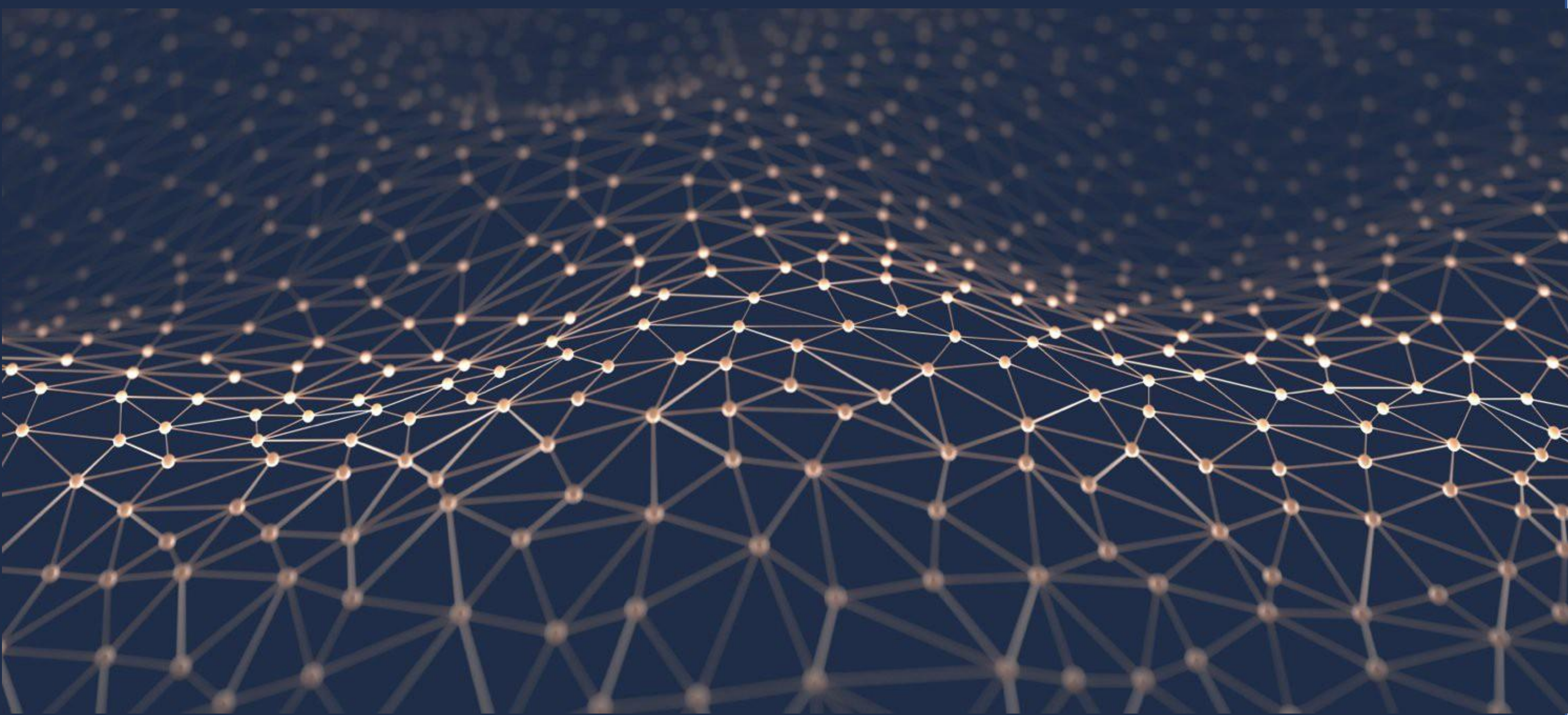
# NEUROMORPHIC MAGNONICS WORKSHOP

## APRIL 24$^{TH}$ – 26$^{TH}$, 2024
## PARIS



## BOOKLET

# WEDNESDAY, APRIL 24TH

# Neuromorphic spintronics and its magnonic wink

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In the field of neuromorphic spintronics, a key aspect lies in the use of vortex-based spin-torque nanoscillators, a trend that has been ongoing since the early stages of exploration in this field [1, 2]. These oscillators, advantageously take advantage of a magnetic texture called the vortex. The later give them extraordinary attributes, including a non-linear response and an inherent memory element due to the transient nature of their oscillatory dynamics. Vortices represent distinct magnetic configurations characterized by planar curling magnetization around the core of the vortex, where the magnetization points out of the plane. The gyroscopic motion inherent in a vortex correlates to some extent with the displacement of the a domain wall. Nevertheless, these magnetic entities have unequivocally demonstrated their effectiveness in hardware implementations of neuromorphic devices [1, 2, 3, 4]. This tutorial endeavors to provide a succinct overview of neuromorphic spintronics, but also introduces the fact that magnetic vortices can efficiently produce and interact with spin-waves [5], with the primary goal of designing neuromorphic devices capable of combining spintronics and manganics.

This comprehensive tutorial explores the complex nuances underlying the symbiotic relationship between emerging technologies, paving the way for innovative solutions at the intersection of neuroscience and materials science. At the heart of this discourse is an exploration of the multiple roles played by vortex-based spin transfer nanoscillators in shaping the landscape of neuromorphic computing paradigms. Here, we address the theoretical underpinnings that guide the design and optimization of neuromorphic devices, with particular emphasis on spin-wave generation as a cornerstone for the realization of advanced computing systems. This talk serves as a fundamental introduction for researchers and practitioners alike, offering insight into the transformative potential of integrating spintronics and manganics in the burgeoning field of neuromorphic engineering.

[1] J. Torrejon, M. Riou, F. Abreu Araujo et al., Nature 547, 7664 (2017).
[2] M. Romera, P. Talatchian, S. Tsunegi, F. Abreu Araujo et al., Nature 563, 7730 (2018).
[3] F. Abreu Araujo et al., Scientific Reports 10, 1 (2020).
[4] A. Moureaux, C. Chopin, S. de Wergifosse, L. Jacques, and F. Abreu Araujo, arXiv:2308.05810v3 (2023).
[5] C. Chopin, S. de Wergifosse, A. Moureaux, and F. Abreu Araujo, arXiv:2312.02800v1 (2023).

# Neuromorphic Overparameterisation: Generalisation and Few-Shot Learning in Multilayer Physical Neural Networks of Nanomagnetic Arrays

**Kilian D. Stenning**[1,2], Jack C. Gartside[1], Luca Manneschi[3], Christopher T. S. Cheung[1] , Tony Chen[1] , Alex Vanstone[1], Jake Love[4,5], Holly H. Holder[1], Francesco Caravelli[6], Hidekazu Kurebayashi[2], Karin Everschor-Sitte[4], Eleni Vasilaki[3], and Will R. Branford[1,2]

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Physical neuromorphic computing leverages the complex internal dynamics of physical systems for computation[1]. The field has recently undergone an explosion in the range and sophistication of implementations, with rapidly improving performance.

Physical reservoir computing[2], a subset of neuromorphic computing where only the output layer is trained, typically employs a single physical system with limited output dimensionality and internal dynamics - restricting strong performance to a few specific tasks[3,4]. This is a roadblock facing the field, inhibiting the power and versatility of physical reservoir computing schemes.

In this talk, we engineer a diverse suite of nanomagnetic arrays serving as physical reservoirs, with readout performed via FMR, and show how tuning microstate space and geometry enables a broad range of dynamics and computing performance. We experimentally interconnect[5,6] physical reservoirs in parallel and series networks where each network node is a distinct physical system and combine the network responses offline to emulate a multilayered neural network architecture. The FMR readout and networking approach grants extremely high output dimensionality and enriched internal dynamics. This enables the system to reach an 'overparameterised' state where the system no longer overfits, exhibits strong performance and learns fast with few data points. We showcase network performance via few-shot learning, rapidly adapting on-the-fly to previously unseen tasks. Methods for networking any physical system and achieving overparameterisation will be discussed.

1. Marković, Danijela, et al. "Physics for neuromorphic computing." *Nature Reviews Physics* 2.9 (2020): 499-510.
2. Tanaka, G. et al. Recent advances in physical reservoir computing: A review. Neural Networks 115, 100–123 (2019
3. Stenning, Kilian D., Gartside, Jack C., Vanstone, Alex. et al. "Reconfigurable training and reservoir computing in an artificial spin-vortex ice via spin-wave fingerprinting." *Nature Nanotechnology* 17.5 (2022): 460-469.
4. Inubushi, Masanobu, and Kazuyuki Yoshimura. "Reservoir computing beyond memory-nonlinearity trade-off." *Scientific reports* 7.1 (2017): 1-10.
5. Manneschi, Luca, et al. "Exploiting multiple timescales in hierarchical echo state networks." *Frontiers in Applied Mathematics and Statistics* 6 (2021): 76.
6. Stenning, Kilian D., et al. "Neuromorphic Few-Shot Learning: Generalization in Multilayer Physical Neural Networks." arXiv preprint arXiv:2211.06373, 2022

# Tutorial on computing

**Giovanni Finocchio**

University of Messina
Piazza Pugliatti, 1, 98122 Messina ME, Italia

In this tutorial I will introduce briefly the main concepts of neuromorphic spintronics and probabilistic computing with p-bits. Neuromorphic spintronics is an emerging approach for reducing the energy consumption of neuromorphic computing architectures which takes advantage of spin-based technology. I will briefly highlight some potential directions of this field.

I will also introduce the main idea behind probabilistic computing with p-bit and how this paradigm can be used to realize Ising machines and solve combinatorial optimization problems.

THURSDAY, APRIL 25TH

# PRESENTATION OF EUROPEAN PROJECTS ABOUT NEUROMORPHIC MAGNONICS

## ANIMATOR – PAOLO BORTOLOTTI, DIRECTOR OF THE SPINTRONIC FACTORY

## PHILIPP PIRRO – CoSpiN PROJECT

**Coherent Spintronic Networks for Neuromorphic Computing**
https://cordis.europa.eu/project/id/101042439/fr

**Research could revolutionise neuromorphic computer technology**

Neuromorphic computing uses networks of artificial neurons and synapses to perform data processing tasks with unprecedented efficiency. Highly interconnected synaptic connections are crucial for the success of neuromorphic computing, but realising them with conventional electronic circuits is challenging. The EU-funded CoSpiN project aims to overcome this problem. To this end, researchers will rely on spin waves, the collective excitations of spins in a magnetic material. The main goal is to create and experimentally validate innovative physical building blocks for creating a novel nanoscaled, all-spintronic network structure that incorporates all necessary properties for neuromorphic computing, including high non-linearity, interconnectivity and reprogrammability.

## SEBASTIAAN VAN DIJKEN – MANNGA PROJECT

**Magnonic Artificial Neural Networks and gate Arrays**
https://cordis.europa.eu/project/id/101070347

**Magnonics as a basis for neuromorphic computing**

The EU-funded MANNGA project aims to develop a novel class of energy-efficient spintronic components and devices for use in data communication, processing and storage. Researchers will combine their expertise in magnonics, which utilises spin waves for signal processing, and neuromorphic computing, which utilises large-scale integrated systems and analogue circuits that mimic the brain and nervous system to solve data problems. They will use nanoscale chiral magnonic resonators as building blocks of artificial neural networks. The power of these networks will be demonstrated by creating magnonic versions of field programmable gate arrays, reservoir computers and recurrent neural networks.

## KATRIN SCHULTHEISS – NIMFEIA PROJECT

**Nonlinear Magnons for Reservoir Computing in Reciprocal Space**
https://cordis.europa.eu/project/id/101070290

**Spintronics offers a path for bio-inspired computing**

The EU-funded NIMFEIA project aims to open up new applications for spintronics outside of the technology's core areas of storage, signal processing and field sensing. Researchers will combine nanomagnetism and spintronics advances to develop a hardware solution for bio-inspired computing – a field of study seeking to solve computer science problems using biology models. Project work will build on advances in reciprocal lattice, where nonlinear spin-wave interactions mediated by nontrivial spin textures (e.g. magnetic vortices) can be efficiently harnessed for reservoir computing tasks like pattern recognition.

## MADJID ANANE – k-NET PROJECT

**k-space Neural computation with magnEtic exciTations**
https://cordis.europa.eu/project/id/899646/fr

**Implementing brain-inspired computing in the reciprocal space of a single magnetic element**

Artificial neural networks are computing systems inspired by biological neural networks. They emulate the brain by using nonlinear elements that act as neurons interconnected through artificial synapses. Current architectures are facing challenges: the number of synapses implemented is very limited compared with the tens of thousands in the human brain. Furthermore, changing the weight of each connection requires additional memory elements. The EU-funded k-NET project will circumvent these issues. It proposes new architecture based on the idea that dynamical hyperconnectivity can be implemented not in real space but in reciprocal or k-space. To demonstrate this novel approach, researchers will select ferromagnetic nanostructures in which the populations of spin waves – the elementary excitations – play the role of neurons.

## FLORIN CIUBOTARU – SPIDER PROJECT

**Computation Systems Based on Hybrid Spin-wave–CMOS Integrated Architectures**
https://cordis.europa.eu/project/id/101070417

**Hybrid spin wave-CMOS for computing systems**

The rapid advancement of electronic devices and computing is constantly pushing for smaller and smaller devices. However, the spread of this trend is limited by increased power density and heating in chips. This is why there's also a push for ultralow-power high-performance computing technologies that optimise their power-to-performance area. In this context, the EU-funded SPIDER project will satisfy this need by developing a novel hybrid spin wave and complementary metal-oxide-semiconductor (CMOS) computing system. This technology has the potential to reduce power and area consumption in computing, along with CMOS chips required for its operation. It will lay the foundation for improved spin wave technologies and also provide low power and area computing.

*These projects acknowledge the support of the European Commission, especially through the H2020 and Horizon Europe programs.*

European Commission

Horizon 2020
European Union funding
for Research & Innovation

# Travelling-spin-wave based reservoir computing

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Recently, our research group proposed using travelling spin waves in yttrium iron garnet (YIG) films for reservoir computing. It is known that to be able to operate as a physical reservoir, a physical system must demonstrate fading memory and the ability to nonlinearly map input data to a higher-dimensional space. The presence of nonlinearity of the response of a system to an input is the prerequisite for the latter requirement.

The basic microwave device employing spin waves is called the spin-wave delay line (SWDL) and is shown in Fig. 1. Spin waves in YIG films have very low thresholds for nonlinear wave interactions; therefore, the SWDL response to application of a microwave signal to its input port is highly nonlinear. In addition, the device is characterised by the presence of short-term memory associated with the finite time of signal propagation through the device. This parameter is called “delay time”. Due to very small group velocity of the spin waves with respect to speed of light, the delay time available from SWDLs is significant – 300 to 400 ns for a reasonably small loss (<35 dB) inserted by the device.

The depth of the memory can be further increased by a adding a positive feedback loop to a SWDL (Fig.1), thus creating a travelling-wave resonator, known as the active spin-wave ring [1]. If the amplification gain in the loop slightly overcompensates losses inserted by the SWDL the system is capable to self-generate single-frequency microwave oscillations. In work we showed that electrically controlling the amplification gain of the feedback loop converts the ring into a physical reservoir. Because the self-oscillation dynamics of the ring is similar to dynamics of a resonator, intrinsic losses of which have been compensated by an external source of power, a reservoir that is based on modulation of the amplification gain is analogous to one employing a spin-torque nano-oscillator (STNO) [2]. However, due to the presence of the delay time, it has an intrinsic memory.

Below the self-oscillation threshold, the ring supports circulation of spin wave waveforms in it, once they have been fed into it from an external microwave source. Due to the presence of residual loss in the device, the waveform amplitude gradually decreases and its width increases, the latter being due to dispersive character of spin waves in YIG films. This mode of ring operation as a physical reservoir allows time multiplexing of signals circulating in the ring [3].

In my talk, I will discuss physical reservoirs based on both above-threshold and below-threshold operations of the active ring and advantages and disadvantages of both modes. In addition, I will present results of our experimental verification of a theoretical concept of “physical reservoir computing for sensing” that was suggested more than a decade ago, but had not been proven experimentally, before we started our work.

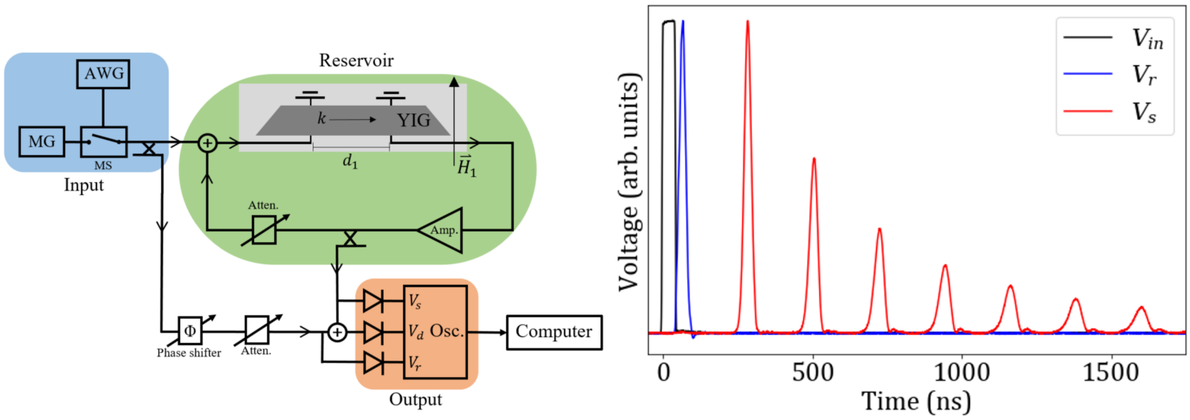


Fig. 1. Left panel: Schematic diagram of the spin-active-ring based reservoir configured for Magnetostatic Surface Spin Wave (MSSW) transmission. Highlighted by the green background: the reservoir itself. The remainder is a microwave circuit for injecting input data into the reservoir and processing reservoir output. Right panel: Time evolution of a single pulse injected into the active ring. The 45 ns voltage pulse from the arbitrary waveform generator (AWG) Vin (black line) applied to a microwave switch (MS) creates a microwave pulse, which travels through the reference line (Vr, blue line) and through the ring (Vs, red line).

[1] J. P. Castera, *IEEE Trans.Magn*. **14**, 826 (1978); Y. K. Fetisov, P. Kabos, and C. E. Patton, *IEEE Trans. Magn.* **34**, 259 (1998); B. A. Kalinikos, N. G. Kovshikov, and C. E. Patton, *Appl. Phys. Lett.* **75**, 265 (1999).
[2] D. Markovic, A. Mizrahi, D. Querlioz and J. Grollier, *Nature Reviews Physics*, **2**, 499 (2020).
[3] L. Appeltant et al., *Nature Communications*, **2**, 466, (2011); S. Watt, M. Kostylev, A. B. Ustinov, and B. A. Kalinikos, *Phys. Rev. Applied* **15**, 064060 (2021).

# Mode-resolved micromagnetics study of parametric spin wave excitation in thin film disks

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Nonlinear spin wave processes, such as three-magnon scattering, can be exploited for pattern recognition tasks within the framework of reservoir computing with modal multiplexing [1]. In magnetic vortices, for example, input signals in the form of radiofrequency (RF) pulses couple directly to radial modes, while magnon scattering results in the excitation of azimuthal modes; machine learning applied to the power spectra of the latter can be used to perform recognition of the input pulse sequences. Here, we discuss the nonlinear population dynamics related to such scattering processes through the use of mode-filtering in micromagnetics simulations. These bring into clearer focus the different transient dynamics that follow the application of each pulse, and allows us to better quantify stimulated scattering processes that underpin the memory capacity of the reservoir. We also examine strongly-driven multimode excitations in other geometries such as in-plane magnetized disks, where processes such as stimulated four-magnon scattering can be induced to mimic the firing of an artificial spin wave neuron. We will discuss some prospects on extending these nonlinear processes to build larger artificial neural network structures.

Acknowledgements: Horizon Europe contract no. 101070290 (NIMFEIA).

[1] L. Körber, C. Heins, T. Hula et al., *Nat. Commun.* **14**, 3954 (2023).

# Mutual inhibition between parametrically excited spin-wave modes

G. Soares[1], A. Kolli[1], R. Lopes Seeger[2], T. Srivastava[2], M. Massouras[2], J. V. Kim[2], S. O. Demokritov[3], V. E. Demidov[3], N. Beaulieu[4], J. Ben Youssef[4], M. Muñoz[5], S. Perna[6], M. d'Aquino[6], C. Serpico[6], P. Che[7], A. Anane[7], H. Merbouche[1], G. de Loubens[1]

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[2]Université Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies, France
[3]Institute for Applied Physics, University of Muenster, Germany
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[5]Instituto de Tecnologías Físicas y de la Información (CSIC), Madrid, Spain
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Leveraging on nonlinear magnetization dynamics is promising for neuromorphic computing [1][2]. In magnetic microstructures, spin-wave eigenmodes are defined in the k-space and are interpreted as neurons. Mutual nonlinear couplings between the modes are predominantly determined by their amplitudes and are interpreted as synaptic weights. We have previously demonstrated that parallel parametric pumping allows the selective excitation of a large number of eigenmodes in YIG microdisks [3], as shown in Fig.1(a). Here, we parametrically excite pairs and trios of modes to study their mutual interactions. Two-tone MRFM and BLS spectroscopy demonstrate that modes can inhibit each other, see Fig.1(b), the strength of this nonlinear interaction being governed by the power of the rf pulses and the time delay between them. We observe similar inhibition of modes as a function of the delays between three different rf pulses, see Fig.1(c), which could be used to demonstrate basic neuromorphic functions.
This work has received financial support from the Horizon 2020 Framework Program of the European Commission under FET-Open grant agreement no. 899646 (k-NET).

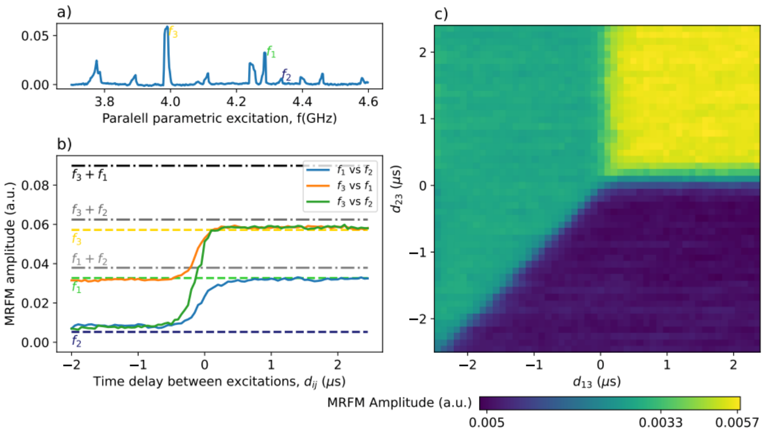


Fig.1 (a) Parametric excitation spectrum in a 1 µm diameter YIG disk, the in-plane magnetic field being fixed to 27 mT. (b) Tow-tone MRFM spectroscopy as a function of the delay between three different pairs of parametric frequencies. (c) Three-tone MRFM spectroscopy as a function of the delays between f1 and f3 and between f2 and f3.

[1] A. Papp, W. Porod, and G. Csaba, Nature Commun. **12**, 6422 (2021)
[2] A. Allwood, et al., *Appl. Phys. Lett.* **122**, 040501 (2023)
[3] T. Srivastava, et al., Phys. Rev. Appl. **19**, 064078 (2023)
[4] S. Perna et al., J. Magn. Magn. Mater. **546**, 168683 (2022)

# Magnonic Fabry-Perot resonators as programmable phase shifters and energy concentrators

**A. Lutsenko**,[a] K. G. Fripp,[b] A. V. Shytov,[b] L. Flajšman,[a] V. V. Kruglyak,[b] and S. van Dijken[a]
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An efficient control of the amplitude of spin waves propagating in YIG magnonic media was recently shown experimentally using Fabry-Pérot resonances [1]. The latter are formed due to spin-wave reflection from magnonic dispersion mismatches at interfaces between YIG regions with and without a metallic ferromagnet overlayer [2]. Here, we demonstrate that such structures, dubbed 'magnonic Fabry-Pérot resonators', can also serve as programmable spin-wave phase-shifters. For example, Fig. 1 shows the measured and simulated frequency dependence of the amplitude and phase of the spin- wave transmission coefficient for a magnonic Fabry-Pérot resonator formed by an 850 nm wide, 30 nm thick CoFeB stripe spaced by 5 nm from an 85 nm thick YIG film. A phase shift of $\sim\pi$ is achieved for spin waves at $\sim 1.25\ GHz$ frequency by switching the orientation of magnetisation in the CoFeB stripe in a longitudinal magnetic field of 3 mT. Our experimental results obtained by super-Nyquist sampling magneto-optic Kerr effect (SNS-MOKE) microscopy are in a good agreement with micromagnetic simulations in MuMax3 software. The latter also reveal concentration of the spin-wave energy in the YIG film under the CoFeB stripe, which contrasts with spin-wave energy "trapping" [3] in the stripe itself for chiral magnonic resonators [4]. Such a device may act as a building block in future magnonic circuitry, while the spin-wave energy concentration may be used in construction of magnonic neurons [5].

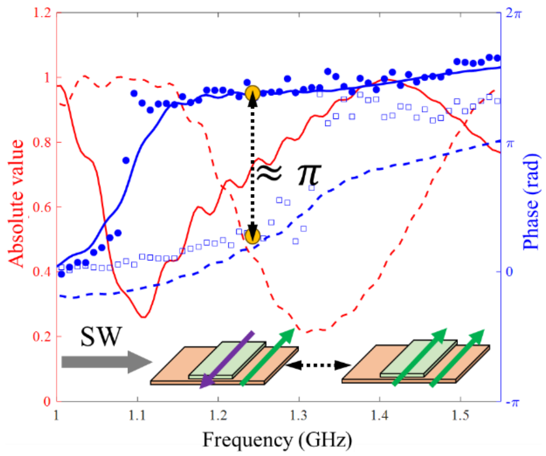


Fig. 1. The absolute value (red) and phase (blue) of the transmission coefficient are shown for a magnonic Fabry-Perot resonator in two different magnetic configurations. The solid / dashed lines and filled / empty symbols correspond to the antiparallel / parallel alignments of the magnetisations in the CoFeB overlayer and YIG medium (see the insets). The lines and symbols are used for simulated and measured results,

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101070347-MANNGA. Yet, views and opinions expressed are those of the authors only and do not necessarily reflect those of the EU, and the EU cannot be held responsible for them.

[1] H. Qin *et al*, *Nanoscale magnonic Fabry-Pérot resonator for low-loss spin-wave manipulation*, Nat. Commun. **12**, 2293 (2021). DOI: 10.1038/s41467-021-22520-6
[2] A. Talapatra *et al*, *Imaging of short-wavelength spin waves in a nanometer-thick YIG/Co bilayer, Appl. Phys. Lett.* **122**, 202404 (2023). DOI: 10.1063/5.0149583
[3] K. G. Fripp, A. V. Shytov, and V. V. Kruglyak, *Spin-wave control using dark modes in chiral magnonic resonators*, Phys. Rev. B **104**, 054437 (2021). DOI: 10.1103/PhysRevB.104.054437.
[4] V. V. Kruglyak, *Chiral magnonic resonators: Rediscovering the basic magnetic chirality in magnonics*, Appl. Phys. Lett. **119**, 200502 (2021). DOI: 10.1063/5.0068820.
[5] K. G. Fripp, Y. Au, A. V. Shytov, and V. V. Kruglyak, *Nonlinear chiral magnonic resonators: Toward magnonic neurons*, Appl. Phys. Lett. **122**, 172403 (2023). DOI: 10.1063/5.0149466.

# FRIDAY, APRIL 26TH

# Spintronic Radio-Frequency neural networks

**Dédalo Sanz-Hernandez**[1], Nathan Leroux[1], Andrew Ross[1], Erwan Plouet[1], Hanuman Singh[1], Sreyas Satheesh[1], Mohamed Menshawi[1], Pankaj Sethi[1], Danijela Marković[1], Juan Trastoy[1], Bruno Dlubak[1], Victor Zatko[1], Damien Querlioz[2], Leandro Martins[3], Alex Jenkins[3], Ricardo Ferreira[3], Frank Mizrahi[1], Julie Grollier[1]

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The combination of the two key effects of spintronics, magnetization dynamics and magneto-resistive effects, allows the realization of nano-neurons and nano-synapses with high computational capabilities. We present two recent developments towards the experimental development of large-scale nanoscale spintronic neural networks capable of performing complex tasks.

First, we will present the realization of multilayer networks using an easily scalable architecture based on successive, clean, and fast conversions from RF to DC and from DC to RF. This architecture employs magnetic tunnel junctions to first perform neural operations on DC signals and output the result as RF, and then apply synaptic operations on RF signals and output the result as DC. Deep multilayer networks can therefore be achieved by a simple concatenation of layers using DC signals.

We will give a proof of concept with a two-layer neural network composed of nine interconnected magnetic tunnel junctions and demonstrate its ability to solve non-linear tasks with high performance. With junctions downscaled to 20 nm, such a network would consume 10fJ per synaptic operation and 100fJ per neuronal operation, several orders of magnitude less than current software neural network implementations.

We will conclude by presenting an experimental realization of a fully parallel spintronic convolutional layer. By exploiting the intrinsic weight redundancy of convolutions (all filters share the same weights) and the frequency tunability of magnetization dynamics, we are able to enhance the compacity of a hardware and greatly simplify the process of updating weights, only requiring updating a single physical variable. This architecture would enable to perform convolutions in one timestep contrary to common time-multiplexed implementations, and a potential decrease by one order of magnitude in energy consumption and two orders of magnitude in operating latency is anticipated in this case.

# Nanoscale chiral magnonic resonators as two-dimensional spin-wave scatterers for neuromorphic computing applications

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We explore nanoscale chiral magnonic resonators (CMRs) [1] as building blocks [2] of magnonic neural networks (Fig.1(a)). Specifically, we model scattering of spin waves propagating in a YIG medium from disk-shaped elements spaced above it. We extract the directivity (Fig.1(c)) of spin-wave scattering observed in numerical micromagnetic simulations and compare it with results of an analytical calculations, achieving a quantitative agreement between the two approaches without any adjustable parameters. The results confirm the “feed-forward” property of the scattering, expected from chiral magnonic resonators. At optimal conditions, the scattered amplitude is concentrated within a forward ‘cone’ of about ±60°, which is the range within which connections with neurons from deeper layers of the network could be established. Due to the energy concentration in the nanoelement [2], the chiral magnonic resonator exhibits a nonlinear quadratic frequency shift of the resonance line with increasing the incident spin wave’s amplitude. This detuning provides the nonlinear, amplitude-dependent response (‘activation’) of an artificial neuron required for a neural network to function.

The research leading to these results has received funding from the UK Research and Innovation (UKRI) under the UK government’s Horizon Europe funding guarantee (Grant No. 10039217) as part of the Horizon Europe (HORIZON-CL4-2021-DIGITAL-EMERGING-01) under Grant Agreement No. 101070347. Yet, views and opinions expressed are those of the authors only and do not necessarily reflect those of the EU, and the EU cannot be held responsible for them.

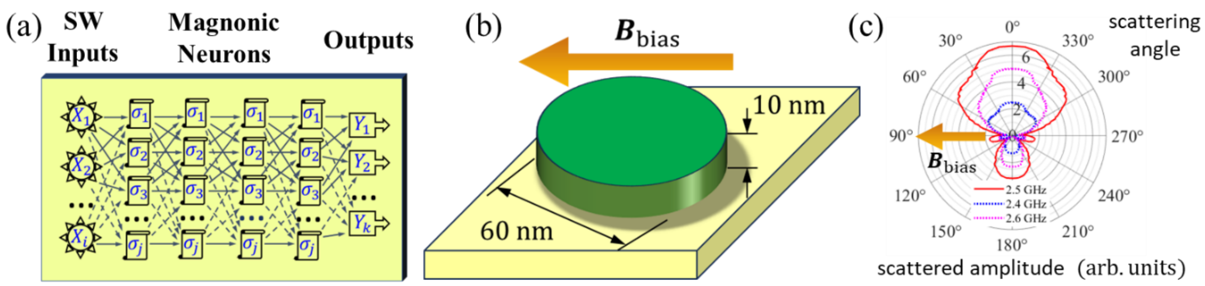


Figure 1. (a) A schematic of an idealised magnonic neural network consisting of spin-wave input couplers, magnonic neurons and output spin-wave couplers. (b) A magnetic nanodisk above YIG medium serving as one of the magnonic neurons $\sigma_j$. (c) The scattering directivity in the reciprocal-space is shown for the incident spin wave at resonance with the fundamental magnonic mode of the disk (red curve) and off-resonance (pink and blue curves).

[1] V. V. Kruglyak, *Chiral magnonic resonators: Rediscovering the basic magnetic chirality in magnonics*, Appl. Phys. Lett. **119**, 200502 (2021).
[2] K. G. Fripp, Y. Au, A. V. Shytov, and V. V. Kruglyak, *Nonlinear chiral magnonic resonators: Toward magnonic neurons*, Appl. Phys. Lett. **122**, 172403 (2023).

# Bistability of P-modes and Chaos in FMR in BiYIG nanodisks

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SPEC, CEA, CNRS, Universite Paris-Saclay, 91191 Gif-sur-Yvette, France

The interactions between magnetic collective excitations (magnons) represent the basic ingredient for neuromorphic computation in magnetic devices [1]. When the magnetic state is driven towards nonlinear oscillations regimes via microwave excitation, depending on the power level several and distinct magnons interactions, from weak nonlinear interference to chaos, may take place [2]. In this context, an interesting quantity is the number of excited magnons as a function of the microwave power from which the ability of the magnetic device to perform neuromorphic computation depends.

In this work, we investigate the nonlinear FMR in a BiYIG nanodisk. The disk is uniformly magnetized along the direction of the DC-field which corresponds to the symmetry axis of the disk and the microwave field is directed in the disk plane (see sketch in the figure below). The normal modes model (NMM) [4] is used in combination with micromagnetic simulations to study the nonlinear magnetization dynamics in terms of transition between different dynamical regimes when the fields amplitudes are changed. We show that by increasing the microwave power, the periodic solution at the same frequency of the excitation (P-mode), which is the only possible dynamics for moderately low microwave power, switches to a stable chaotic attractor. Such a transition is characterized by rate-independent hysteresis and bistability. The NMM is then used to investigate the distinct mechanisms responsible for the transitions between P-modes and the chaotic attractor. Moreover, increasing the microwave power, the normal modes population changes too. We show that, contrary to what expected, the number of modes involved into the dynamics does not grow in a monotonic fashion but depends in nontrivial way by the fields amplitudes.

In the left panel of the figure, the phase diagram computed from micromagnetic simulations in the control plane (DC-field vs microwave field amplitudes) is shown. Pointing-up symbols correspond to transitions from P-mode to the chaotic attractor and they are computed starting from zero field value and increasing the microwave field amplitude. Pointing-down symbols correspond to transitions from the chaotic attractor to P-mode. They are computed by decreasing the microwave field amplitude starting from a large value. The right panel shows the number of modes involved in the dynamics as a function of the microwave field amplitude for several values of the DC-field amplitude.

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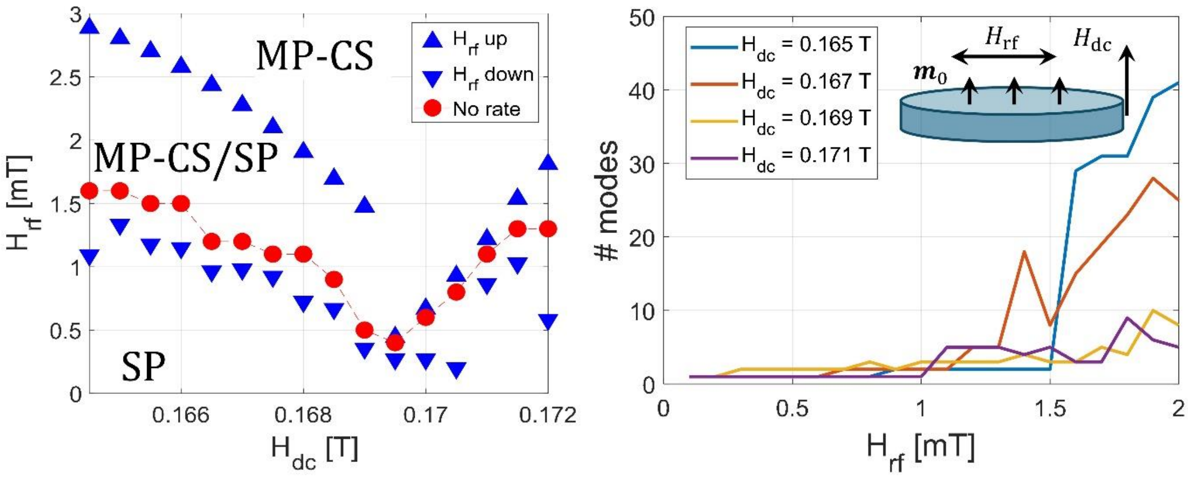


Figure: (left) Phase Diagram of the dynamical regimes in the control plane. The label MP-CS indicates regions of the control plane where multi-peaks continuum spectrum is observed, while SP indicates regions where single-peak spectrum is observed. (right) Number of normal modes excited for a certain microwave field amplitude for four different values of the DC-field.

# Hybrid magnonic-oscillator system: towards the development of hybrid artificial network structures

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The tremendous increase in available data from various sources fuels the search for sophisticated methods of data processing and analysis. Nano-spintronic devices, operating on the physical concept of spin-momentum transfer, can provide alternative solutions ("more than Moore") for analyzing, processing and transmitting vast amounts of information.

We present a novel device that combines physical components from two subfields of magnetism, namely spintronics and magnonics, whereby spin torque oscillators and magnonic waveguides are utilized to enable new means for spin-wave-based circuits. The device comprises a spin transfer torque oscillator that is dipolarly coupled to a nanoscale spin-wave waveguide with longitudinal magnetization. In the auto-oscillatory regime, the oscillator emits coherent spin waves with tunable and controllable frequencies and amplitudes into the waveguide. By changing the configuration of the oscillator from a uniform state to a vortex state, the controllability of the chirality and polarity of the magnetic vortex allows for an element of reconfigurability, where spin waves can be emitted with high non-reciprocity, with the preferred direction depending on the core polarity of the vortex. Varying the vortex chirality leads to different amplitudes of the emitted waves [1].

Furthermore, we have studied a pair of oscillators in the uniform state, each with individual electrical contacts, and both coupled to a spin-wave waveguide. Using micromagnetic simulations, we demonstrated that synchronization is robustly achievable even for large separations of 10 µm. We confirmed that the resulting interference pattern of the spin waves depends on the stationary phase difference between the oscillators, and the phase accumulation of the waves in between them, resulting in distinct distributions of the stationary interference patterns. We believe that the combination and optimization of these features can pave way for the development of new energy-efficient signal processing devices for unconventional computing.

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# PT-symmetry assisted logic operations

**BERAKDAR Jamal**.

A new concept for a non-linear magnonic element which enables thermomagnonic logic operations is presented. The basic information channel consists of two magnonic waveguides with a sandwiched normal metal spacer. The information signal is embodied in magnetic excitations and it can be transported, locally enhanced, and controllably steered by virtue of a charge current pulses in the spacer. Using analytical and full numerical simulations we demonstrate the functionality of essential thermal logic gates. The operation principle is based on a spin-orbit-torque-induced magnonic gain/loss mechanism which renders the circuit parity-time symmetric with a highly non-linear behavior at the so-called exceptional points beyond which the modes become strongly damped. These points can be approached controllably by adjusting the current strength in the spacer. Heat flow at these points can be enhanced, be non-reciprocal, or may oscillate between the information channels enabling controlled thermal diode and thermal gate operations [1]. At the conference a network of such non-linear and dynamic [2] elements is presented and the relevance to neuromorphic computing is discussed.

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# Floquet Magnons in a Periodically-Driven Magnetic Vortex

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Magnetic vortices (Fig. 1a) are prominent examples for topology in magnetism with a rich set of dynamic properties. They exhibit an intricate magnon spectrum and show an eigen-resonance of the vortex texture itself, the gyration of the vortex core. While there have been studies about magnon-assisted reversal of the vortex core polarity [1], the impact of the vortex core gyration on the magnon spectrum has not been addressed so far.
The fundamental modes of both excitation types are clearly separated in their resonance frequencies. While the vortex typically gyrates at a few hundred MHz (Fig. 1b), the magnon modes typically have frequencies in the lower GHz range (Figs. 1c,d). This separation allows for experiments studying the temporal evolution of the magnon spectrum when the gyration of the vortex core is driven by an external drive. Under the influence of such a periodic driving field, Floquet states emerge due to a temporal periodicity imposed on the system's ground state, much like the formation of Bloch states in the periodic potential of a crystal lattice. While Bloch states are shifted in momentum space, Floquet states are shifted in energy by multiples of the drive frequency, facilitating the design of novel properties and functionalities in condensed matter systems.

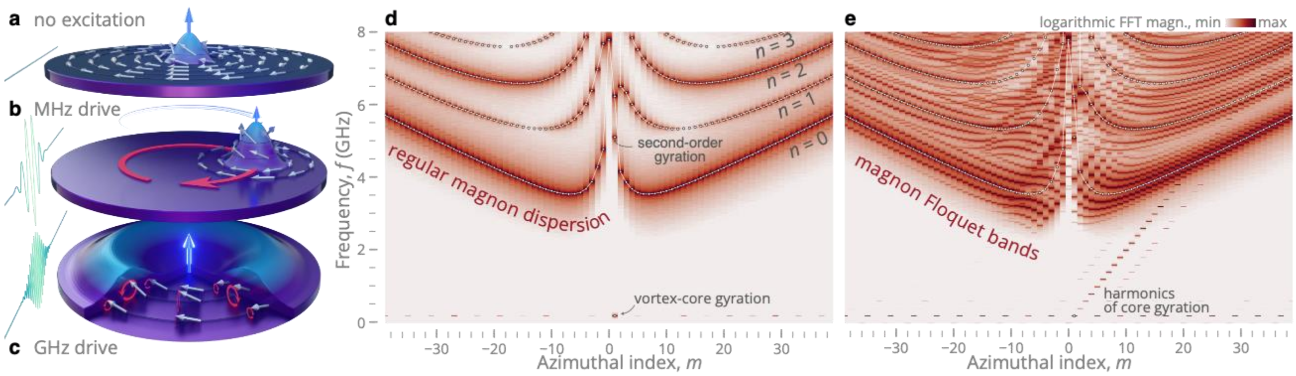


**Fig. 1**: Schematic illustrations of (a) a static magnetic vortex, (b) a gyrating magnetic vortex driven by a MHz microwave signal, and (c) a magnon mode with lowest radial and azimuthal mode index ($n = 0$, $m = 0$). Dimensions are not to scale. (d) Simulated dispersion of thermally populated magnon modes in the vortex with a static core plotted as a function of azimuthal mode index $m$ for different radial indices $n$. (f) Micromagnetic simulations of the thermal magnon population in a gyrating vortex show the magnon Floquet bands.

This poster delivers experimental results and numerical simulations on how the regular magnon modes in a magnetic vortex transform into novel Floquet bands (Fig. 1e), when the vortex ground state is modulated in time by driving the vortex core gyration simultaneously. The observed magnon Floquet states are both distinct from the well-known regular magnon modes as well as from the vortex gyration and represent truly unique excitations providing new opportunities to study and control nonlinear magnon dynamics.

Acknowledgements: Support by the Nanofabrication Facilities Rossendorf (NanoFaRo) at the IBC is gratefully acknowledged. This work has received funding from the EU Research and Innovation Programme Horizon Europe under grant agreement no. 101070290 (NIMFEIA).

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# Training Neuromorphic Computing Devices for Time Series and Digit Recognition using Non-Linear Spin Wave Interference

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Strongly interacting magnonic systems have recently emerged as a versatile platform for reconfigurable neuromorphic computing [1]. This research showcases the computational modelling of a magnonic neural network hardware platform, where spin-wave propagation and interference serve as the fundamental mechanisms for executing neuromorphic computing functions, including challenging signal classification and image recognition. Weights and interconnections within the network are reconfigured by flipping magnets in an array pattern above the spin-wave propagating substrate, inducing scattering of the spin waves. The resulting interference among the scattered waves establishes a mapping between the sources and detectors at either end of the device. The magnetisation pattern is trained using SpinTorch [2] to realize the desired input-output mapping, analogously to training a neural network. Combining multiple devices in series, similar to a multi-layer neural network, outperforms single systems. We demonstrate that the simulated double layer design can classify multi-frequency inputs with up to 8 different frequencies with near-100% accuracy and can currently achieve up to 86% accuracy when classifying a complex audio tagging task [3]. The device is also applied to computer vision tasks by setting a fixed input magnet array separate from the trainable array region (see image).

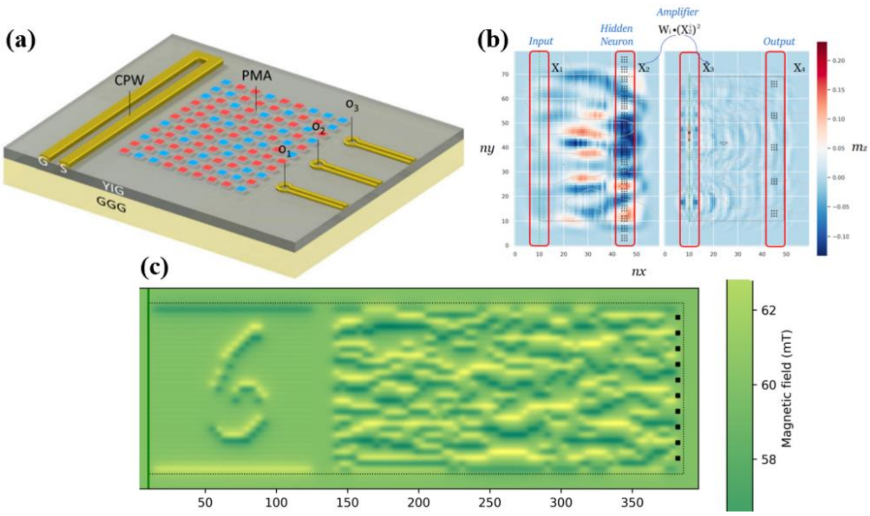


Figure: Spintronic neuromorphic devices studied here. (a) Original device architecture proposed by Papp et al in [2]. Spin waves are excited by the coplanar waveguide (CPW) on the left, then travel through the spin wave propagating substrate below a trainable array of out-of-plane magnets before reaching the output sensors on the right. (b) Double layer design for improved time series classification performance. The outputs of the first layer are passed through a linear amplification layer before and fed into the input of the second layer. (c) Magnetic field configuration from the magnet array showing the image classification design. The input region on the left contains fixed magnets to project the shape of a digit.

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# Electrical measurement of the non-linear coupling between vortex gyration and spin waves

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Non-linear coupling between spin waves is at the core of neuromorphic magnonics. Electrical characterization of the coupling channels would be welcome. This can be conducted if the magnetic system under test is embedded in a high sensitivity tunnel junction with rf excitation/detection capability. We have fabricated MTJs whose free layer is a nanomagnet with a vortex ground state. The system hosts the well-known vortex gyration mode, and higher order azimuthal/radial spin waves. The excitation/detection scheme allows the characterization of the gyration mode, as well as all azimuthal modes of index |m|=1 at remanence. By applying strong Zeeman torque of appropriate frequencies, we could time-resolve the transient processes that couple the gyration mode to the spin waves, and vice-versa. Direct excitation of the (presumably) |m|=1 spin waves above a given threshold leads to steady-state indirect excitation of the gyration mode, as well as the generation of a frequency-comb. Additional specific features appear when the spin wave frequency is an integer multiple of the gyration frequency. Conversely, the direct excitation of the low frequency gyration above a given threshold leads to perfectly periodic firing of intense bursts of high frequency spin waves. This is accompanied with a periodic self-modulation of the gyration amplitude (see figure). Our results evidence that strong coupling between the modes can lead to various phenomena, ranging from peaceful mode coexistence, periodic energy transfer between modes, to chaotic population transfers.

Acknowledgements: Horizon Europe, contract no. 101070290 (NIMFEIA).

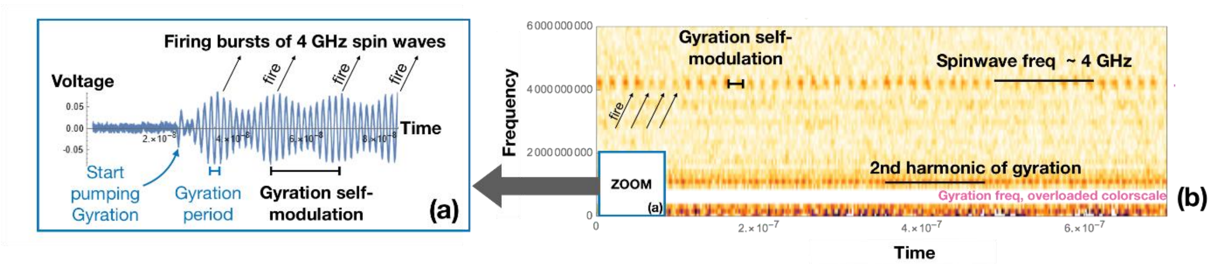


*Figure: Response to a step-like application of an rf field quasi-resonant with the vortex gyration. Panel (a): time-resolved response illustrating the onset of the gyration and the subsequent automodulation of its amplitude. Panel (b): frequency-time spectrogram illustrating that each time the gyration amplitude reaches a maximum, a burst of high frequency spin waves is emitted.*

# Dynamical diversity of magnetization dynamics in interacting systems through tunable coupling strength

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Whenever dissecting the universe to its fundamentals was the prerequisite, coupled systems emerged as a focal point at the very core of the ever-expanding need to understand and advance. From their diverse nature encompassing macroscopic systems governed by classical mechanics, all the way down to microscopic systems and their complexity rich dynamics bound by the quantum realm, interacting systems carve world evolution as we know it. In the field of magnonics, we present a comprehensive study aiming at realizing and manipulating the coupled dynamics of gyrating physical solitons in the form of magnetic vortex states. Within its scope, we developed an efficient theoretical model to describe the behavior of two auto-oscillating vortex cores that are coupled under the influence of both conservative(i.e., dipolar) and non-conservative (i.e., spin transfer torque) coupling terms. We also conducted experiments to validate our theory and observe the various dynamics and patterns that the system exhibits. To detect these dynamics, we used electrical detection through the giant magneto-resistance effect, which allows us to distinguish between different behaviors of the coupled system. We observed symmetry breaking, manifested qualitatively as different complex vortex core trajectories for different current/field values, which highlight the system's diverse behavior. We also used micromagnetic simulations to gain a deeper understanding of the system's dynamics and to explore ways to manipulate it by adjusting the coupling strength between the vortices. We then elevate the proposed model to the universal picture of $N$ coupled systems, enhancing the physical richness and diversity, thus pushing the envelope to uniquely complex aspects of interacting magnetic systems. Achieving an understating of such systems paves perspectives for beyond the state of the art computing, through utilizing coupled diverse dynamics for probabilistic and reservoir based computers.

# Noncommutativity of Parametric Excitations in YIG disks: a promising playground for magnonic-based computing

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The recent proof of pattern recognition using 3-magnon scattering [1] has led way for using nonlinear excitations to perform magnonic-based computing. One could be parametric excitation by parallel pumping known as an efficient way to populate individual eigenmodes in confined microstructures. We investigate these excitations in YIG disks at 300 K whereby the transient mode population dynamics is computed with the MuMax3 code [2] by projecting the magnetization dynamics onto precomputed eigenmode profiles [3] [Fig. a)]. Figure shows the main features for two modes k = 11, 18, with frequencies of $f_{11}$ = 2.885 GHz and $f_{18}$ = 3.139 GHz. When pumped at 2$f_{11}$ at $b_{rf}$ = 1.05 mT, populated modes are k = 11 along with 17, 7 [Fig.b)i.] whereas at 2$f_{19}$ and same field, populated mode are k = 18, 19 reaching plateau one after the other [Fig.b)ii.]. When toggling these excitations [Fig.c)], we see from the mode spectrogram that the order of the frequency toggle has a strong bearing on the overall dynamics: we observe mode annihilation of k = 19 by the first excitation [Fig.c)i.] and when the sequence is reversed [Fig.c)ii.] we observe the same selection along with mode creation of k = 12, 29.This noncommutativity changes with the modes at play: both noncommutative and commutative scenarios along with full inhibition of modes and/or satellites are observed, scenarios that also depend on the pumping field, variety demonstrating a rich playground for computing applications. This work is supported by the Horizon2020 Framework Programme of the European Commission under contract number 899646 (k-Net).

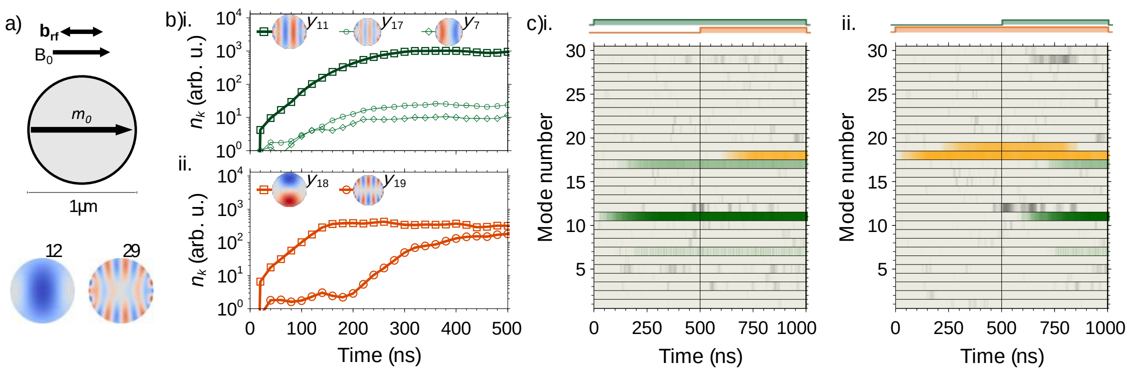


Fig. a) Geometry and eigenmode profiles k=12, 29. b) Populated modes when pumped at i. 2$f_{11}$ and ii. 2$f_{18}$. c) Populations of the first 30 modes under the pulse sequences i. $f_A$, $f_A + f_B$ and ii. $f_B$, $f_B + f_A$.

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## Reconfiguring Magnonic Devices with Magnetic MEMS

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Magnonics shows great potential for advancing analog computing by using spin excitation's flexibility to process, encode, and transport RF signals [1]. However, integrating magnonics circuits with conventional electronics faces challenges, including the need for a bias magnetic field, typically achieved with power-intensive and bulky components.
To overcome these limitations, we are developing tunable magnonic devices where the bias field is provided by permanent micromagnets integrated on micro-actuators. By properly designing the magnet and varying the distance between the magnet and magnonic conduits, fast field tunability can be achieved within compact and energy efficient RF components.
In this study, conducted as part of the M&MEMS project [2], we investigate the feasibility of integrating micromagnets with magnonic devices and explore the impact of the micromagnet stray field on spin wave (SW) propagation in the Damon-Eshbach configuration using micro-focused Brillouin Light Scattering experiments (Fig. 1b). We observe that when the micromagnet and external field are aligned, the SW propagation gets strongly attenuated in the region in between the micromagnets, where the micromagnet stray field is stronger (Fig. 1c). This behavior is caused by the upward shift in the ferromagnetic resonance frequency (FMR) caused by the locally stronger field.
Furthermore, we demonstrate that the attenuation can be adjusted by altering the distance between the micromagnets and the conduit. Specifically, a variation of 4 µm in the distance leads to a variation of 32 dB in the intensity of the spin wave at a position 12 µm away from the antenna (Fig. 1d).
These findings suggest potential avenues for developing integrated and reconfigurable magnonic devices with potential applications in unconventional and neuromorphic computing.

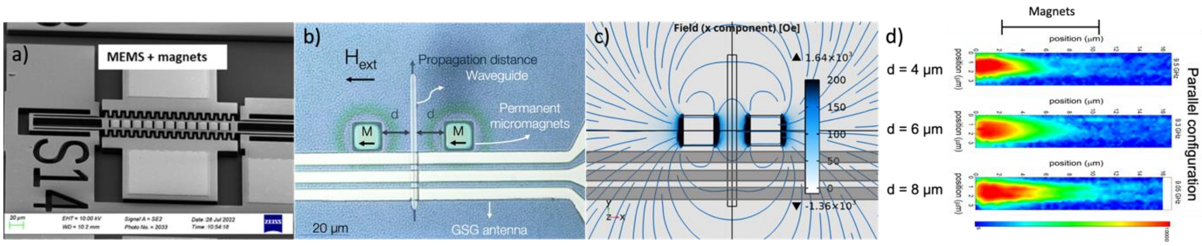


Figure 1: a) SEM image of micro-actuator with an array of permanent magnets on top. a) Device layout and b) field profile (x-component). d) Micro-focused BLS intensity mapping recorded at fixed frequency at different distances *d* between magnet and conduit.

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## Magnonic reservoir computing with resonator-based delays

# Analytical modelling of magnonic resonators and their application for neuromorphic computing

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Abstract: Various magnonic devices host resonant spin-wave modes that could be driven into a nonlinear regime. Such resonators have potential for engineering artificial neurons, neural networks and reservoir computers. However, detailed micromagnetic analysis of such systems is hindered by their large size. We present an analytical framework that can be used to describe the behaviour of resonant magnonic elements and circuits. We demonstrate that our framework yields quantitatively accurate predictions for individual resonators of various designs. (Examples include Fabry-Perot and chiral resonators also presented in this workshop.) Unlike full-fledged simulations, our method can be easily scaled up to analyse large neuromorphic circuits.

The research leading to these results has received funding from the UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee (Grant No. 10039217) as part of the Horizon Europe (HORIZON-CL4-2021-DIGITAL-EMERGING-01) under Grant Agreement No. 101070347. Yet, views and opinions expressed are those of the authors only and do not necessarily reflect those of the EU, and the EU cannot be held responsible for them.

# Non-degenerate parametric excitation in YIG nanostructures for k-space neuromorphic computing

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Abstract: Spin-waves represent a promising alternative to charge carriers for new information technology due to their low energy, their small wavelength, their large degree of freedom (frequency and phase), and their easily attainable non-linear dynamics. These characteristics make them particularly suited for the implementation of neuromorphic computing schemes that can take advantage of the massive parallelization of operations in the frequency space and of the non-linear spin-wave interactions. Such schemes require the excitation and manipulation of many modes in small magnetic structures. This task can be fulfilled by parametric processes, where a photon or a magnon at frequency $2f$ splits in two magnons at frequencies $f - \delta f$ and $f + \delta f$ [1]. The splitting can be degenerate ($\delta f = 0$) or non-degenerate ($\delta f \neq 0$). Recently, the non-degeneracy was shown to open the possibility to cross-stimulate a mode using multiple parametric excitations, effectively implementing an interconnected recurrent neural network capable of classifying rf signals [2]. While exciting degenerate magnon pairs is simple, the observation of non-degenerate pairs has been limited to µm-thick YIG films [3] and metallic microstructures with a vortex ground state [2].

In this study, we demonstrate that by varying the direction of the parametric excitation field one can efficiently excite degenerate or non-degenerate magnon-pairs in a 500nm diameter YIG disk. When the rf field is applied parallel to the static magnetization, a photon splits into a degenerate magnon-pair at half the pump frequency as expected (Fig1.a). However, when the rf field is applied transverse to the static magnetization, it non-resonantly excites a magnon which splits into a magnon-pair that is typically non-degenerate (Fig1.b). This non-resonant transverse parametric pumping technique in YIG is flexible in terms of external field and sample shape. These findings greatly facilitate the implementation of promising k-space computing schemes in the most attractive magnonic material that is YIG.

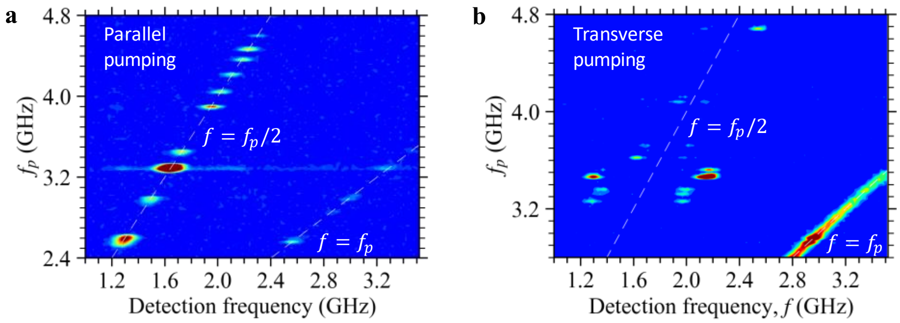


Figure 1: µ-BLS spectra as a function of the pump frequency ($f_p$) for a pumping field parallel **(a)** and transverse **(b)** to the static magnetic field. In the parallel case, there is no excitation at $f = f_{pump}$ and a degenerate magnon-pair can be excited at $f_{pump}/2$ when it coincides with a discrete mode frequency. In the transverse case, non-resonant excitation is observed at $f = f_{pump}$ and non-degenerate magnon-pairs are excited at $f_{pump}/2 \pm \delta f$.

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# POSTERS

# Leaky integrate-and-fire behavior in a spin-torque vortex oscillator through spin-wave emission

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**Abstract:**
Spin-torque vortex oscillators (STVOs) are devices based on a magnetic tunnel junction structure renowned for their capability to emit microwave signals through sustained magnetization oscillations. These oscillations arise from the nonlinear gyrotropic excitation of the vortex magnetization within the free layer, induced by a spin-polarized current. Leveraging this phenomenon, STVOs have shown promise in addressing complex cognitive tasks in the framework of neuromorphic computing [1]. Typically, as a current is injected into these devices, the vortex core initially at equilibrium at the center of the nanodot transitions to a stable orbit of oscillations. The greater the current density, the closer the vortex core approaches the edge of the free layer, until it becomes unstable [2].
In this study (see Fig. 1), conducted via micromagnetic simulations [3], we unveil a distinctive dynamic phenomenon emerging under specific geometric and topological parameters of the vortex. Upon reaching a critical orbit, the vortex core undergoes polarity reversal triggered by the formation and annihilation of a vortex-antivortex pair [4]. This event induces damping, guiding the core back towards the center of the dot. As spin waves are emitted to facilitate the relaxation of exchange energy, a secondary polarity reversal occurs. The vortex then accelerates, with the orbit increasing again until reaching the critical speed once more; which restarts the process. Notably, the frequency and orbit of these consecutive polarity reversals are modulable through variation in the injected current intensity.
In summary, our research unveils a confinement regime in spin-torque vortex oscillators, where the vortex core is locked between two orbits [5]. This regime displays nonlinear, periodic dynamics, offering potential for neuromorphic computing. Specifically, it aligns with the leaky integrate-and-fire neuron model, where injected current controls properties, and polarity reversal signifies firing.

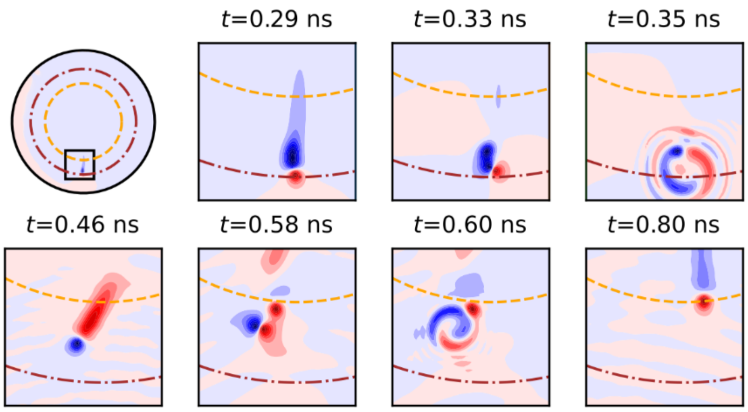


***Figure 1:*** *Evolution of the out-of-plane magnetization component as a function of time, at the moment of the successive polarity reversal. The magnetic dot is shown in its entirety in the top left corner. The other images zoom in on the vortex core, showing snapshots of its polarity reversals.*

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# All-optical & surface probe writing of chiral spin textures and avalanche control in nanomagnetic arrays

Holly Holder[1,2], Alex Vanstone[1], Kilian Stenning[1,3], Xiaofei Xiao[1], Rupert Oulton[1], Will Branford[1,2] , **Jack C. Gartside**[1,2]

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Artificial spin-vortex ice ('ASVI') is a reconfigurable metamaterial which supports both Ising macrospin and vortex textures, providing an excellent platform for the realisation of physical neuromorphic computation[1]. Both macrospin and vortex textures have rich magnonic signals, but the field requires development of new techniques for precisely controlling the magnetic state.

Here we demonstrate two solutions: All-optical writing using a 2 mW continuous-wave laser and surface-probe writing using a magnetic tip. New development in these techniques now allows writing of macrospin[2], vortex and double-vortex textures (new results).

Written vortex textures may be leveraged to locally nucleate avalanche reversal events, with promising potential for inducing self-evolved magnetic states with complex magnon spectra and magnonic wave-guiding[3].

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# Non commutative interactions between parametrically excited spin-wave modes in a YIG microdisk

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Leveraging on nonlinear magnetization dynamics is promising for neuromorphic computing [1]. Recently, pattern recognition has been demonstrated using a magnon-scattering reservoir [2]. To proceed further from this stage, one should be able to characterize the connectivity and to program the neural network. In magnetic microstructures, spin-wave eigenmodes – neurons – are defined in the k-space. Mutual nonlinear couplings between these modes – synaptic weights – are predominantly determined by their amplitudes. We have previously demonstrated that parametric pumping allows the selective excitation of a large number of eigenmodes in YIG microdisks [3]. Here, we simultaneously excite pairs of modes by this mean to study their mutual nonlinear interactions. Two-tone MRFM spectroscopy demonstrates that each mode is coupled to all other modes, and that some of these couplings are non commutative, i.e., the resulting dynamical state depends on which of the two modes is pumped first into the system (Fig. 1). Full micromagnetic simulations and a description of the nonlinear magnetization dynamics in terms of normal modes [4] provide some insights into these nonlinear processes.
This work has received financial support from the Horizon 2020 Framework Program of the European Commission under FET-Open grant agreement no. 899646 (k-NET).

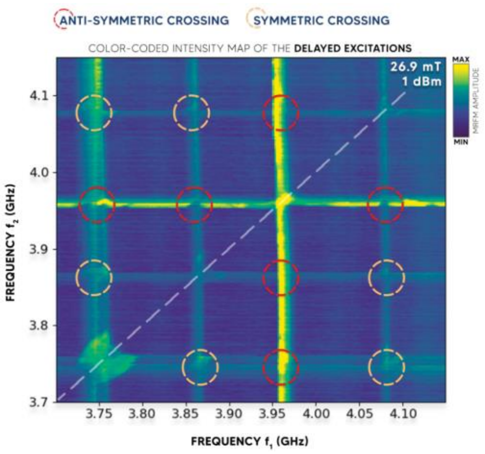


Fig.1 Two-tone MRFM parametric spectroscopy in a 1 µm diameter YIG disk.

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[4] S. Perna et al., J. Magn. Magn. Mater. **546**, 168683 (2022)

# Nonlinear interactions between spin waves in YIG discs

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Nonlinear magnetization dynamics is promising for nonconventional computing applications, such as neuromorphic computing [1]. For example, pattern recognition has recently been demonstrated using a magnon-scattering reservoir [2]. In this context, it was demonstrated that parametric pumping allows the selective excitation of a large number of eigenmodes (spin wave "neurons") in micro-discs of yttrium iron garnet (YIG) [3]. Here, we will discuss the nonlinear couplings (synaptic weights) between these modes that have been probed in experiment and in simulation. In magnetic resonance force microscopy (MRFM) experiments, we used multiple radiofrequency field excitations to examine how each of the lowest-order modes is coupled to the other modes, which are characterised by enhanced or suppressed peaks in the spectral response, along with the appearance of additional peaks in the spectrum. Micromagnetic simulations have also been performed to gain greater insight into the nonlinear processes at play.
This work is supported by the Horizon2020 Framework Programme of the European Commission under contract number 899646 (k-Net).

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# Non-volatile binary radio-frequency synapses using vortex polarities

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Spintronic devices have been identified as promising candidates for neuromorphic computing. Ross et al. [1] have demonstrated a fully spintronic neural network where magnetic tunnel junctions implement both neurons and synapses. In particular, magnetic junctions perform weighted sums – an operation at the core of neural networks – on radio-frequency (RF) signals, through the spin-diode effect. The synaptic weights are controlled by the resonance frequency of the devices. However, in [1], the control of the resonance frequency is volatile, which is an obstacle to building large artificial neural networks with low energy consumption. Here, we propose to implement non-volatile RF synapses using vortex-based magnetic tunnel junctions. In such a device, the free layer is in a vortex state which magnetic core is out-of-plane and can thus take two opposite directions, called polarities. We observe that each polarity has a different resonance frequency, leading to two synaptic weights of opposite signs. The polarity state is stable and thus the binary synapse is non-volatile. We control the polarity state (i.e. the weight) by sending an RF signal of large amplitude (about 1 mW). This leads the vortex to gyrate at a critical velocity where it reverses. We demonstrate that we can selectively program the synaptic weight be choosing the frequency of the RF signal. We connect magnetic tunnel junctions of different frequencies in series. The chain performs a weighted sum of RF inputs of different frequencies sent in parallel. Furthermore, leveraging the frequency-selectivity of the vortex polarity reversal, we can program each synapse by sending RF signals in the chain. This removes the need for individual accesses to the devices to program them. Our system uses frequency-multiplexing both to perform the weighted sum and to program the synaptic weights, which greatly simplifies the architecture and opens the path to scaling up the size of the network and the density of its connections. As binary neural networks can achieve high accuracy on state-of-the art artificial intelligence tasks [2], these results open the path to large densely connected neural networks implemented in low energy consumption hardware.

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# All-inductive observation of nonlinear spin wave processes in synthetic antiferromagnet microstripes

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Spin waves (SW) are the eigen-excitations of magnetic order parameters. The transport of information by spin is one of the important domains in condensed matter physics and of fundamental importance for the further development of spintronic devices due to their specific properties such as: GHz frequency, nanoscale wavelength, anisotropic propagation, non-linearity [1, 2], and non-reciprocal character. Synthetic antiferromagnet (SAF) which consists of two magnetic layers separated by a thin nonmagnetic spacing is adequate to study the nonlin- earity of spin waves. Here we report on an all-inductive study of nonlinear processes in microstripes of SAF. Such films exhibit two types of SW modes, known as acoustical and optical modes. The frequencies of these modes vary with the applied magnetic field. For specific configurations of the applied static magnetic field $H_{DC}$, the frequency of the acoustical magnon mode ($f_{ac}$) becomes half that of the optical magnon mode ($f_{op}$), a favorable condition to investigate nonlinear phenomena in SAF [1].

We used the experimental configuration shown in Fig.1.a to measure the nonlinear SW processes in a SAF inductively. An RF stimulus is sent through an inductive antenna using a synthesizer to excite spin waves in an optimized $Co_{40}Fe_{40}B_{20}$/Ru/CoFeB stripe [3] acting as spin wave conduit. The response is then recorded on a spectrum analyzer using a second antenna. To investigate nonlinear effects, three parameters are varied: i) the static field $H_{DC}$ chosen for each sample to ensure $f_{op}$=2 $f_{ac}$, ii) the microwave power arriving at the sample (-15<$P_{in}$<11 dBm), and iii) the pump frequency to excite the optical mode (10<$f_{pump}$<15 GHz). To evidence the nonlinear behaviors, an excess power spectral density is determined by subtracting values recorded on the same sample but for a slightly different value of $H_{DC}$. A typical spectra is shown in Fig.1.b. The doublets near $f_{pump}/2$ evidence a three-magnon process where one optical magnon at $f_{pump}$ splits into two acoustical magnons at $f_{pump}/2-\delta$ and $f_{pump}/2+\delta$. 2). The second harmonics of the doublet around the $f_{pump}$ indicates that we are deep in the nonlinear regime and the strong halo around $f_{pump}$ corresponds to a four-magnon scattering process, in which two optical magnons excited at $f_{pump}$ annihilate and create two new optical magnons [1, 4].

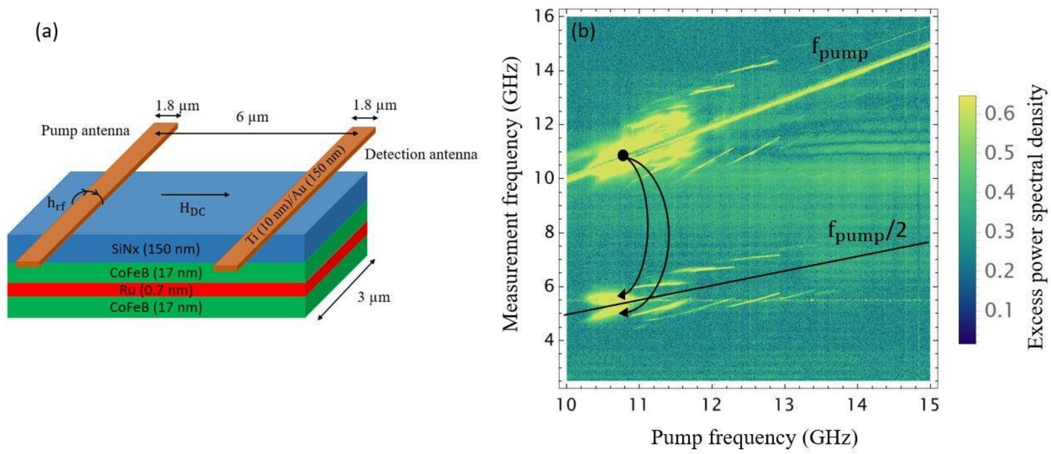


Figure 1: a) Scheme of the experimental configuration. In practice, 4 well separated $Co_{40}Fe_{40}B_{20}$ microstripes are positioned under the antennas to improve the signal-to-noise ratio. b) Spectra of excess power spectral density versus pump frequency at excitation power arriving at the sample 11 dBm and $H_{DC}$=20 mT, for a SAF with 2x17 nm of CoFeB.

For the three-magnon scattering process, we observe that the frequency of the split magnons is directly related to the input frequency and the power level applied. To further investigate the threshold behavior, we performed a detailed study on the power dependence of the magnon amplitude at various input frequencies. Figure 2.b demonstrates the threshold character of the splitting process.

Furthermore, we are developing a methodology to investigate a time-resolved measurement of nonlinear SW where we use a pulsed RF excitation instead of a continuous wave. The mechanisms of splitting are closely related to the timescales of magnetization dynamics. Magnon lifetimes are on the order of a few nanoseconds, so it is important to ensure that the duration of the pulsed excitation is sufficient to induce nonlinear interactions. To achieve this, we varied the duration of RF pulses from 500 ns to 5 ns. By systematically varying the pulse duration and analyzing the measurements, we can determine the time of the magnons creation and gain insight into their dynamics.

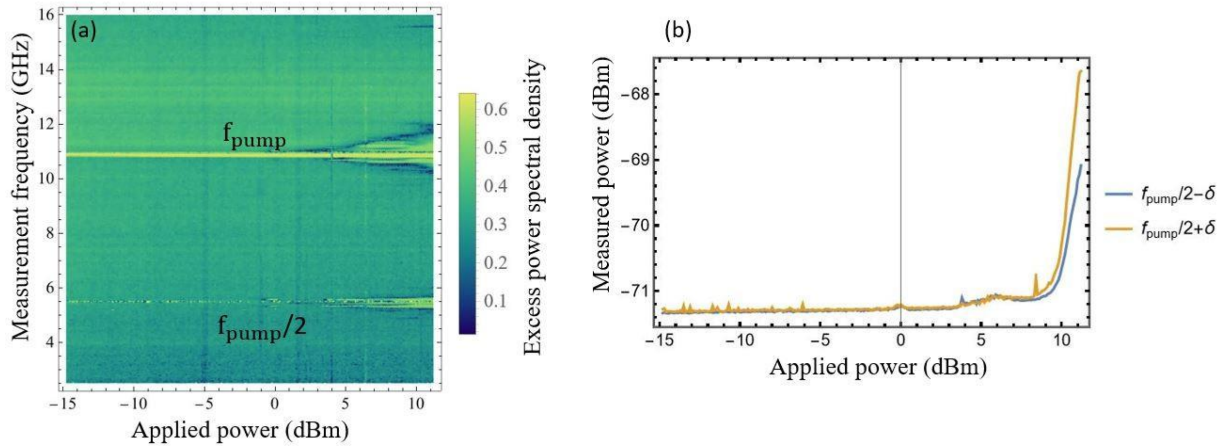


Figure 2: a) The power dependence of the non-linear effects at $f_{pump}$=10.8 GHz. b) The power threshold of the three-magnon splitting process around the frequencies $f_{pump}/2-\delta$=5.4 GHz and $f_{pump}/2+\delta$=5.6 GHz as a function of the microwave power arriving at the sample.

## Acknowledgments

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**Task-adaptive physical reservoir computing using magnetic Skyrmions**

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Physical reservoir computing (PRC) is a specific neuromorphic architecture potentially offering energy-efficient solutions for processing machine learning (ML) tasks requiring heavy computation. However, establishing a methodology for on-demand control of reservoir properties remains challenging. This is due to the rigidity of configuring the crucial hyperparameters required to maximise computational performance. Hence, physical reservoirs are typically constrained to well-execute a pre-defined set of ML tasks. In this talk, we experimentally demonstrate a flexible task-adaptive PRC using the spectrum space of a single magnetic system with distinctive phase properties. The reservoir is constructed with data-mapped collective spinwave excitations of skyrmion and conical modes. We scrutinise the task-adaptive nature via trivial magnetic phase control in a chiral magnetic insulator Cu2OSeO3 as a model system and bridge the key reservoir properties with various magnetic phases. Our results highlight that skyrmions excel in forecasting chaotic signals, unlike the conical modes that are optimal for nonlinear transformation tasks. Room-temperature demonstrations on FeGe and Co8.5Zn8.5Mn8.5 confirm that our task-adaptive approach to PRC via magnetic phase control is transferable to other phase-rich systems, taking a step closer to energy-efficient computing.

# Micromagnetic simulations of magnon nonlinearinteractions in YIG disk magnetic vortex

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Magnons that describe the Eigen excitations of a magnetic system possess unique properties that make them suitable for carrying, processing, and storing information. For instance, they exhibit nonlinear interactions when excited at high amplitudes. These nonlinear interactions can be used to perform nonconventional computing which aims at reducing the energy consumption in data processing. This study presents micromagnetic simula- tions to understand magnon nonlinear interactions in Yttrium iron garnet (YIG) disks with a vortex state. Weobtain the dispersion relation which is essential in understanding the linear and the nonlinear phenomena. Then we move from linear to the nonlinear regime, focusing on three magnon splitting and coupling with the core gyration. We use MuMax3, a software that utilizes finite difference discretization of space, to perform the micro- magnetic simulations. It calculates the magnetization dynamics in both space and time. The micromagnetic pa- rameters used in the simulations are: saturation magnetization $M_s$ = 140 $10^3 A/m$, damping constant $\alpha = 10^{-3}$, exchange stiffness constant $A_{ex}$ = 3.7 * $10^{-12} J/m$ and first order cubic anisotropy constant $K_{c1}$ = 464 $J.m^{-3}$. Due to cubic anisotropy, the static out-of-plane magnetization outside the vortex core will not exhibit uniformity. Instead, it will display a distinct three-fold symmetry.

The disk used in this study has a thickness of 65 *nm* and a diameter of 500 *nm*. The rotational symmetryof the disk leads to the formation of radial eigenmodes with mode number *n* and azimuthal eigenmodes with mode number *m*[1]. To obtain the dispersion relation, we excite the disk in the r.f. range using a cardinal sine function perpendicular to the disk plane with specific spatial symmetry, a Bessel function to excite a given radial mode, and a cosine function to excite azimuthal mode. Fig.1 shows the obtained dispersion relation with the mode spatial profiles [2]. It shows a splitting of the azimuthal number 1 due to the hybridization with the core gyration. The mode at 2.019 GHz exhibits azimuthal number 3 and radial number 0 and can be excited despite

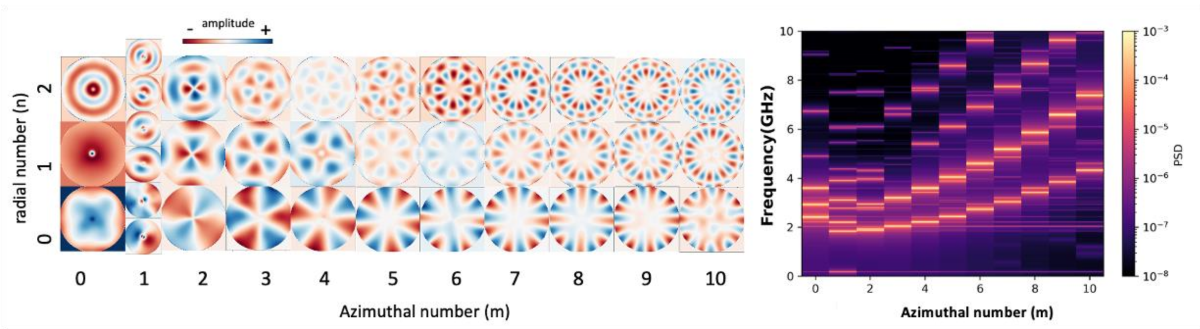


Figure 1: The dispersion relation for 500nm YIG disk with the mode spatial profiles the

symmetry of the excitation due to the cubic anisotropy.

Applying a 0.01 mT rf magnetic field amplitude yields a linear response, as indicated by the diagonal linein Figure 2a. Increasing the rf field to 0.1 mT produces some bands of nonlinear interactions. At an excitation frequency of 2.92 GHz, corresponding to radial mode number $n$ = 1 and azimuthal mode $m$ = 0 in Figure 1, we observe four magnon modes equally distributed around $f_{exc}$, with a frequency spacing of 170 MHz ($\delta f$ ). The in-plane component of the magnetization exhibits a gyration with a frequency of 170 MHz starting after 200ns,the same as the modes distributed around $f_{exc}$, which indicates coupling to the gyration frequency. Exciting the disk with 2mT rf magnetic field amplitude results in different processes of nonlinear interactions. The vertical bands below 3GHz are coming from coupling with the core gyration. However the nonlinear interactions above 4GHz are coming from 3 magnon scattering except the process at 4.02GHz where we have two kinds of nonlinear interactions. Initially, three magnon scattering occurs at 1.824GHz and 2.194GHz, followed by gyration motion

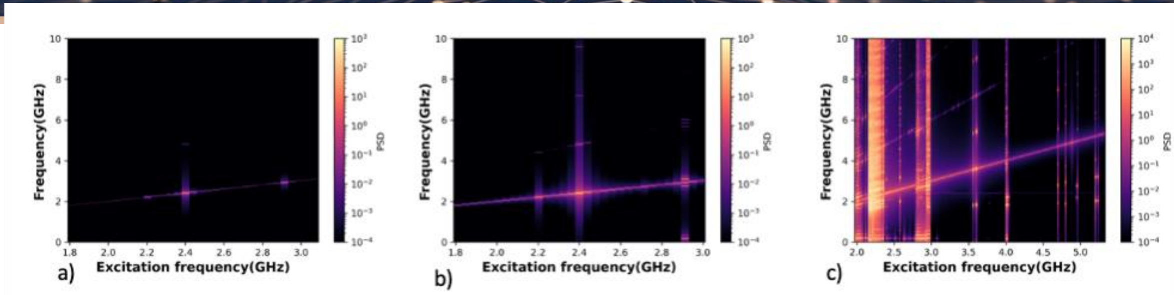


Figure 2: The power spectral density map for 500nm YIG disk with 65nm thickness a)the linear response at 0.01mT rf magnetic field amplitude b)the nonlinear response at 0.1mT c)2mT

that begins 400ns later. Additionally, the secondary modes arising from three magnon scattering couple to this gyration, as demonstrated by the evolution of the mode population over time in Fig.3 so the gyration is like a relaxation channel for these modes. These two modes coming from three magnon scattering have the same radial and azimuthal numbers as the selection rule of having different radial numbers is relaxed due to the hybridizationwith the core gyration [3]. Another two modes appear at the same time as the gyration motion, the mode which has 3 fold symmetry and a mode with azimuthal 2 and radial 0. The effect of having two processes, three magnon scattering followed by coupling with the gyration motion is coming from the anisotropy because removing the anisotropy will suppress the gyration motion, and we will have just three magnon scattering processes.

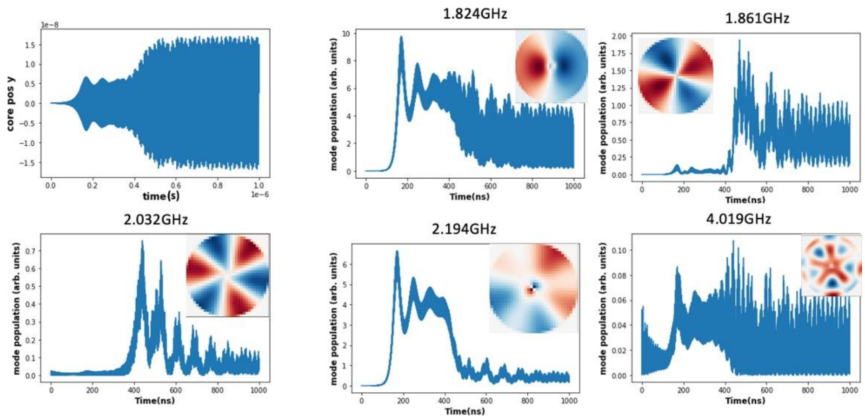


Figure 3: The evolution of the mode populations and the spatial profiles for the gyration motion and the secondarymodes of three magnon scattering when the disk is excited with 2mT and 4.02GHz

## Acknowledgments

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# A Magnonic Convolutional Neural Network

**Hongwei Tan**[*,1], Nikolai Kuznetsov[1], Anton Lutsenko[1], Lukáš Flajšman[1], and Sebastiaan van Dijken[*,1]

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Magnonics is an emerging field that investigates the generation, propagation, and manipulation of magnons, presenting substantial promise for groundbreaking applications in energy-efficient information processing and communication devices. However, realizing efficient magnonic computing devices remains challenging. Here, we experimentally demonstrate a magnonic convolutional neural network that leverages spin-wave interference in a patterned YIG film for direct convolution. As a conceptual demonstration, we apply the magnonic convolutional neural network to achieve image classification and reconstruction, unveiling its potential for transformative applications in neuromorphic hardware.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101070347-MANNGA. Yet, views and opinions expressed are those of the authors only and do not necessarily reflect those of the EU, and the EU cannot be held responsible for them.

# Spin Wave Threshold Logic Gate

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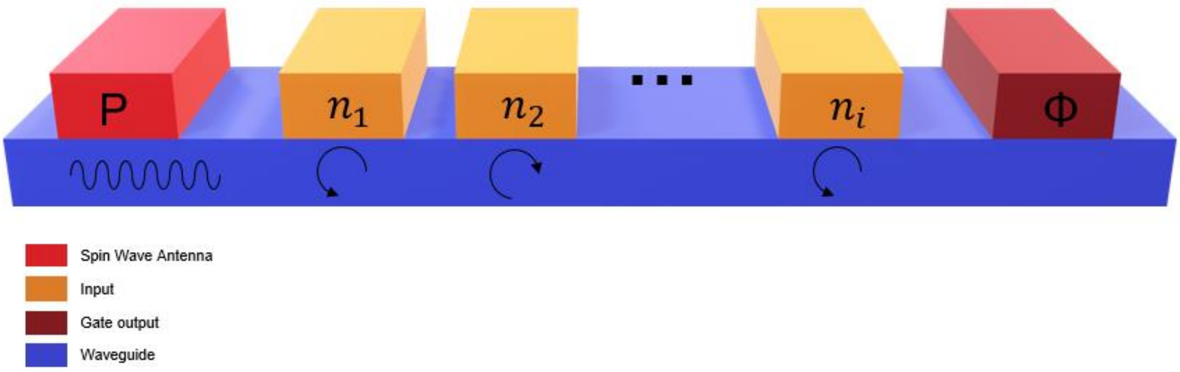
Abstract:

While Spin Waves (SW) interaction provides natural support for low power Majority (MAJ) gate implementations many hurdles still exists on the road towards the realization of practically relevant SW circuits. In this paper we leave the SW interaction avenue and propose Threshold Logic (TL) inspired SW computing, which relies on successive phase rotations applied to one single SW instead of on the interference of an odd number of SWs. We introduce the SW TL gate concept and discuss the way to mirror TL gate weight and threshold values into physical phase-shifter parameters. We discuss some parameters with which we can play to design the device to our specifications and show different way in which weight can be implemented. Subsequently, we demonstrate proper operation of a SW TL based Full Adder (FA) by means of micro-magnetic simulations. We also show how we can implement variable weights allowing for hardware neural networks implemented using the gate. Finally we conclude using the potential advantages of our proposal with a conceptual comparison of Maj and TL based FA implementations.




References: Van Zegbroeck, Arne, Pantazis Anagnostou, Said Hamdioui, Christoph Adelmann, Florin Ciubotaru, and Sorin Cotofana. “Spin Wave Threshold Logic Gates.” In Proceedings of the 18th ACM International Symposium on Nanoscale Architectures, 1–6. Dresden Germany: ACM, 2023. https://doi.org/10.1145/3611315.3633269.